Activity Report Sophia Antipolis - Méditerranée 2019

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List of Inria's Research Teams

Project-Team ABS

Algorithms, Biology, Structure

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Computational Biology

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Project-Team ABS

Creation of the Project-Team: 2008 July 01

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1. Team, Visitors, External Collaborators

Research Scientists

Frédéric Cazals [Team leader, Inria, Senior Researcher, HDR]
Mehmet Serkan Apaydin [Inria, Starting Research Position, until May 2019]
Dorian Mazauric [Inria, Researcher]

External Collaborator

Charles Robert [CNRS, HDR]

PhD Students

Thi Viet Ha Nguyen [Inria, PhD Student]
Timothée O'Donnell [Inria, PhD Student]
Méliné Simsir [Univ Côte d'Azur, PhD Student]

Visiting Scientist

Thiziri Nait Saada [Eurecom, from Sep 2019]

Administrative Assistant

Florence Barbara [Inria, Administrative Assistant]

2. Overall Objectives

2.1. Overall Objectives

Computational Biology and Computational Structural Biology. Understanding the lineage between species and the genetic drift of genes and genomes, apprehending the control and feed-back loops governing the behavior of a cell, a tissue, an organ or a body, and inferring the relationship between the structure of biological (macro)-molecules and their functions are amongst the major challenges of modern biology. The investigation of these challenges is supported by three types of data: genomic data, transcription and expression data, and structural data.

Genetic data feature sequences of nucleotides on DNA and RNA molecules, and are symbolic data whose processing falls in the realm of Theoretical Computer Science: dynamic programming, algorithms on texts and strings, graph theory dedicated to phylogenetic problems. Transcription and expression data feature evolving concentrations of molecules (RNAs, proteins, metabolites) over time, and fit in the formalism of discrete and continuous dynamical systems, and of graph theory. The exploration and the modeling of these data are covered by a rapidly expanding research field termed *systems biology*. Structural data encode informations about the 3D structures of molecules (nucleic acids (DNA, RNA), proteins, small molecules) and their interactions, and come from three main sources: X ray crystallography, NMR spectroscopy, cryo Electron Microscopy. Ultimately, structural data should expand our understanding of how the structure accounts for the function of macro-molecules – one of the central questions in structural biology. This goal actually subsumes two equally difficult challenges, which are *folding* – the process through which a protein adopts its 3D structure, and *docking* – the process through which two or several molecules assemble. Folding and docking are driven by non covalent interactions, and for complex systems, are actually inter-twined [44]. Apart from the bio-physical interests raised by these processes, two different application domains are concerned: in fundamental biology, one is primarily interested in understanding the machinery of the cell; in medicine, applications to drug design are developed.

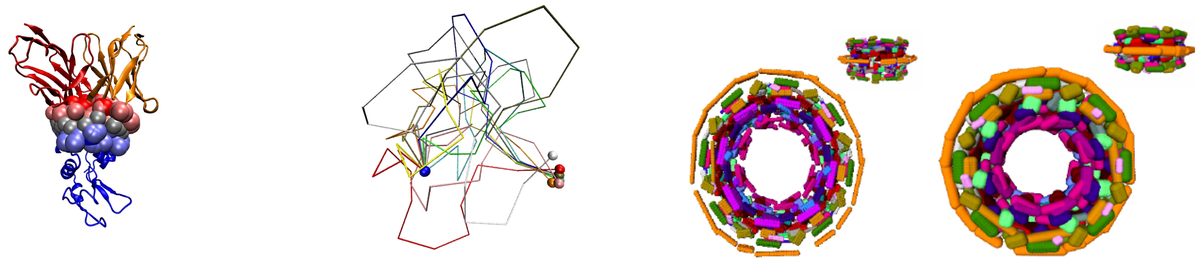
Modeling in Computational Structural Biology. Acquiring structural data is not always possible: NMR is restricted to relatively small molecules; membrane proteins do not crystallize, etc. As a matter of fact, the order of magnitude of the number of genomes sequenced is of the order of one thousand, which results in circa one million of genes recorded in the manually curated Swiss-Prot database. On the other hand, the Protein Data Bank contains circa 90,000 structures. Thus, the paucity of structures with respect to the known number of genes calls for modeling in structural biology, so as to foster our understanding of the structure-to-function relationship.

Ideally, bio-physical models of macro-molecules should resort to quantum mechanics. While this is possible for small systems, say up to 50 atoms, large systems are investigated within the framework of the Born-Oppenheimer approximation which stipulates the nuclei and the electron cloud can be decoupled. Example force fields developed in this realm are AMBER, CHARMM, OPLS. Of particular importance are Van der Waals models, where each atom is modeled by a sphere whose radius depends on the atom chemical type. From an historical perspective, Richards [42], [31] and later Connolly [27], while defining molecular surfaces and developing algorithms to compute them, established the connexions between molecular modeling and geometric constructions. Remarkably, a number of difficult problems (e.g. additively weighted Voronoi diagrams) were touched upon in these early days.

The models developed in this vein are instrumental in investigating the interactions of molecules for which no structural data is available. But such models often fall short from providing complete answers, which we illustrate with the folding problem. On one hand, as the conformations of side-chains belong to discrete sets (the so-called rotamers or rotational isomers) [33], the number of distinct conformations of a poly-peptidic chain is exponential in the number of amino-acids. On the other hand, Nature folds proteins within time scales ranging from milliseconds to hours, while time-steps used in molecular dynamics simulations are of the order of the femto-second, so that biologically relevant time-scales are out reach for simulations. The fact that Nature avoids the exponential trap is known as Levinthal's paradox. The intrinsic difficulty of problems calls for models exploiting several classes of informations. For small systems, *ab initio* models can be built from first principles. But for more complex systems, *homology* or template-based models integrating a variable amount of knowledge acquired on similar systems are resorted to.

The variety of approaches developed are illustrated by the two community wide experiments CASP (*Critical Assessment of Techniques for Protein Structure Prediction*; http://predictioncenter.org) and CAPRI (*Critical Assessment of Prediction of Interactions*; http://capri.ebi.ac.uk), which allow models and prediction algorithms to be compared to experimentally resolved structures.

As illustrated by the previous discussion, modeling macro-molecules touches upon biology, physics and chemistry, as well as mathematics and computer science. In the following, we present the topics investigated within ABS.



(a) (b) (c)

Figure 1. ***Geometric constructions in computational structural biology.*** *(a) An antibody-antigen complex, with interface atoms identified by our Voronoi based interface model. This model is instrumental in mining correlations between structural and biological as well as biophysical properties of protein complexes [12]. (b) A diverse set of conformations of a backbone loop, selected thanks to a geometric optimization algorithm [8]. Such conformations are used by mean field theory based docking algorithms. (c) A toleranced model (TOM) of the nuclear pore complex, visualized at two different scales [9]. The parameterized family of shapes coded by a TOM is instrumental to identify stable properties of the underlying macro-molecular system.*

3. Research Program

3.1. Introduction

The research conducted by ABS focuses on three main directions in Computational Structural Biology (CSB), together with the associated methodological developments:
– Modeling interfaces and contacts,
– Modeling macro-molecular assemblies,
– Modeling the flexibility of macro-molecules,
– Algorithmic foundations.

3.2. Modeling interfaces and contacts

Keywords: Docking, interfaces, protein complexes, structural alphabets, scoring functions, Voronoi diagrams, arrangements of balls.

The Protein Data Bank, http://www.rcsb.org/pdb, contains the structural data which have been resolved experimentally. Most of the entries of the PDB feature isolated proteins [0], the remaining ones being protein - protein or protein - drug complexes. These structures feature what Nature does – up to the bias imposed by the experimental conditions inherent to structure elucidation, and are of special interest to investigate non-covalent contacts in biological complexes. More precisely, given two proteins defining a complex, interface atoms are defined as the atoms of one protein *interacting* with atoms of the second one. Understanding the structure of interfaces is central to understand biological complexes and thus the function of biological molecules [44]. Yet, in spite of almost three decades of investigations, the basic principles guiding the formation of interfaces and accounting for its stability are unknown [47]. Current investigations follow two routes. From the experimental perspective [30], directed mutagenesis enables one to quantify the energetic importance of residues, important residues being termed *hot* residues. Such studies recently evidenced the *modular* architecture of interfaces

[0]For structures resolved by crystallography, the PDB contains the asymmetric unit of the crystal. Determining the biological unit from the asymmetric unit is a problem in itself.

[41]. From the modeling perspective, the main issue consists of guessing the hot residues from sequence and/or structural informations [36].

The description of interfaces is also of special interest to improve *scoring functions*. By scoring function, two things are meant: either a function which assigns to a complex a quantity homogeneous to a free energy change [0], or a function stating that a complex is more stable than another one, in which case the value returned is a score and not an energy. Borrowing to statistical mechanics [25], the usual way to design scoring functions is to mimic the so-called potentials of mean force. To put it briefly, one reverts Boltzmann's law, that is, denoting $p_i(r)$ the probability of two atoms –defining type i– to be located at distance r, the (free) energy assigned to the pair is computed as $E_i(r) = -kT \log p_i(r)$. Estimating from the PDB one function $p_i(r)$ for each type of pair of atoms, the energy of a complex is computed as the sum of the energies of the pairs located within a distance threshold [45], [32]. To compare the energy thus obtained to a reference state, one may compute $E = \sum_i p_i \log p_i/q_i$, with p_i the observed frequencies, and q_i the frequencies stemming from an a priori model [37]. In doing so, the energy defined is nothing but the Kullback-Leibler divergence between the distributions $\{p_i\}$ and $\{q_i\}$.

Describing interfaces poses problems in two settings: static and dynamic.

In the static setting, one seeks the minimalist geometric model providing a relevant bio-physical signal. A first step in doing so consists of identifying interface atoms, so as to relate the geometry and the bio-chemistry at the interface level [12]. To elaborate at the atomic level, one seeks a structural alphabet encoding the spatial structure of proteins. At the side-chain and backbone level, an example of such alphabet is that of [26]. At the atomic level and in spite of recent observations on the local structure of the neighborhood of a given atom [46], no such alphabet is known. Specific important local conformations are known, though. One of them is the so-called dehydron structure, which is an under-desolvated hydrogen bond – a property that can be directly inferred from the spatial configuration of the C_α carbons surrounding a hydrogen bond [29].

In the dynamic setting, one wishes to understand whether selected (hot) residues exhibit specific dynamic properties, so as to serve as anchors in a binding process [40]. More generally, any significant observation raised in the static setting deserves investigations in the dynamic setting, so as to assess its stability. Such questions are also related to the problem of correlated motions, which we discuss next.

3.3. Modeling macro-molecular assemblies

Keywords: Macro-molecular assembly, reconstruction by data integration, proteomics, modeling with uncertainties, curved Voronoi diagrams, topological persistence.

3.3.1. Reconstruction by Data Integration

Large protein assemblies such as the Nuclear Pore Complex (NPC), chaperonin cavities, the proteasome or ATP synthases, to name a few, are key to numerous biological functions. To improve our understanding of these functions, one would ideally like to build and animate atomic models of these molecular machines. However, this task is especially tough, due to their size and their plasticity, but also due to the flexibility of the proteins involved. In a sense, the modeling challenges arising in this context are different from those faced for binary docking, and also from those encountered for intermediate size complexes which are often amenable to a processing mixing (cryo-EM) image analysis and classical docking. To face these new challenges, an emerging paradigm is that of reconstruction by data integration [24]. In a nutshell, the strategy is reminiscent from NMR and consists of mixing experimental data from a variety of sources, so as to find out the model(s) best complying with the data. This strategy has been in particular used to propose plausible models of the Nuclear Pore Complex [23], the largest assembly known to date in the eukaryotic cell, and consisting of 456 protein *instances* of 30 *types*.

[0]The Gibbs free energy of a system is defined by $G = H - TS$, with $H = U + PV$. G is minimum at an equilibrium, and differences in G drive chemical reactions.

3.3.2. Modeling with Uncertainties and Model Assessment

Reconstruction by data integration requires three ingredients. First, a parametrized model must be adopted, typically a collection of balls to model a protein with pseudo-atoms. Second, as in NMR, a functional measuring the agreement between a model and the data must be chosen. In [22], this functional is based upon *restraints*, namely penalties associated to the experimental data. Third, an optimization scheme must be selected. The design of restraints is notoriously challenging, due to the ambiguous nature and/or the noise level of the data. For example, Tandem Affinity Purification (TAP) gives access to a *pullout* i.e. a list of protein types which are known to interact with one tagged protein type, but no information on the number of complexes or on the stoichiometry of proteins types within a complex is provided. In cryo-EM, the envelope enclosing an assembly is often imprecisely defined, in particular in regions of low density. For immuno-EM labelling experiments, positional uncertainties arise from the microscope resolution.

These uncertainties coupled with the complexity of the functional being optimized, which in general is non convex, have two consequences. First, it is impossible to single out a unique reconstruction, and a set of plausible reconstructions must be considered. As an example, 1000 plausible models of the NPC were reported in [22]. Interestingly, averaging the positions of all balls of a particular protein type across these models resulted in 30 so-called *probability density maps*, each such map encoding the probability of presence of a particular protein type at a particular location in the NPC. Second, the assessment of all models (individual and averaged) is non trivial. In particular, the lack of straightforward statistical analysis of the individual models and the absence of assessment for the averaged models are detrimental to the mechanistic exploitation of the reconstruction results. At this stage, such models therefore remain qualitative.

3.4. Modeling the flexibility of macro-molecules

Keywords: Folding, docking, energy landscapes, induced fit, molecular dynamics, conformers, conformer ensembles, point clouds, reconstruction, shape learning, Morse theory.

Proteins in vivo vibrate at various frequencies: high frequencies correspond to small amplitude deformations of chemical bonds, while low frequencies characterize more global deformations. This flexibility contributes to the entropy thus the *free energy* of the system *protein - solvent*. From the experimental standpoint, NMR studies generate ensembles of conformations, called *conformers*, and so do molecular dynamics (MD) simulations. Of particular interest while investigating flexibility is the notion of correlated motion. Intuitively, when a protein is folded, all atomic movements must be correlated, a constraint which gets alleviated when the protein unfolds since the steric constraints get relaxed [0]. Understanding correlations is of special interest to predict the folding pathway that leads a protein towards its native state. A similar discussion holds for the case of partners within a complex, for example in the third step of the *diffusion - conformer selection - induced fit* complex formation model.

Parameterizing these correlated motions, describing the corresponding energy landscapes, as well as handling collections of conformations pose challenging algorithmic problems.

At the side-chain level, the question of improving rotamer libraries is still of interest [28]. This question is essentially a clustering problem in the parameter space describing the side-chains conformations.

At the atomic level, flexibility is essentially investigated resorting to methods based on a classical potential energy (molecular dynamics), and (inverse) kinematics. A molecular dynamics simulation provides a point cloud sampling the conformational landscape of the molecular system investigated, as each step in the simulation corresponds to one point in the parameter space describing the system (the conformational space) [43]. The standard methodology to analyze such a point cloud consists of resorting to normal modes. Recently, though, more elaborate methods resorting to more local analysis [39], to Morse theory [34] and to analysis of meta-stable states of time series [35] have been proposed.

3.5. Algorithmic foundations

Keywords: Computational geometry, computational topology, optimization, data analysis.

[0] Assuming local forces are prominent, which in turn subsumes electrostatic interactions are not prominent.

Making a stride towards a better understanding of the biophysical questions discussed in the previous sections requires various methodological developments, which we briefly discuss now.

3.5.1. Modeling Interfaces and Contacts

In modeling interfaces and contacts, one may favor geometric or topological information.

On the geometric side, the problem of modeling contacts at the atomic level is tantamount to encoding multi-body relations between an atom and its neighbors. On the one hand, one may use an encoding of neighborhoods based on geometric constructions such as Voronoi diagrams (affine or curved) or arrangements of balls. On the other hand, one may resort to clustering strategies in higher dimensional spaces, as the p neighbors of a given atom are represented by $3p - 6$ degrees of freedom – the neighborhood being invariant upon rigid motions. The information gathered while modeling contacts can further be integrated into interface models.

On the topological side, one may favor constructions which remain stable if each atom in a structure *retains* the same neighbors, even though the 3D positions of these neighbors change to some extent. This process is observed in flexible docking cases, and call for the development of methods to encode and compare shapes undergoing tame geometric deformations.

3.5.2. Modeling Macro-molecular Assemblies

In dealing with large assemblies, a number of methodological developments are called for.

On the experimental side, of particular interest is the disambiguation of proteomics signals. For example, TAP and mass spectrometry data call for the development of combinatorial algorithms aiming at unraveling pairwise contacts between proteins within an assembly. Likewise, density maps coming from electron microscopy, which are often of intermediate resolution (5-10Å) call the development of noise resilient segmentation and interpretation algorithms. The results produced by such algorithms can further be used to guide the docking of high resolutions crystal structures into maps.

As for modeling, two classes of developments are particularly stimulating. The first one is concerned with the design of algorithms performing reconstruction by data integration, a process reminiscent from non convex optimization. The second one encompasses assessment methods, in order to single out the reconstructions which best comply with the experimental data. For that endeavor, the development of geometric and topological models accommodating uncertainties is particularly important.

3.5.3. Modeling the Flexibility of Macro-molecules

Given a sampling on an energy landscape, a number of fundamental issues actually arise: how does the point cloud describe the topography of the energy landscape (a question reminiscent from Morse theory)? Can one infer the effective number of degrees of freedom of the system over the simulation, and is this number varying? Answers to these questions would be of major interest to refine our understanding of folding and docking, with applications to the prediction of structural properties. It should be noted in passing that such questions are probably related to modeling phase transitions in statistical physics where geometric and topological methods are being used [38].

From an algorithmic standpoint, such questions are reminiscent of *shape learning*. Given a collection of samples on an (unknown) *model*, *learning* consists of guessing the model from the samples – the result of this process may be called the *reconstruction*. In doing so, two types of guarantees are sought: topologically speaking, the reconstruction and the model should (ideally!) be isotopic; geometrically speaking, their Hausdorff distance should be small. Motivated by applications in Computer Aided Geometric Design, surface reconstruction triggered a major activity in the Computational Geometry community over the past ten years. Aside from applications, reconstruction raises a number of deep issues: the study of distance functions to the model and to the samples, and their comparison; the study of Morse-like constructions stemming from distance functions to points; the analysis of topological invariants of the model and the samples, and their comparison.

4. New Software and Platforms

4.1. SBL

Structural Bioinformatics Library

KEYWORDS: Structural Biology - Biophysics - Software architecture

FUNCTIONAL DESCRIPTION: The SBL is a generic C++/python cross-platform software library targeting complex problems in structural bioinformatics. Its tenet is based on a modular design offering a rich and versatile framework allowing the development of novel applications requiring well specified complex operations, without compromising robustness and performances.

More specifically, the SBL involves four software components (1-4 thereafter). For end-users, the SBL provides ready to use, state-of-the-art (1) applications to handle molecular models defined by unions of balls, to deal with molecular flexibility, to model macro-molecular assemblies. These applications can also be combined to tackle integrated analysis problems. For developers, the SBL provides a broad C++ toolbox with modular design, involving core (2) algorithms, (3) biophysical models, and (4) modules, the latter being especially suited to develop novel applications. The SBL comes with a thorough documentation consisting of user and reference manuals, and a bugzilla platform to handle community feedback.

RELEASE FUNCTIONAL DESCRIPTION: In 2018, major efforts targeted two points. First, the simplification of installation procedures – now possible with conda/python. Second, the development of packages revolving on molecular flexibility at large: representations in internal and Cartesian coordinates, generic representation of molecular mechanics force fields (and computation of gradients), exploration algorithms for conformational spaces.

- Contact: Frédéric Cazals
- Publication: The Structural Bioinformatics Library: modeling in biomolecular science and beyond
- URL: https://sbl.inria.fr/

5. New Results

5.1. Modeling interfaces and contacts

Keywords: docking, scoring, interfaces, protein complexes, Voronoi diagrams, arrangements of balls.

5.1.1. Characterizing molecular flexibility by combining lRMSD measures

Participants: F. Cazals, R. Tetley.

The root mean square deviation (RMSD) and the least RMSD are two widely used similarity measures in structural bioinformatics. Yet, they stem from global comparisons, possibly obliterating locally conserved motifs. In this work [16], we correct these limitations with the so-called *combined RMSD*, which mixes independent lRMSD measures, each computed with its own rigid motion. The combined RMSD is relevant in two main scenarios, namely to compare (quaternary) structures based on motifs defined from the sequence (domains, SSE), and to compare structures based on structural motifs yielded by local structural alignment methods.

We illustrate the benefits of combined RMSD over the usual lRMSD on three problems, namely (i) the assignment of quaternary structures for hemoglobin (scenario #1), (ii) the calculation of structural phylogenies (case study: class II fusion proteins; scenario #1), and (iii) the analysis of conformational changes based on combined RMSD of rigid structural motifs (case study: one class II fusion protein; scenario #2). Using these, we argue that the combined RMSD is a tool of choice to perform positive and negative discrimination of degree of freedom, with applications to the design of move sets and collective coordinates.

Executables to compute combined RMSD are available within the Structural Bioinformatics Library (http://sbl.inria.fr).

5.2. Modeling the flexibility of macro-molecules

Keywords: protein, flexibility, collective coordinate, conformational sampling dimensionality reduction.

5.2.1. Wang-Landau Algorithm: an adapted random walk to boost convergence

Participants: F. Cazals, A. Chevallier.

The Wang-Landau (WL) algorithm is a recently developed stochastic algorithm computing densities of states of a physical system, and also performing numerical integration in high dimensional spaces. Since its inception, it has been used on a variety of (bio-)physical systems, and in selected cases, its convergence has been proved. The convergence speed of the algorithm is tightly tied to the connectivity properties of the underlying random walk.

In this work [19], we propose an efficient random walk that uses geometrical information to circumvent the following inherent difficulties: avoiding overstepping strata, toning down concentration phenomena in high-dimensional spaces, and accommodating multidimensional distributions. These improvements are especially well suited to improve calculations on a per basin basis – included anharmonic ones.

Experiments on various models stress the importance of these improvements to make WL effective in challenging cases. Altogether, these improvements make it possible to compute density of states for regions of the phase space of small biomolecules.

5.2.2. Survey of the analysis of continuous conformational variability of biological macromolecules by electron microscopy

Participant: F. Cazals.

In collaboration with a group of colleagues led by J. M. Carazo, CSIC, Biocomputing Unit, National Center for Biotechnology, Spain.

Single-particle analysis by electron microscopy is a well established technique for analyzing the three-dimensional structures of biological macromolecules. Besides its ability to produce high-resolution structures, it also provides insights into the dynamic behavior of the structures by elucidating their conformational variability. In this work [17], the different image-processing methods currently available to study continuous conformational changes are reviewed.

5.3. Algorithmic foundations

Keywords: Computational geometry, computational topology, optimization, data analysis.

5.3.1. Comparing two clusterings using matchings between clusters of clusters

Participants: F. Cazals, D. Mazauric, R. Tetley.

In collaboration with R. Watrigant, University Lyon I.

Clustering is a fundamental problem in data science, yet, the variety of clustering methods and their sensitivity to parameters make clustering hard. To analyze the stability of a given clustering algorithm while varying its parameters, and to compare clusters yielded by different algorithms, several comparison schemes based on matchings, information theory and various indices (Rand, Jaccard) have been developed. In this work [15], we go beyond these by providing a novel class of methods computing meta-clusters within each clustering– a meta-cluster is a group of clusters, together with a matching between these.

Let the intersection graph of two clusterings be the edge-weighted bipartite graph in which the nodes represent the clusters, the edges represent the non empty intersection between two clusters, and the weight of an edge is the number of common items. We introduce the so-called D-Family matching problem on intersection graphs, with D the upper-bound on the diameter of the graph induced by the clusters of any meta-cluster. First we prove NP-completeness and APX-hardness results, and unbounded approximation ratio of simple strategies. Second, we design exact polynomial time dynamic programming algorithms for some classes of graphs (in particular trees). Then, we prove spanning-tree based efficient heuristic algorithms for general graphs.

Our experiments illustrate the role of D as a scale parameter providing information on the relationship between clusters within a clustering and in-between two clusterings. They also show the advantages of our built-in mapping over classical cluster comparison measures such as the variation of information (VI).

5.3.2. *Low-Complexity Nonparametric Bayesian Online Prediction with Universal Guarantees*

Participant: F. Cazals.

In collaboration with A. Lhéritier, Amadeus SA.

In this work [18], we propose a novel nonparametric online predictor for discrete labels conditioned on multivariate continuous features. The predictor is based on a feature space discretization induced by a full-fledged k-d tree with randomly picked directions and a recursive Bayesian distribution, which allows to automatically learn the most relevant feature scales characterizing the conditional distribution. We prove its pointwise universality, i.e., it achieves a normalized log loss performance asymptotically as good as the true conditional entropy of the labels given the features. The time complexity to process the n-th sample point is $O(\log n)$ in probability with respect to the distribution generating the data points, whereas other exact nonparametric methods require to process all past observations. Experiments on challenging datasets show the computational and statistical efficiency of our algorithm in comparison to standard and state-of-the-art methods.

5.3.3. *How long does it take for all users in a social network to choose their communities?*

Participant: D. Mazauric.

In collaboration with J.-C. Bermond (Coati project-team), A. Chaintreau (Columbia University), and G. Ducoffe (National Institute for Research and Development in Informatics, Bucharest).

In this work [14], we consider a community formation problem in social networks, where the users are either friends or enemies. The users are partitioned into conflict-free groups (*i.e.*, independent sets in the *conflict graph*$G^- = (V, E)$ that represents the enmities between users). The dynamics goes on as long as there exists any set of at most k users, k being any fixed parameter, that can change their current groups in the partition *simultaneously*, in such a way that they all strictly increase their utilities (number of friends *i.e.*, the cardinality of their respective groups minus one). Previously, the best-known upper-bounds on the maximum time of convergence were $\mathcal{O}(|V|\alpha(G^-))$ for $k \leq 2$ and $\mathcal{O}(|V|^3)$ for $k = 3$, with $\alpha(G^-)$ being the independence number of G^-. Our first contribution in this paper consists in reinterpreting the initial problem as the study of a dominance ordering over the vectors of integer partitions. With this approach, we obtain for $k \leq 2$ the tight upper-bound $\mathcal{O}(|V| \min\{\alpha(G^-), \sqrt{|V|}\})$ and, when G^- is the empty graph, the exact value of order $\frac{(2|V|)^{3/2}}{3}$. The time of convergence, for any fixed $k \geq 4$, was conjectured to be polynomial. In this paper we disprove this. Specifically, we prove that for any $k \geq 4$, the maximum time of convergence is in $\Omega(|V|^{\Theta(\log |V|)})$.

6. Partnerships and Cooperations

6.1. Regional Initiatives

– Frédéric Cazals is endowed chair within the 3IA Côte d'Azur (http://3ia.univ-cotedazur.fr/), within the focus area *Computational Biology and Bio-Inspired AI.*

6.2. International Research Visitors

6.2.1. Visits of International Scientists

6.2.1.1. Internships

- Internship of Maria Guramare, Harvard University, Cambridge, Massachusetts. Supervision: Frédéric Cazals and Dorian Mazauric. *Shortest Paths under Constraints Problem with Application for Structural Alignments.*
- Internship of Guilherme Santa Cruz, Polytech Nice. Supervision: Frédéric Cazals and Dorian Mazauric. *New method for assessing protein-phenotype relevance interpolating gene expression and biological networks*.
- Internship of Gabriel Djebbar, École Polytechnique de l'Université Nice Sophia Antipolis. Filière Sciences Informatiques, deuxième année du cursus ingénieur (niveau Master 1). Supervision: Frédéric Havet and Dorian Mazauric. *Graph Coloring Games with application on Algorithmic Geometry.*
- Projet de fin d'études de Youssef Benjelloun et Quentin Sautel, École Polytechnique de l'Université Nice Sophia Antipolis. Filière Mathématiques Appliquées et Modélisation, deuxième année du cursus ingénieur (niveau Master 1). Supervision: Dorian Mazauric. *Algorithmes pour le calcul de motif commun d'un ensemble de conformations d'une protéine.*

7. Dissemination

7.1. Promoting Scientific Activities

7.1.1. Scientific Events: Organisation

7.1.1.1. General Chair, Scientific Chair

– Frédéric Cazals:

- F. Cazals co-organized, with P. Alliez and F. Chazal, the conference *New Horizons in Computational Geometry and Topology*, held at Sophia Antipolis (September 5-6, 2019) in honor of J-D. Boissonnat. See https://project.inria.fr/jdb2019/en/.

7.1.2. Scientific Events: Selection

7.1.2.1. Member of the Conference Program Committees

– Frédéric Cazals was member of the following program committees:

- Symposium on Computational Geometry
- Symposium On Geometry Processing
- International Conference on Computational Systems-Biology and Bioinformatics:
- Intelligent Systems for Molecular Biology (ISMB), PC member of Protein Interactions & Molecular Networks

7.1.2.2. Reviewer

– Frédéric Cazals reviewed for the following journals:

- Bioinformatics
- Discrete and applied mathematics
- PLOS Computational Biology
- PLOS One

7.1.3. Invited Talks

– Frédéric Cazals gave the following invited talks:

- *Multiscale molecular flexibility analysis: novel insights.* MPI Frankfurt, July 2019.
- *Multiscale molecular flexibility analysis: novel insights.* Conference of the Polish Bioinformatics Society, Torun, June 2019.
- *Bio-molecules: on the role of geometry in the tryptic structure - dynamics -function.* Meeting of the French Academy of Sciences, French Riviera, June 2019.
- *Leveraging structural data by decoupling structure, thermodynamics and dynamics*, Challenges in large scale biomolecular simulation, Inst. Etudes Sc. de Cargese, France, May 2019
- *Mining molecular flexibility: novel tools, novel insights*, University College, London, April 2019.
- *Novel structural parameters of IG-Ag complexes yield a quantitative description of interaction specificity and binding affinity*, Journées scientifiques de la SFHI (Soc. Fr. d'histocompatibilité et d'immunogénétique), Paris, Mars 2019.

7.1.4. Leadership within the Scientific Community

– Frédéric Cazals:

- 2010-.... Member of the steering committee of the *GDR Bioinformatique Moléculaire*, for the *Structure and macro-molecular interactions* theme.
- 2017-2019. Co-chair, with Yann Ponty, of the working group / groupe de travail *(GT MASIM - Méthodes Algorithmiques pour les Structures et Interactions Macromoléculaires*, within the *GDR de BIoinformatique Moléculaire* (GDR BIM, http://www.gdr-bim.cnrs.fr/).

7.1.5. Scientific Expertise

– Frédéric Cazals:

- 2019: reviewer for ERC consolidator grants.

7.1.6. Research Administration

– Frédéric Cazals:

- 2017-.... President of the *Comité de suivi doctoral* (CSD), Inria Sophia Antipolis - Méditerranée. The CSD supervises all aspects of PhD student's life within Inria Sophia Antipolis - Méditerranée.
- 2018-.... Member of the *bureau du comité des équipes projets*.

– Dorian Mazauric:

- 2019-.... Head of *Commission Mastic* (Médiation et Animation des MAthématiques, des Sciences et Techniques Informatiques et des Communications), Inria Sophia Antipolis - Méditerranée.
- 2016-2019. Member of the *Comité de Centre*, Inria Sophia Antipolis - Méditerranée.
- 2018-2019. Member of the *Commission de Développement Technologique*, Inria Sophia Antipolis - Méditerranée.

7.2. Teaching - Supervision - Juries

7.2.1. Teaching

- Master: Frédéric Cazals (Inria ABS) and Frédéric Chazal (Inria Saclay), *Foundations of Geometric Methods in Data Analysis*, Data Sciences Program, Department of Applied Mathematics, Ecole Centrale Paris. (http://www-sop.inria.fr/abs/teaching/centrale-FGMDA/centrale-FGMDA.html)
- Master : Dorian Mazauric, Algorithmique et Complexité, 23h30 TD, niveau M1, École Polytechnique de l'Université Nice Sophia Antipolis, filière Sciences Informatiques, France.
- Bachelor : Dorian Mazauric, Langages Formelles et Automates, 24h TD, niveau L3, École Polytechnique de l'Université Nice Sophia Antipolis, filière Sciences Informatiques, France.
- Bachelor : Dorian Mazauric, Algorithmique, 3h de cours et 8 heures de TD, niveau licence, Université Côte d'Azur, Diplôme interuniversitaire (formation des enseignants de lycée), Sophia Antipolis, France.

7.2.2. Supervision

- **PhD, 4th year:** Augustin Chevallier, *Random walks for estimating the volume of convex bodies and densities of states in high dimensional spaces*. Defended on the 08/04/2019. Université Côte d'Azur.
- **PhD in progress, 3rd year:** Méliné Simsir, *Modeling drug efflux by Patched*. Université Côte d'Azur. Thesis co-supervised by Frédéric Cazals and Isabelle Mus-Veteau, IPMC/CNRS.
- **PhD in progress, 2nd year:** Timothée O'Donnel, *Modeling the influenza polymerase*. Université Côte d'Azur. Thesis co-supervised by Frédéric Cazals and Bernard Delmas, INRA Jouy-en-Josas.
- **PhD in progress, 2nd year** : Thi Viet Ha Nguyen, Graph Algorithms techniques for (low and high) resolution models of large protein assemblies, Frédéric Havet (Inria/I3S project-team Coati) and Dorian Mazauric.

7.2.3. Juries

– Frédéric Cazals:

- Maria Elisa Ruiz Echartea, Université de Lorraine, December 2019. Rapporteur on the PhD thesis *Multi-component protein assembly using distance constraints*. Advisors: David W. Ritchie - Marie-Dominique Devignes.
- Alba Chiara De Vitis, Université Côte d'Azur, May 2019. Committee member. *Kernel Methods for High Dimensional Data Analysis*. Advisors: D. Cohen-Steiner, J-D. Boissonnat.
- Juraj Michalik, Ecole Polytechnique, March 2019. Rapporteur on the PhD thesis *Non-redundant sampling in RNA bioinformatics*. Advisors: Yann Ponty and Hélène Touzet.

7.3. Popularization

This part mainly concerns Dorian Mazauric.

7.3.1. Internal or external Inria responsibilities

- 2019-.... Head of *Commission Mastic* (Médiation et Animation des MAthématiques, des Sciences et Techniques Informatiques et des Communications), Inria Sophia Antipolis - Méditerranée.
- 2019-.... Coordinator of *Terra Numerica – vers une Cité du Numérique*.
- 2018-2019. Member of the *Conseil d'Administration de l'association les Petits Débrouillards*.
- 2018-2019. Coordinator of *projet de médiation Galéjade* : Graphes et ALgorithmes : Ensemble de Jeux À Destination des Ecoliers... (mais pas que).

7.3.2. Articles and contents

See https://galejade.inria.fr and http://terra-numerica.org/.

7.3.3. Education

- 26/10/2019. Animation d'ateliers de GALEJADE au weekend d'initiation à la culture numérique organisé par Class'Code MED. Graphes, algorithmes et magie des mathématiques et de l'informatique.
- 03/06/2019. Formation d'enseignants à Draguignan (ÉSPÉ de l'Académie de Nice). Graphes et algorithmes.
- 05/04/2019. Coordination d'ateliers Galejade animés par des enseignants et des parents d'élèves de l'école Pasteur du Cannet (suite à une formation Galejade quelques mois plus tôt). Ateliers Galejade.
- 22/03/2019. Formation d'enseignants de REP+ à l'ÉSPÉ de l'Académie de Nice (site de Stéphen Liégeard).
- 26/02/2019. Formation des étudiants de l'ÉSPÉ de l'Académie de Nice (site de Stéphen Liégeard) à l'animation d'activités informatiques et mathématiques. En collaboration avec l'Inspection Académique. Dans le cadre de la semaine des mathématiques. Graphes, algorithmes, jeux et magie des mathématiques.

7.3.4. Interventions

- National events:
  - 19-20/10/2019. Ateliers au village des sciences et de l'innovation au Palais des Congrès d'Antibes Juan-les-Pins. Voyage en train au pays des graphes, des algorithmes et de l'intelligence artificielle.
  - 06/10/2019. Atelier au village des sciences de Nice. Fête de la Science 2019. Le plus grand réseau de tri humain du monde.
  - 05/10/2019. Ateliers et conférence au village des sciences de Villeneuve-Loubet. Fête de la Science 2019. Algorithmes grandeur nature ? La magie des graphes et du binaire.
  - 4/10/2019. Conférence à la maison des associations de Nice (114 élèves de première et terminal). Fête de la Science 2019. Pas besoin de réfléchir, les ordinateurs calculent tellement vite ?
  - 03/10/2019. Deux conférences et ateliers au collège de la Vésubie-Jean Salines à Roquebillière. Fête de la Science 2019. La magie des graphes et du binaire ? Algorithmes grandeur nature ? Pas besoin de réfléchir, les ordinateurs calculent tellement vite ? Théorie des graphes et algorithmique pour les réseaux.
  - 26/03/2019. Fête des maths à l'ÉSPÉ de l'Académie de Nice (site de Stéphen Liégeard). Graphes et Algorithmes.
  - 26/02/2019. Formation des étudiants de l'ÉSPÉ de l'Académie de Nice (site de Stéphen Liégeard) à l'animation d'activités informatiques et mathématiques. En collaboration avec l'Inspection Académique. Dans le cadre de la semaine des mathématiques. Graphes, algorithmes, jeux et magie des mathématiques.
- Public exhibitions (Futurs en Seine,...)
  - 24/05/2019. Présentation du projet Galéjade à l'AFINEF'Tour Sophia Antipolis (avec EducAzur).
  - 18/05/2019. Semaine du Numérique à Valbonne. Algorithmes pour toute la famille.
  - 27-28/04/2019. Atelier et conférences au festival Les Souffleurs d'Avenir. La magie des graphes, des algorithmes et du binaire.
- In educational institutions
  - 11/01/2019. Conférence au lycée Léonard de Vinci d'Antibes (deux classes de terminale). Pas besoin de réfléchir, les ordinateurs calculent tellement vite ? Théorie des graphes et algorithmique pour les réseaux ? Présentation du métier de chercheur.

   - 11/10/2019. Deux conférences au collège la Chênaie à Mouans Sartoux. La magie des graphes et du binaire ? Jeux combinatoires.
   - Année scolaire 2019/2020. Projets dans le cadre de MATh.en.JEANS au collège Jean Rostand de Nice. Avec Olivier Ginola.
   - 03/10/2019. Deux conférences et ateliers au collège de la Vésubie-Jean Salines à Roquebillière. Fête de la Science 2019. La magie des graphes et du binaire ? Algorithmes grandeur nature ? Pas besoin de réfléchir, les ordinateurs calculent tellement vite ? Théorie des graphes et algorithmique pour les réseaux.
   - 26/03/2019. Conférence au collège Jules Romains de Nice (classes de sixième). La magie des graphes, des algorithmes et du binaire.
   - 13/03/2019. Conférences et ateliers au collège Alphonse Daudet de Nice (deux classes de sixième et deux classes de cinquième). Magie mathématique et jeux combinatoires.
   - 05/04/2019. Coordination d'ateliers Galejade animés par des enseignants et des parents d'élèves de l'école Pasteur du Cannet (suite à une formation Galéjade quelques mois plus tôt). Ateliers Galejade.
- Welcoming of schoolchildren or the general public in an Inria center: MathC2+ internship, open days,...
   - Semaine du 16 décembre 2019. Accueil de 12 stagiaires de troisième à Inria Sophia Antipolis - Méditerranée.
   - 28/06/2019. Activité pour une quarantaine d'étudiants de classes préparatoires scientifiques de Sophia Antipolis. Algorithmes de tri.
   - 14/06/2019. Activité pour une quarantaine de lycéens des Alpes-Maritimes (accueillis à Inria Sophia Antipolis - Méditerranée durant 4 jours dans le cadre du stage MathC2+). Algorithmes grandeur nature.
   - 26/04/2019. Visite d'une dizaine de jeunes de la mission locale de Grasse à Inria Sophia Antipolis - Méditerranée. La magie des graphes, des algorithmes et du binaire.

7.3.5. Internal action

- Internal meetings such as Café des sciences
   - 29/04/2019. Café-in à Inria Sophia Antipolis - Méditerranée (séminaire interne pour tous les membres du centre de recherche : chercheurs, ingénieurs, administratifs...). Ateliers Galejade.
- Training of colleagues on new contents or media (activités débranchées, Poppy Ergo, TensorFlow,...)
- Training follow-up (Media Training, new media such as Poppy ergo, with SIF, etc.)
- Science outreach towards services (DPEI, STIP...)

7.3.6. Creation of media or tools for science outreach

See https://galejade.inria.fr and http://terra-numerica.org/.

8. Bibliography

Major publications by the team in recent years

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[3] D. AGARWAL, C. CAILLOUET, D. COUDERT, F. CAZALS.*Unveiling Contacts within Macro-molecular assemblies by solving Minimum Weight Connectivity Inference Problems*, in "Molecular and Cellular Proteomics", 2015, vol. 14, p. 2274–2282 [*DOI :* 10.1074/MCP.M114.047779], https://hal.archives-ouvertes.fr/hal-01078378

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[9] T. DREYFUS, V. DOYE, F. CAZALS.*Assessing the Reconstruction of Macro-molecular Assemblies with Toleranced Models*, in "Proteins: structure, function, and bioinformatics", 2012, vol. 80, n^{o} 9, p. 2125–2136

[10] T. DREYFUS, V. DOYE, F. CAZALS.*Probing a Continuum of Macro-molecular Assembly Models with Graph Templates of Sub-complexes*, in "Proteins: structure, function, and bioinformatics", 2013, vol. 81, n^{o} 11, p. 2034–2044 [*DOI :* 10.1002/PROT.24313], http://hal.inria.fr/hal-00849795

[11] N. MALOD-DOGNIN, A. BANSAL, F. CAZALS.*Characterizing the Morphology of Protein Binding Patches*, in "Proteins: structure, function, and bioinformatics", 2012, vol. 80, n^{o} 12, p. 2652–2665

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Articles in International Peer-Reviewed Journal

[14] J.-C. BERMOND, A. CHAINTREAU, G. DUCOFFE, D. MAZAURIC.*How long does it take for all users in a social network to choose their communities?*, in "Discrete Applied Mathematics", 2019, vol. 270, p. 37-57 [*DOI :* 10.1016/J.DAM.2019.07.023], https://hal.inria.fr/hal-02264327

[15] F. CAZALS, D. MAZAURIC, R. TETLEY, R. WATRIGANT.*Comparing Two Clusterings Using Matchings between Clusters of Clusters*, in "ACM Journal of Experimental Algorithmics", December 2019, vol. 24, n° 1, p. 1-41 [*DOI :* 10.1145/3345951], https://hal.inria.fr/hal-02425599

[16] F. CAZALS, R. TETLEY.*Characterizing molecular flexibility by combining least root mean square deviation measures*, in "Proteins - Structure, Function and Bioinformatics", March 2019, vol. 87, n° 5, p. 380-389 [*DOI :* 10.1002/PROT.25658], https://hal.inria.fr/hal-02425596

[17] C. O. SORZANO, A. JIMÉNEZ, J. MOTA, J. L. VILAS, D. MALUENDA, M. MARTÍNEZ, E. RAMÍREZ-APORTELA, T. MAJTNER, J. SEGURA, R. SÁNCHEZ-GARCÍA, Y. RANCEL, L. DEL CAÑO, P. CONESA, R. MELERO, S. JONIC, J. VARGAS, F. CAZALS, Z. FREYBERG, J. KRIEGER, I. BAHAR, R. MARABINI, J. M. CARAZO.*Survey of the analysis of continuous conformational variability of biological macromolecules by electron microscopy*, in "Acta crystallographica. Section F, Structural biology communications", January 2019, vol. 75, n° 1, p. 19-32 [*DOI :* 10.1107/S2053230X1801510], https://hal.inria.fr/hal-01968170

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[18] F. CAZALS, A. LHÉRITIER.*Low-Complexity Nonparametric Bayesian Online Prediction with Universal Guarantees*, in "NeurIPS 2019 - Thirty-third Conference on Neural Information Processing Systems", Vancouver, Canada, December 2019, https://hal.inria.fr/hal-02425602

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[20] F. HAVET, D. MAZAURIC, V.-H. NGUYEN, R. WATRIGANT.*Overlaying a hypergraph with a graph with bounded maximum degree*, Inria Sophia Antipolis, February 2019, n° RR-9258, https://hal.inria.fr/hal-02025469

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[21] J.-C. BERMOND, D. MAZAURIC, V. MISRA, P. NAIN.*Distributed Link Scheduling in Wireless Networks*, January 2019, working paper or preprint, https://hal.inria.fr/hal-01977266

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Project-Team ACUMES

Analysis and Control of Unsteady Models for Engineering Sciences

IN COLLABORATION WITH: Laboratoire Jean-Alexandre Dieudonné (JAD)

IN PARTNERSHIP WITH:
Université Nice - Sophia Antipolis

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Numerical schemes and simulations

Table of contents

Project-Team ACUMES

Creation of the Team: 2015 January 01, updated into Project-Team: 2016 July 01

Keywords:

Computer Science and Digital Science:

A6. - Modeling, simulation and control
A6.1. - Methods in mathematical modeling
A6.1.1. - Continuous Modeling (PDE, ODE)
A6.1.4. - Multiscale modeling
A6.1.5. - Multiphysics modeling
A6.2. - Scientific computing, Numerical Analysis & Optimization
A6.2.1. - Numerical analysis of PDE and ODE
A6.2.4. - Statistical methods
A6.2.6. - Optimization
A6.3. - Computation-data interaction
A6.3.1. - Inverse problems
A6.3.2. - Data assimilation
A6.3.5. - Uncertainty Quantification
A9. - Artificial intelligence
A9.2. - Machine learning

Other Research Topics and Application Domains:

B1.1.8. - Mathematical biology
B1.1.11. - Plant Biology
B2.2.1. - Cardiovascular and respiratory diseases
B5.2.1. - Road vehicles
B5.2.3. - Aviation
B5.3. - Nanotechnology
B7.1.1. - Pedestrian traffic and crowds
B7.1.2. - Road traffic
B8.1.1. - Energy for smart buildings

1. Team, Visitors, External Collaborators

Research Scientists

Paola Goatin [Team leader, Inria, Senior Researcher, HDR]
Mickaël Binois [Inria, Researcher, from Feb 2019]
Jean-Antoine Désidéri [Inria, Senior Researcher, emeritus, HDR]
Régis Duvigneau [Inria, Researcher, HDR]

Faculty Member

Abderrahmane Habbal [Univ Côte d'Azur, Associate Professor, HDR]

Technical Staff

Ibrahim Yapici [Inria, Engineer, until May 2019]

PhD Students

Felisia Angela Chiarello [Univ Côte d'Azur, PhD Student]
Nikodem Dymski [Univ. Maria Curie-Sklodowska (Poland), PhD Student, until Sep 2019]
Jan Friedrich [Univ. Mannheim (Germany), PhD Student, from Jun 2019 until Nov 2019]
Nicolas Laurent-Brouty [Ecole Nationale des Ponts et Chaussées, PhD Student, until Sep 2019]
Marwa Ouni [Univ. Tunis Al Manar (Tunisia), PhD Student, from Jun 2019]
Stefano Pezzano [Inria, PhD Student]
Keltoum Chahour [Univ. Mohammed V (Morocco), until Jul 2019]
Rabeb Chamekh [Univ. Tunis Al Manar (Tunisia), from Aug 2019 until Sep 2019]

Post-Doctoral Fellows

Elena Rossi [Inria, Post-Doctoral Fellow, until Apr 2019]
Maxime Stauffert [Inria, Post-Doctoral Fellow, until Nov 2019]
Shuxia Tang [Inria, Post-Doctoral Fellow, until Apr 2019]

Visiting Scientists

Jennifer Kotz [Univ. Mannheim (Germany), Nov 2019]
Rafael Ordonez Cardales [Univ. Concepcion (Chili), from Nov 2019]
Giulia Piacentini [Univ. Pavia (Italy), from Mar 2019 until Apr 2019]
Luis Miguel Villada Osorio [Univ. Bio-Bio (Chili), Nov 2019]

Administrative Assistant

Montserrat Argente [Inria, Administrative Assistant]

2. Overall Objectives

2.1. Overall Objectives

ACUMES aims at developing a rigorous framework for numerical simulations and optimal control for transportation and buildings, with focus on multi-scale, heterogeneous, unsteady phenomena subject to uncertainty. Starting from established macroscopic Partial Differential Equation (PDE) models, we pursue a set of innovative approaches to include small-scale phenomena, which impact the whole system. Targeting applications contributing to sustainability of urban environments, we couple the resulting models with robust control and optimization techniques.

Modern engineering sciences make an important use of mathematical models and numerical simulations at the conception stage. Effective models and efficient numerical tools allow for optimization before production and to avoid the construction of expensive prototypes or costly post-process adjustments. Most up-to-date modeling techniques aim at helping engineers to increase performances and safety and reduce costs and pollutant emissions of their products. For example, mathematical traffic flow models are used by civil engineers to test new management strategies in order to reduce congestion on the existing road networks and improve crowd evacuation from buildings or other confined spaces without constructing new infrastructures. Similar models are also used in mechanical engineering, in conjunction with concurrent optimization methods, to reduce energy consumption, noise and pollutant emissions of cars, or to increase thermal and structural efficiency of buildings while, in both cases, reducing ecological costs.

Nevertheless, current models and numerical methods exhibit some limitations:

- Most simulation-based design procedures used in engineering still rely on steady (time-averaged) state models. Significant improvements have already been obtained with such a modeling level, for instance by optimizing car shapes, but finer models taking into account unsteady phenomena are required in the design phase for further improvements.

- The classical purely macroscopic approach, while offering a framework with a sound analytical basis, performing numerical techniques and good modeling features to some extent, is not able to reproduce some particular phenomena related to specific interactions occurring at lower (possibly micro) level. We refer for example to self-organizing phenomena observed in pedestrian flows, or to the dynamics of turbulent flows for which large scale / small scale vortical structures interfere. These flow characteristics need to be taken into account to obtain more precise models and improved optimal solutions.
- Uncertainty related to operational conditions (e.g. inflow velocity in aerodynamics), or models (e.g. individual behavior in crowds) is still rarely considered in engineering analysis and design, yielding solutions of poor robustness.

This project focuses on the analysis and optimal control of classical and non-classical evolutionary systems of Partial Differential Equations (PDEs) arising in the modeling and optimization of engineering problems related to safety and sustainability of urban environments, mostly involving fluid-dynamics and structural mechanics. The complexity of the involved dynamical systems is expressed by multi-scale, time-dependent phenomena, possibly subject to uncertainty, which can hardly be tackled using classical approaches, and require the development of unconventional techniques.

3. Research Program

3.1. Research directions

The project develops along the following two axes:

- modeling complex systems through novel (unconventional) PDE systems, accounting for multi-scale phenomena and uncertainty;
- optimization and optimal control algorithms for systems governed by the above PDE systems.

These themes are motivated by the specific problems treated in the applications, and represent important and up-to-date issues in engineering sciences. For example, improving the design of transportation means and civil buildings, and the control of traffic flows, would result not only in better performances of the object of the optimization strategy (vehicles, buildings or road networks level of service), but also in enhanced safety and lower energy consumption, contributing to reduce costs and pollutant emissions.

3.1.1. PDE models accounting for multi-scale phenomena and uncertainties

Dynamical models consisting of evolutionary PDEs, mainly of hyperbolic type, appear classically in the applications studied by the previous Project-Team Opale (compressible flows, traffic, cell-dynamics, medicine, etc). Yet, the classical purely macroscopic approach is not able to account for some particular phenomena related to specific interactions occurring at smaller scales. These phenomena can be of greater importance when dealing with particular applications, where the "first order" approximation given by the purely macroscopic approach reveals to be inadequate. We refer for example to self-organizing phenomena observed in pedestrian flows [126], or to the dynamics of turbulent flows for which large scale / small scale vortical structures interfere [155].

Nevertheless, macroscopic models offer well known advantages, namely a sound analytical framework, fast numerical schemes, the presence of a low number of parameters to be calibrated, and efficient optimization procedures. Therefore, we are convinced of the interest of keeping this point of view as dominant, while completing the models with information on the dynamics at the small scale / microscopic level. This can be achieved through several techniques, like hybrid models, homogenization, mean field games. In this project, we will focus on the aspects detailed below.

The development of adapted and efficient numerical schemes is a mandatory completion, and sometimes ingredient, of all the approaches listed below. The numerical schemes developed by the team are based on finite volumes or finite elements techniques, and constitute an important tool in the study of the considered models, providing a necessary step towards the design and implementation of the corresponding optimization algorithms, see Section 3.1.2.

3.1.1.1. *Micro-macro couplings*

Modeling of complex problems with a dominant macroscopic point of view often requires couplings with small scale descriptions. Accounting for systems heterogeneity or different degrees of accuracy usually leads to coupled PDE-ODE systems.

In the case of heterogeneous problems the coupling is "intrinsic", i.e. the two models evolve together and mutually affect each-other. For example, accounting for the impact of a large and slow vehicle (like a bus or a truck) on traffic flow leads to a strongly coupled system consisting of a (system of) conservation law(s) coupled with an ODE describing the bus trajectory, which acts as a moving bottleneck.The coupling is realized through a local unilateral moving constraint on the flow at the bus location, see [94] for an existence result and [77], [93] for numerical schemes.

If the coupling is intended to offer higher degree of accuracy at some locations, a macroscopic and a microscopic model are connected through an artificial boundary, and exchange information across it through suitable boundary conditions. See [84], [115] for some applications in traffic flow modelling, and [106], [111], [113] for applications to cell dynamics.

The corresponding numerical schemes are usually based on classical finite volume or finite element methods for the PDE, and Euler or Runge-Kutta schemes for the ODE, coupled in order to take into account the interaction fronts. In particular, the dynamics of the coupling boundaries require an accurate handling capturing the possible presence of non-classical shocks and preventing diffusion, which could produce wrong solutions, see for example [77], [93].

We plan to pursue our activity in this framework, also extending the above mentioned approaches to problems in two or higher space dimensions, to cover applications to crowd dynamics or fluid-structure interaction.

3.1.1.2. *Micro-macro limits*

Rigorous derivation of macroscopic models from microscopic ones offers a sound basis for the proposed modeling approach, and can provide alternative numerical schemes, see for example [85], [96] for the derivation of Lighthill-Whitham-Richards [138], [154] traffic flow model from Follow-the-Leader and [107] for results on crowd motion models (see also [128]). To tackle this aspect, we will rely mainly on two (interconnected) concepts: measure-valued solutions and mean-field limits.

The notion of **measure-valued solutions** for conservation laws was first introduced by DiPerna [97], and extensively used since then to prove convergence of approximate solutions and deduce existence results, see for example [108] and references therein. Measure-valued functions have been recently advocated as the appropriate notion of solution to tackle problems for which analytical results (such as existence and uniqueness of weak solutions in distributional sense) and numerical convergence are missing [64], [110]. We refer, for example, to the notion of solution for non-hyperbolic systems [116], for which no general theoretical result is available at present, and to the convergence of finite volume schemes for systems of hyperbolic conservation laws in several space dimensions, see [110].

In this framework, we plan to investigate and make use of measure-based PDE models for vehicular and pedestrian traffic flows. Indeed, a modeling approach based on (multi-scale) time-evolving measures (expressing the agents probability distribution in space) has been recently introduced (see the monograph [89]), and proved to be successful for studying emerging self-organised flow patterns [88]. The theoretical measure framework proves to be also relevant in addressing micro-macro limiting procedures of mean field type [117], where one lets the number of agents going to infinity, while keeping the total mass constant. In this case, one must prove that the *empirical measure*, corresponding to the sum of Dirac measures concentrated at the agents positions, converges to a measure-valued solution of the corresponding macroscopic evolution equation. We recall that a key ingredient in this approach is the use of the *Wasserstein distances* [163], [164]. Indeed, as observed in [147], the usual L^1 spaces are not natural in this context, since they don't guarantee uniqueness of solutions.

This procedure can potentially be extended to more complex configurations, like for example road networks or different classes of interacting agents, or to other application domains, like cell-dynamics.

Another powerful tool we shall consider to deal with micro-macro limits is the so-called **Mean Field Games (MFG)** technique (see the seminal paper [136]). This approach has been recently applied to some of the systems studied by the team, such as traffic flow and cell dynamics. In the context of crowd dynamics, including the case of several populations with different targets, the mean field game approach has been adopted in [72], [73], [98], [135], under the assumption that the individual behavior evolves according to a stochastic process, which gives rise to parabolic equations greatly simplifying the analysis of the system. Besides, a deterministic context is studied in [150], which considers a non-local velocity field. For cell dynamics, in order to take into account the fast processes that occur in the migration-related machinery, a framework such the one developed in [92] to handle games "where agents evolve their strategies according to the best-reply scheme on a much faster time scale than their social configuration variables" may turn out to be suitable. An alternative framework to MFG is also considered. This framework is based on the formulation of -Nash- games constrained by the **Fokker-Planck** (FP, [62]) partial differential equations that govern the time evolution of the probability density functions -PDF- of stochastic systems and on objectives that may require to follow a given PDF trajectory or to minimize an expectation functional.

3.1.1.3. Non-local flows

Non-local interactions can be described through macroscopic models based on integro-differential equations. Systems of the type

$$\partial_t u + \mathrm{div}_{\mathbf{x}} F(t, \mathbf{x}, u, W) = 0, \qquad t > 0, x \in R^d, d \geq 1, \tag{1}$$

where $u = u(t, \mathbf{x}) \in R^N$, $N \geq 1$ is the vector of conserved quantities and the variable $W = W(t, x, u)$ depends on an integral evaluation of u, arise in a variety of physical applications. Space-integral terms are considered for example in models for granular flows [59], sedimentation [66], supply chains [120], conveyor belts [121], biological applications like structured populations dynamics [146], or more general problems like gradient constrained equations [60]. Also, non-local in time terms arise in conservation laws with memory, starting from [91]. In particular, equations with non-local flux have been recently introduced in traffic flow modeling to account for the reaction of drivers or pedestrians to the surrounding density of other individuals, see [68], [75], [81], [118], [158]. While pedestrians are likely to react to the presence of people all around them, drivers will mainly adapt their velocity to the downstream traffic, assigning a greater importance to closer vehicles. In particular, and in contrast to classical (without integral terms) macroscopic equations, these models are able to display finite acceleration of vehicles through Lipschitz bounds on the mean velocity [68], [118] and lane formation in crossing pedestrian flows.

General analytical results on non-local conservation laws, proving existence and eventually uniqueness of solutions of the Cauchy problem for 1, can be found in [61] for scalar equations in one space dimension ($N = d = 1$), in [82] for scalar equations in several space dimensions ($N = 1$, $d \geq 1$) and in [55], [83], [87] for multi-dimensional systems of conservation laws. Besides, specific finite volume numerical methods have been developed recently in [55], [118] and [134].

Relying on these encouraging results, we aim to push a step further the analytical and numerical study of non-local models of type 1, in particular concerning well-posedness of initial - regularity of solutions, boundary value problems and high-order numerical schemes.

3.1.1.4. Uncertainty in parameters and initial-boundary data

Different sources of uncertainty can be identified in PDE models, related to the fact that the problem of interest is not perfectly known. At first, initial and boundary condition values can be uncertain. For instance, in traffic flows, the time-dependent value of inlet and outlet fluxes, as well as the initial distribution of vehicles density, are not perfectly determined [74]. In aerodynamics, inflow conditions like velocity modulus and direction, are subject to fluctuations [124], [145]. For some engineering problems, the geometry of the boundary can also be uncertain, due to structural deformation, mechanical wear or disregard of some details [100]. Another source of uncertainty is related to the value of some parameters in the PDE models. This is typically the case of parameters in turbulence models in fluid mechanics, which have been calibrated according to some reference flows but are not universal [156], [162], or in traffic flow models, which may depend on the type of road, weather conditions, or even the country of interest (due to differences in driving rules and conductors behaviour). This leads to equations with flux functions depending on random parameters [157], [160], for which the mean and the variance of the solutions can be computed using different techniques. Indeed, uncertainty quantification for systems governed by PDEs has become a very active research topic in the last years. Most approaches are embedded in a probabilistic framework and aim at quantifying statistical moments of the PDE solutions, under the assumption that the characteristics of uncertain parameters are known. Note that classical Monte-Carlo approaches exhibit low convergence rate and consequently accurate simulations require huge computational times. In this respect, some enhanced algorithms have been proposed, for example in the balance law framework [143]. Different approaches propose to modify the PDE solvers to account for this probabilistic context, for instance by defining the non-deterministic part of the solution on an orthogonal basis (Polynomial Chaos decomposition) and using a Galerkin projection [124], [133], [139], [166] or an entropy closure method [95], or by discretizing the probability space and extending the numerical schemes to the stochastic components [54]. Alternatively, some other approaches maintain a fully deterministic PDE resolution, but approximate the solution in the vicinity of the reference parameter values by Taylor series expansions based on first- or second-order sensitivities [151], [162], [165].

Our objective regarding this topic is twofold. In a pure modeling perspective, we aim at including uncertainty quantification in models calibration and validation for predictive use. In this case, the choice of the techniques will depend on the specific problem considered [65]. Besides, we plan to extend previous works on sensitivity analysis [100], [140] to more complex and more demanding problems. In particular, high-order Taylor expansions of the solution (greater than two) will be considered in the framework of the Sensitivity Equation Method [69] (SEM) for unsteady aerodynamic applications, to improve the accuracy of mean and variance estimations. A second targeted topic in this context is the study of the uncertainty related to turbulence closure parameters, in the sequel of [162]. We aim at exploring the capability of the SEM approach to detect a change of flow topology, in case of detached flows. Our ambition is to contribute to the emergence of a new generation of simulation tools, which will provide solution densities rather than values, to tackle real-life uncertain problems. This task will also include a reflection about numerical schemes used to solve PDE systems, in the perspective of constructing a unified numerical framework able to account for exact geometries (isogeometric methods), uncertainty propagation and sensitivity analysis w.r.t. control parameters.

3.1.2. Optimization and control algorithms for systems governed by PDEs

The non-classical models described above are developed in the perspective of design improvement for real-life applications. Therefore, control and optimization algorithms are also developed in conjunction with these models. The focus here is on the methodological development and analysis of optimization algorithms for PDE systems in general, keeping in mind the application domains in the way the problems are mathematically formulated.

3.1.2.1. Sensitivity vs. adjoint equation

Adjoint methods (achieved at continuous or discrete level) are now commonly used in industry for steady PDE problems. Our recent developments [153] have shown that the (discrete) adjoint method can be efficiently applied to cost gradient computations for time-evolving traffic flow on networks, thanks to the special structure of the associated linear systems and the underlying one dimensionality of the problem. However, this strategy

is questionable for more complex (e.g. 2D/3D) unsteady problems, because it requires sophisticated and time-consuming check-pointing and/or re-computing strategies [63], [119] for the backward time integration of the adjoint variables. The sensitivity equation method (SEM) offers a promising alternative [99], [129], if the number of design parameters is moderate. Moreover, this approach can be employed for other goals, like fast evaluation of neighboring solutions or uncertainty propagation [100].
Regarding this topic, we intend to apply the continuous sensitivity equation method to challenging problems. In particular, in aerodynamics, multi-scale turbulence models like Large-Eddy Simulation (LES) [155] , Detached-Eddy Simulation (DES) [159] or Organized-Eddy Simulation (OES) [70], are more and more employed to analyse the unsteady dynamics of the flows around bluff-bodies, because they have the ability to compute the interactions of vortices at different scales, contrary to classical Reynolds-Averaged Navier-Stokes models. However, their use in design optimization is tedious, due to the long time integration required. In collaboration with turbulence specialists (M. Braza, CNRS - IMFT), we aim at developing numerical methods for effective sensitivity analysis in this context, and apply them to realistic problems, like the optimization of active flow control devices. Note that the use of SEM allows computing cost functional gradients at any time, which permits to construct new gradient-based optimization strategies like instantaneous-feedback method [131] or multiobjective optimization algorithm (see section below).

3.1.2.2. Multi-objective descent algorithms for multi-disciplinary, multi-point, unsteady optimization or robust-design

In differentiable optimization, multi-disciplinary, multi-point, unsteady optimization or robust-design can all be formulated as multi-objective optimization problems. In this area, we have proposed the *Multiple-Gradient Descent Algorithm (MGDA)* to handle all criteria concurrently [102] [103]. Originally, we have stated a principle according which, given a family of local gradients, a descent direction common to all considered objective-functions simultaneously is identified, assuming the Pareto-stationarity condition is not satisfied. When the family is linearly-independent, we dispose of a direct algorithm. Inversely, when the family is linearly-dependent, a quadratic-programming problem should be solved. Hence, the technical difficulty is mostly conditioned by the number m of objective functions relative to the search space dimension n. In this respect, the basic algorithm has recently been revised [104] to handle the case where $m > n$, and even $m \gg n$, and is currently being tested on a test-case of robust design subject to a periodic time-dependent Navier-Stokes flow.

The multi-point situation is very similar and, being of great importance for engineering applications, will be treated at large.

Moreover, we intend to develop and test a new methodology for robust design that will include uncertainty effects. More precisely, we propose to employ MGDA to achieve an effective improvement of all criteria simultaneously, which can be of statistical nature or discrete functional values evaluated in confidence intervals of parameters. Some recent results obtained at ONERA [148] by a stochastic variant of our methodology confirm the viability of the approach. A PhD thesis has also been launched at ONERA/DADS.

Lastly, we note that in situations where gradients are difficult to evaluate, the method can be assisted by a meta-model [168].

3.1.2.3. Bayesian Optimization algorithms for efficient computation of general equilibria

Bayesian Optimization (BO) relies on Gaussian processes, which are used as emulators (or surrogates) of the black-box model outputs based on a small set of model evaluations. Posterior distributions provided by the Gaussian process are used to design acquisition functions that guide sequential search strategies that balance between exploration and exploitation. Such approaches have been transposed to frameworks other than optimization, such as uncertainty quantification. Our aim is to investigate how the BO apparatus can be applied to the search of general game equilibria, and in particular the classical Nash equilibrium (NE). To this end, we propose two complementary acquisition functions, one based on a greedy search approach and one based on the Stepwise Uncertainty Reduction paradigm [112]. Our proposal is designed to tackle derivative-free, expensive models, hence requiring very few model evaluations to converge to the solution.

3.1.2.4. Decentralized strategies for inverse problems

Most if not all the mathematical formulations of inverse problems (a.k.a. reconstruction, identification, data recovery, non destructive engineering,...) are known to be ill posed in the Hadamard sense. Indeed, in general, inverse problems try to fulfill (minimize) two or more very antagonistic criteria. One classical example is the Tikhonov regularization, trying to find artificially smoothed solutions close to naturally non-smooth data.

We consider here the theoretical general framework of parameter identification coupled to (missing) data recovery. Our aim is to design, study and implement algorithms derived within a game theoretic framework, which are able to find, with computational efficiency, equilibria between the "identification related players" and the "data recovery players". These two parts are known to pose many challenges, from a theoretical point of view, like the identifiability issue, and from a numerical one, like convergence, stability and robustness problems. These questions are tricky [56] and still completely open for systems like e.g. coupled heat and thermoelastic joint data and material detection.

4. Application Domains

4.1. Active flow control for vehicles

The reduction of CO2 emissions represents a great challenge for the automotive and aeronautic industries, which committed respectively a decrease of 20% for 2020 and 75% for 2050. This goal will not be reachable, unless a significant improvement of the aerodynamic performance of cars and aircrafts is achieved (e.g. aerodynamic resistance represents 70% of energy losses for cars above 90 km/h). Since vehicle design cannot be significantly modified, due to marketing or structural reasons, active flow control technologies are one of the most promising approaches to improve aerodynamic performance. This consists in introducing micro-devices, like pulsating jets or vibrating membranes, that can modify vortices generated by vehicles. Thanks to flow non-linearities, a small energy expense for actuation can significantly reduce energy losses. The efficiency of this approach has been demonstrated, experimentally as well as numerically, for simple configurations [167].

However, the lack of efficient and flexible numerical tools, that allow to simulate and optimize a large number of such devices on realistic configurations, is still a bottleneck for the emergence of this technology in industry. The main issue is the necessity of using high-order schemes and complex models to simulate actuated flows, accounting for phenomena occurring at different scales. In this context, we intend to contribute to the following research axes:

- *Sensitivity analysis for actuated flows.* Adjoint-based (reverse) approaches, classically employed in design optimization procedure to compute functional gradients, are not well suited to this context. Therefore, we propose to explore the alternative (direct) formulation, which is not so much used, in the perspective of a better characterization of actuated flows and optimization of control devices.
- *Isogeometric simulation of control devices.* To simulate flows perturbed by small-scale actuators, we investigate the use of isogeometric analysis methods, which allow to account exactly for CAD-based geometries in a high-order hierarchical representation framework. In particular, we try to exploit the features of the method to simulate more accurately complex flows including moving devices and multiscale phenomena.

4.2. Vehicular and pedestrian traffic flows

Intelligent Transportation Systems (ITS) is nowadays a booming sector, where the contribution of mathematical modeling and optimization is widely recognized. In this perspective, traffic flow models are a commonly cited example of "complex systems", in which individual behavior and self-organization phenomena must be taken into account to obtain a realistic description of the observed macroscopic dynamics [125]. Further improvements require more advanced models, keeping into better account interactions at the microscopic scale, and adapted control techniques, see [71] and references therein. In particular, we will focus on the following aspects:

- *Junction models.* We are interested in designing a general junction model both satisfying basic analytical properties guaranteeing well-posedness and being realistic for traffic applications. In particular, the model should be able to overcome severe drawbacks of existing models, such as restrictions on the number of involved roads and prescribed split ratios [86], [114], which limit their applicability to real world situations. Hamilton-Jacobi equations could be also an interesting direction of research, following the recent results obtained in [130].
- *Data assimilation.* In traffic flow modeling, the capability of correctly estimating and predicting the state of the system depends on the availability of rich and accurate data on the network. Up to now, the most classical sensors are fixed ones. They are composed of inductive loops (electrical wires) that are installed at different spatial positions of the network and that can measure the traffic flow, the occupancy rate (i.e. the proportion of time during which a vehicle is detected to be over the loop) and the speed (in case of a system of two distant loops). These data are useful / essential to calibrate the phenomenological relationship between flow and density which is known in the traffic literature as the Fundamental Diagram. Nowadays, thanks to the wide development of mobile internet and geolocalization techniques and its increasing adoption by the road users, smartphones have turned into perfect mobile sensors in many domains, including in traffic flow management. They can provide the research community with a large database of individual trajectory sets that are known as Floating Car Data (FCD), see [127] for a real field experiment. Classical macroscopic models, say (hyperbolic systems of) conservation laws, are not designed to take into account this new kind of microscopic data. Other formulations, like Hamilton-Jacobi partial differential equations, are most suited and have been intensively studied in the past five years (see [79], [80]), with a stress on the (fixed) Eulerian framework. Up to our knowledge, there exist a few studies in the time-Lagrangian as well as space-Lagrangian frameworks, where data coming from mobile sensors could be easily assimilated, due to the fact that the Lagrangian coordinate (say the label of a vehicle) is fixed.
- *Control of autonomous vehicles.* Traffic flow is usually controlled via traffic lights or variable speed limits, which have fixed space locations. The deployment of autonomous vehicles opens new perspectives in traffic management, as the use of a small fraction of cars to optimize the overall traffic. In this perspective, the possibility to track vehicles trajectories either by coupled micro-macro models [94], [115] or via the Hamilton-Jacobi approach [79], [80] could allow to optimize the flow by controlling some specific vehicles corresponding to internal conditions.

4.3. Virtual Fractional Flow Reserve in coronary stenting

Atherosclerosis is a chronic inflammatory disease that affects the entire arterial network and especially the coronary arteries. It is an accumulation of lipids over the arterial surface due to a dysfunction of this latter. The objective of clinical intervention, in this case, is to establish a revascularization using different angioplasty techniques, among which the implantation of stents is the most widespread. This intervention involves introducing a stent into the damaged portion in order to allow the blood to circulate in a normal way over all the vessels. Revascularization is based on the principle of remedying ischemia, which is a decrease or an interruption of the supply of oxygen to the various organs. This anomaly is attenuated by the presence of several lesions (multivessel disease patients), which can lead to several complications. The key of a good medical intervention is the fact of establishing a good diagnosis, in order to decide which lesion requires to be treated. In the diagnosis phase, the clinician uses several techniques, among which angiography is the most popular. Angiography is an X-ray technique to show the inside (the lumen) of blood vessels, in order to identify vessel narrowing: stenosis. Despite its widespread use, angiography is often imperfect in determining the physiological significance of coronary stenosis. If the problem remains simple for non significant lesions ($\leq 40\%$) or very severe ($\geq 70\%$), a very important category of intermediate lesions must benefit from a functional evaluation which will determine the strategy of treatment [90].

The technique of the Fractional Flow Reserve (FFR) has derived from the initial coronary physical approaches decades ago. Since then, many studies have demonstrated its effectiveness in improving the patients prognosis, by applying the appropriate approach. Its contribution in the reduction of mortality was statistically proved by the FAME (Fractional Flow Reserve Versus Angiography for Multivessel Evaluation) study [169]. It is established that the FFR can be easily measured during coronary angiography by calculating the ratio of distal coronary pressure P_d to aortic pressure P_a. These pressures are measured simultaneously with a special guide-wire. FFR in a normal coronary artery equals to 1.0. FFR value of 0.80 or less identifies ischemia-causing coronary lesions with an accuracy of more than 90% [169].

Obviously, from an interventional point of view, the FFR is binding since it is invasive. It should also be noted that this technique induces additional costs, which are not covered by insurances in several countries. For these reasons, it is used only in less than 10% of the cases.

In this perspective, a new virtual version of the FFR, entitled VFFR, has emerged as an attractive and non-invasive alternative to standard FFR, see [161], [144]. VFFR is based on computational modeling, mainly fluid and fluid-structural dynamics. However, there are key scientific, logistic and commercial challenges that need to be overcome before VFFR can be translated into routine clinical practice.

While most of the studies related to VFFR use Navier-Stokes models, we focus on the non-newtonian case, starting with a generalized fluid flow approach. These models are more relevant for the coronary arteries, and we expect that the computation of the FFR should then be more accurate. We are also leading numerical studies to assess the impact (on the FFR) of the interaction of the physical devices (catheter, optical captors, spheroids) with the blood flow.

4.4. Other application fields

Besides the above mentioned axes, which constitute the project's identity, the methodological tools described in Section have a wider range of application. We currently carry on also the following research actions, in collaboration with external partners.

- **Modeling cell dynamics.** Migration and proliferation of epithelial cell sheets are the two keystone aspects of the collective cell dynamics in most biological processes such as morphogenesis, embryogenesis, cancer and wound healing. It is then of utmost importance to understand their underlying mechanisms.

  Semilinear reaction-diffusion equations are widely used to give a phenomenological description of the temporal and spatial changes occurring within cell populations that undergo scattering (moving), spreading (expanding cell surface) and proliferation. We have followed the same methodology and contributed to assess the validity of such approaches in different settings (cell sheets [122], dorsal closure [58], actin organization [57]). However, epithelial cell-sheet movement is complex enough to undermine most of the mathematical approaches based on *locality*, that is mainly traveling wavefront-like partial differential equations. In [109] it is shown that Madin-Darby Canine Kidney (MDCK) cells extend cryptic lamellipodia to drive the migration, several rows behind the wound edge. In [149] MDCK monolayers are shown to exhibit similar non-local behavior (long range velocity fields, very active border-localized leader cells).

  Our aim is to start from a mesoscopic description of cell interaction: considering cells as independent anonymous agents, we plan to investigate the use of mathematical techniques adapted from the mean-field game theory. Otherwise, looking at them as interacting particles, we will use a multi-agent approach (at least for the actin dynamics). We intend also to consider approaches stemming from compartment-based simulation in the spirit of those developed in [106], [111], [113].

- **Game strategies for thermoelastography.** Thermoelastography is an innovative non-invasive control technology, which has numerous advantages over other techniques, notably in medical imaging [142]. Indeed, it is well known that most pathological changes are associated with changes in tissue stiffness, while remaining isoechoic, and hence difficult to detect by ultrasound techniques. Based on elastic waves and heat flux reconstruction, thermoelastography shows no destructive or aggressive medical sequel, unlike X-ray and comparables techniques, making it a potentially prominent choice for patients.

Physical principles of thermoelastography originally rely on dynamical structural responses of tissues, but as a first approach, we only consider static responses of linear elastic structures.
The mathematical formulation of the thermoelasticity reconstruction is based on data completion and material identification, making it a harsh ill posed inverse problem. In previous works [123], [132], we have demonstrated that Nash game approaches are efficient to tackle ill-posedness. We intend to extend the results obtained for Laplace equations in [123], and the algorithms developed in Section 3.1.2.4 to the following problems (of increasing difficulty):
- Simultaneous data and parameter recovery in linear elasticity, using the so-called Kohn and Vogelius functional (ongoing work, some promising results obtained).
- Data recovery in coupled heat-thermoelasticity systems.
- Data recovery in linear thermoelasticity under stochastic heat flux, where the imposed flux is stochastic.
- Data recovery in coupled heat-thermoelasticity systems under stochastic heat flux, formulated as an incomplete information Nash game.
- Application to robust identification of cracks.

- **Constraint elimination in Quasi-Newton methods.** In single-objective differentiable optimization, Newton's method requires the specification of both gradient and Hessian. As a result, the convergence is quadratic, and Newton's method is often considered as the target reference. However, in applications to distributed systems, the functions to be minimized are usually "functionals", which depend on the optimization variables by the solution of an often complex set of PDE's, through a chain of computational procedures. Hence, the exact calculation of the full Hessian becomes a complex and costly computational endeavor.

  This has fostered the development of *quasi-Newton's methods* that mimic Newton's method but use only the gradient, the Hessian being iteratively constructed by successive approximations inside the algorithm itself. Among such methods, the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm is well-known and commonly employed. In this method, the Hessian is corrected at each new iteration by rank-one matrices defined from several evaluations of the gradient only. The BFGS method has "super-linear convergence".

  For constrained problems, certain authors have developed so-called *Riemannian BFGS*, e.g. [152], that have the desirable convergence property in constrained problems. However, in this approach, the constraints are assumed to be known formally, by explicit expressions.

  In collaboration with ONERA-Meudon, we are exploring the possibility of representing constraints, in successive iterations, through local approximations of the constraint surfaces, splitting the design space locally into tangent and normal sub-spaces, and eliminating the normal coordinates through a linearization, or more generally a finite expansion, and applying the BFGS method through dependencies on the coordinates in the tangent subspace only. Preliminary experiments on the difficult Rosenbrock test-case, although in low dimensions, demonstrate the feasibility of this approach. On-going research is on theorizing this method, and testing cases of higher dimensions.

- **Multi-objective optimization for nanotechnologies.** Our team takes part in a larger collaboration with CEA/LETI (Grenoble), initiated by the Inria Project-Team Nachos, and related to the Maxwell equations. Our component in this activity relates to the optimization of nanophotonic devices, in particular with respect to the control of thermal loads. We have first identified a gradation of representative test-cases of increasing complexity:
  - infrared micro-source;
  - micro-photoacoustic cell;
  - nanophotonic device.

These cases involve from a few geometric parameters to be optimized to a functional minimization subject to a finite-element solution involving a large number of dof's. CEA disposes of such codes, but considering the computational cost of the objective functions in the complex cases, the first part of our study is focused on the construction and validation of meta-models, typically of RBF-type. Multi-objective optimization will be carried out subsequently by MGDA, and possibly Nash games.

5. New Software and Platforms

5.1. MGDA

Multiple Gradient Descent Algorithm

KEYWORDS: Descent direction - Multiple gradients - Multi-objective differentiable optimization - Prioritized multi-objective optimization

SCIENTIFIC DESCRIPTION: The software relies upon a basic MGDA tool which permits to calculate a descent direction common to an arbitrary set of cost functions whose gradients at a computational point are provided by the user, as long as a solution exists, that is, with the exclusion of a Pareto-stationarity situation.

More specifically, the basic software computes a vector d whose scalar product with each of the given gradients (or directional derivative) is positive. When the gradients are linearly independent, the algorithm is direct following a Gram-Schmidt orthogonalization. Otherwise, a sub-family of the gradients is identified according to a hierarchical criterion as a basis of the spanned subspace associated with a cone that contains almost all the gradient directions. Then, one solves a quadratic programming problem formulated in this basis.

This basic tool admits the following extensions: - constrained multi-objective optimization - prioritized multi-objective optimization - stochastic multi-objective optimization.

FUNCTIONAL DESCRIPTION: Chapter 1: Basic MGDA tool Software to compute a descent direction common to an arbitrary set of cost functions whose gradients are provided in situations other than Pareto stationarity.

Chapter 2: Directions for solving a constrained problem Guidelines and examples are provided according the Inria research report 9007 for solving constrained problems by a quasi-Riemannian approach and the basic MGDA tool.

Chapter 3: Tool for prioritized optimization Software permitting to solve a multi-objective optimization problem in which the cost functions are defined by two subsets: - a primary subset of cost functions subject to constraints for which a Pareto optimal point is provided by the user (after using the previous tool or any other multiobjective method, possibly an evolutionary algorithm) - a secondary subset of cost functions to be reduced while maintaining quasi Pareto optimality of the first set. Procedures defining the cost and constraint functions, and a small set of numerical parameters are uploaded to the platform by an external user. The site returns an archive containing datafiles of results including graphics automatically generated.

Chapter 4: Stochastic MGDA Information and bibliographic references about SMGDA, an extension of MGDA applicable to certain stochastic formulations.

Concerning Chapter 1, the utilization of the platform can be made via two modes : – the interactive mode, through a web interface that facilitates the data exchange between the user and an Inria dedicated machine, – the iterative mode, in which the user downloads the object library to be included in a personal optimization software. Concerning Chapters 2 and 3, the utilizer specifies cost and constraint functions by providing procedures compatible with Fortran 90. Chapter 3 does not require the specification of gradients, but only the functions themselves that are approximated by the software by quadratic meta-models.

- Participant: Jean-Antoine Désidéri
- Contact: Jean-Antoine Désidéri

- Publications: Revision of the Multiple-Gradient Descent Algorithm (MGDA) by Hierarchical Orthogonalization - Parametric optimization of pulsating jets in unsteady flow by Multiple-Gradient Descent Algorithm (MGDA) - A quasi-Riemannian approach to constrained optimization - Platform for prioritized multi-objective optimization by metamodel-assisted Nash games - Direct and adaptive approaches to multi-objective optimization
- URL: http://mgda.inria.fr

5.2. Igloo

Iso-Geometric anaLysis using discOntinuOus galerkin methods

KEYWORDS: Numerical simulations - Isogeometric analysis

SCIENTIFIC DESCRIPTION: Igloo contains numerical methods to solve partial differential equations of hyperbolic type, or convection-dominant type, using an isogeometric formulation (NURBS bases) with a discontinuous Galerkin method.

FUNCTIONAL DESCRIPTION: Igloo is composed of a set of C++ libraries and applications, which allow to simulate time-dependent physical phenomena using natively CAD-based geometry descriptions.

- Author: Régis Duvigneau
- Contact: Régis Duvigneau

5.3. BuildingSmart

BuildingSmart interactive visualization

KEYWORDS: Physical simulation - 3D rendering - 3D interaction

SCIENTIFIC DESCRIPTION: The aim of the BuildingSmart project is to develop a software environment for the simulation and interactive visualisation for the design of buildings (structural safety, thermal confort).

FUNCTIONAL DESCRIPTION: The main task of the project is to study and develop solutions dedicated to interactive visualisation of building performances (heat, structural) in relation to the Building Information Modeling BIM framework, using Occulus Rift immersion.

NEWS OF THE YEAR: Demo movies are available from Youtube (see web site)

- Participants: Régis Duvigneau, Jean-Luc Szpyrka, David Rey, Clement Welsch and Abderrahmane Habbal
- Contact: Abderrahmane Habbal
- URL: http://youtu.be/MW_gIF8hUdk

6. New Results

6.1. Macroscopic traffic flow models on networks

Participants: Régis Duvigneau, Nikodem Dymski, Paola Goatin, Nicolas Laurent-Brouty, Elena Rossi, Shuxia Tang, Alexandre Bayen [UC Berkeley, CA, USA], Enrico Bertino [Politecnico Milano, Italy], Guillaume Costeseque [Cerema, Nantes], Alexander Keimer [UC Berkeley, CA, USA], Antonella Ferrara [U Pavia, Italy], Adriano Festa [Politecnico Torino, Italy], Mauro Garavello [U Milano-Bicocca, Italy], Thibault Liard [DeustoTech, Spain], Benedetto Piccoli [U Rutgers, NJ, USA], Giulia Piacentini [U Pavia, Italy].

Bounded acceleration. In [50], we study a mathematical model accounting for the boundedness of traffic acceleration at a macroscopic scale that was introduced in [137]. Our model is built on a first order macroscopic PDE model coupled with an ODE describing the trajectory of the leader of a platoon accelerating at a given constant rate. We propose a Wave Front Tracking Algorithm to construct approximate solutions. We use this algorithm to prove the existence of solutions to the associated Cauchy Problem, and provide some numerical examples illustrating the solution behaviour.

This work was part of N. Laurent-Brouty's PhD thesis.

Moving bottlenecks on road networks. In [48], we generalize the Lighthill-Witham-Richards model for vehicular traffic coupled with moving bottlenecks introduced in [6] to the case of road networks. Such models can be applied to study the traffic evolution in the presence of a slow-moving vehicle, like a bus. At last, a numerical experiment is shown.
This work was part of N. Dymski's PhD thesis.

Traffic control by autonomous vehicles. Autonomous vehicles (AVs) allow new ways of regulating the traffic flow on road networks. Most of available results in this direction are based on microscopic approaches, where ODEs describe the evolution of regular cars and AVs. In [49], we propose a multiscale approach, based on recently developed models for moving bottlenecks. Our main result is the proof of existence of solutions for open-loop controls with bounded variation.

Vehicle platooning in highway traffic. In [52], we consider a model describing the presence of a platoon of vehicles moving in the traffic flow. The model consists of a coupled PDE-ODE system describing the interaction between the platoon and the surrounding traffic flow. The scalar conservation law takes into account the main traffic evolution, while the ODEs describe the trajectories of the initial and final points of the platoon, whose length can vary in time. The presence of the platoon acts as a road capacity reduction, resulting in a space-time discontinuous flux function. We describe the solutions of Riemann problems and design a finite volume numerical scheme sharply capturing non-classical discontinuities. Some numerical tests are presented to show the effectiveness of the method.
This work is part of G. Piacentini's PhD thesis.

Well-posedness of conservation laws on networks with finite buffers. In [51], we introduce a model dealing with conservation laws on networks and coupled boundary conditions at the junctions. In particular, we introduce buffers of fixed arbitrary size and time dependent split ratios at the junctions, which represent how traffic is routed through the network, while guaranteeing spill-back phenomena at nodes. Having defined the dynamics at the level of conservation laws, we lift it up to the Hamilton-Jacobi (H-J) formulation and write boundary datum of incoming and outgoing junctions as functions of the queue sizes and vice-versa. The Hamilton-Jacobi formulation provides the necessary regularity estimates to derive a fixed-point problem in a proper Banach space setting, which is used to prove well-posedness of the model. Finally, we detail how to apply our framework to a non-trivial road network, with several intersections and finite-length links.
This work was realized in the framework of the IIP ORESTE and was part of N. Laurent-Brouty's PhD thesis.

Traffic flow on multi-lane networks. In [28], we prove the well-posedness of a system of balance laws describing macroscopically the traffic flow on a multi-lane road network. Motivated by real applications, we allow for the the presence of space discontinuities both in the speed law and in the number of lanes. This allows to describe a number of realistic situations. Existence of solutions follows from compactness results on a sequence of Godunov's approximations, while L^1-stability is obtained by the doubling of variables technique. Some numerical simulations illustrate the behaviour of solutions in sample cases.

Minimum time boundary controls. The paper [35] is motivated by the practical problem of controlling traffic flow by imposing restrictive boundary conditions. For a one-dimensional congested road segment, we study the minimum time control problem of how to control the upstream vehicular flow appropriately to regulate the downstream traffic into a desired (constant) free flow state in minimum time. We consider the Initial-Boundary Value Problem (IBVP) for a scalar nonlinear conservation law, associated to the Lighthill-Whitham-Richards (LWR) Partial Differential Equation (PDE), where the left boundary condition, also treated as a valve for the traffic flow from the upstream, serves as a control. Besides, we set absorbing downstream boundary conditions. We prove first a comparison principle for the solutions of the considered IBVP, subject to comparable initial, left and right boundary data, which provides estimates on the minimal time required to control the system. Then we consider a (sub-) optimal control problem and we give numerical results based on Godunov scheme. The article serves as a starting point for studying time-optimal boundary control of the LWR model and for computing numerical results.
This work was realized in the framework of the IIP ORESTE.

Impact of on-line navigation devices in traffic flows. In [34], we consider a macroscopic multi-population traffic flow model on networks accounting for the presence of drivers (or autonomous vehicles) using navigation devices to minimize their instantaneous travel cost to destination. The strategic choices of each population differ in the degree of information about the system: while part of the agents knows only the structure of the network and minimizes the traveled distance, others are informed of the current traffic distribution, and can minimize their travel time avoiding the most congested areas. In particular, the different route choices are computed solving eikonal equations on the road network and they are implemented at road junctions. The impact on traffic flow efficiency is illustrated by numerical experiments. We show that, even if the use of routing devices contributes to alleviate congestion on the whole network, it also results in increased traffic on secondary roads. Moreover, the generalized use of real-time information can even deteriorate the efficiency of the network.

Uncertainty quantification in a macroscopic traffic flow model calibrated on GPS data. In [18], we analyze the inclusion of one or more random parameters into the deterministic Lighthill-Whitham-Richards traffic flow model and use a semi-intrusive approach to quantify uncertainty propagation. To verify the validity of the method, we test it against real data coming from vehicle embedded GPS systems, provided by AUTOROUTES TRAFIC.

6.2. Non-local conservation laws

Participants: Felisia Angela Chiarello, Paola Goatin, Elena Rossi, Jan Friedrich [U Mannheim, Germany], Simone Göttlich [U Mannheim, Germany], Jennifer Kotz [U Mannheim, Germany], Luis Miguel Villada [U Bìo-Bìo, Chile].

F.A. Chiarello's PhD thesis focused on non-local conservation laws. In [23], we proved the stability of entropy weak solutions, considering smooth kernels. We obtained an estimate on the dependence of the solution with respect to the kernel function, the speed and the initial datum, applying the doubling of variables technique. We also provided some numerical simulations illustrating the dependencies above for some cost functionals derived from traffic flow applications.
In the paper [22], we proved the existence for small times of weak solutions for a class of non-local systems in one space dimension, arising in traffic modeling. We approximated the problem by a Godunov type numerical scheme and we provided uniform L^∞ and BV estimates for the sequence of approximate solutions. We showed some numerical simulations illustrating the behavior of different classes of vehicles and we analyzed two cost functionals measuring the dependence of congestion on traffic composition.
We also conducted a study on Lagrangian-Antidiffusive Remap schemes (previously proposed for classical hyperbolic systems) for the above mentioned non-local multi-class traffic flow model. The error and convergence analysis show the effectiveness of the method, which is first order, in sharply capturing shock discontinuities, and better precision with respect to other methods as Lax-Friedrichs or Godunov (even 2nd order). A journal article about these results has been published [24]. Besides, high-order numerical schemes for the same model were proposed in [78].
Finally, in [21], we present a model for a class of non-local conservation laws arising in traffic flow modeling at road junctions. Instead of a single velocity function for the whole road, we consider two different road segments, which may differ for their speed law and number of lanes (hence their maximal vehicle density). We use an upwind type numerical scheme to construct a sequence of approximate solutions and we provide uniform L^∞ and total variation estimates. In particular, the solutions of the proposed model stay positive and below the maximum density of each road segment. Using a Lax-Wendroff type argument and the doubling of variables technique, we prove the well-posedness of the proposed model. Finally, some numerical simulations are provided and compared with the corresponding (discontinuous) local model.

Besides, in [31], we focus on finite volume approximation schemes to solve a non-local material flow model in two space dimensions. Based on the numerical discretisation with dimensional splitting, we prove the convergence of the approximate solutions, where the main difficulty arises in the treatment of the discontinuity occurring in the flux function. In particular, we compare a Roe-type scheme to the well-established Lax-Friedrichs method and provide a numerical study highlighting the benefits of the Roe discretisation. We also prove the L^1-Lipschitz continuous dependence on the initial datum, ensuring the uniqueness of the solution.

6.3. Isogeometric Discontinuous Galerkin method for compressible flows

Participants: Régis Duvigneau, Stefano Pezzano, Maxime Stauffert.

The co-existence of different geometrical representations in the design loop (CAD-based and mesh-based) is a real bottleneck for the application of design optimization procedures in industry, yielding a major waste of human time to convert geometrical data. Isogeometric analysis methods, which consists in using CAD bases like NURBS in a Finite-Element framework, were proposed a decade ago to facilitate interactions between geometry and simulation domains.

We investigate the extension of such methods to Discontinuous Galerkin (DG) formulations, which are better suited to hyperbolic or convection-dominated problems. Specifically, we develop a DG method for compressible Euler and Navier-Stokes equations, based on rational parametric elements, that preserves exactly the geometry of boundaries defined by NURBS, while the same rational approximation space is adopted for the solution [37]. The following research axes are considered in this context:

- **Adaptive refinement**
  Properties of NURBS functions are used to define an adaptive refinement strategy, which refines locally the discretization according to an error indicator, while describing exactly CAD geometries whatever the refinement level. The resulting approach exhibits an optimal convergence rate and capture efficiently local flow features, like shocks or vortices, avoiding refinement due to geometry approximation [36], [47].
- **Arbitrary Eulerian-Lagrangian formulation**
  To enable the simulation of flows around moving bodies, an Arbitrary Eulerian-Lagrangian (ALE) formulation is proposed in the context of the isogeometric DG method. It relies on a NURBS-based boundary velocity, integrated along time over moving NURBS elements. The gain of using exact-geometry representations is clearly quantified [39].
- **Isogeometric shape optimization**
  On the basis of the isogeometric DG method, we develop a shape optimization procedure with sensitivity analysis, entirely based on NURBS representations [40]. The mesh, the shape parameters as well as the flow solutions are represented by NURBS, which avoids any geometrical conversion and allows to exploit NURBS properties, like regularity, hierarchy, etc.

6.4. Sensitivity analysis for unsteady flows

Participants: Régis Duvigneau, Maxime Stauffert, Camilla Fiorini [UVST], Christophe Chalons [UVST].

The adjoint equation method, classically employed in design optimization to compute functional gradients, is not well suited to complex unsteady problems, because of the necessity to solve it backward in time. Therefore, we investigate the use of the sensitivity equation method, which is integrated forward in time, in the context of compressible flows. More specifically, the following research axes are considered:

- **Sensitivity analysis in presence of shocks**
  While the sensitivity equation method is a common approach for parabolic systems, its use for hyperbolic ones is still tedious, because of the generation of discontinuities in the state solution, yielding Dirac distributions in the sensitivity solution. To overcome this difficulty, we investigate a modified sensitivity equation, that includes an additional source term when the state solution exhibits discontinuities, to avoid the generation of delta-peaks in the sensitivity solution. We consider as typical example the 1D compressible Euler equations. Different approaches are tested to integrate the additional source term: a Roe solver, a Godunov method and a moving cells approach. Applications to uncertainty quantification in presence of shocks are demonstrated and compared to the classical Monte-Carlo method [26]. This study is achieved in collaboration with C. Chalons and C. Fiorini from University of Versailles.
- **High-order derivatives**

For problems with regular solution, we investigate the recursive use of the sensitivity equation method to estimate high-order derivatives of the solution with respect to parameters of interest. Such derivatives provide useful information for optimization or uncertainty quantification. More precisely, the third-order derivatives of flow solutions governed by 2D compressible Navier-Stokes equations are estimated with a satisfactory accuracy.

- **Shape sensitivity analysis**
  When shape parameters are considered, the evaluation of flow sensitivities is more difficult, because equations include an additional term, involving flow gradient, due to the fact that the parameter affects the boundary condition location. To overcome this difficulty, we propose to solve sensitivity equations using an isogeometric Discontinuous Galerkin (DG) method, which allows to estimate accurately flow gradients at boundary and consider boundary control points as shape parameters. First results obtained for 2D compressible Euler equations exhibit a sub-optimal convergence rate, as expected, but a better accuracy with respect to a classical DG method [40].

6.5. Optimization of nano-photonic devices

Participants: Mickaël Binois, Régis Duvigneau, Mahmoud Elsawy [NACHOS team], Alexis Gobé [NACHOS team], Stéphane Lanteri [NACHOS team].

In collaboration with NACHOS Project-Team, we consider the optimization of optical meta-surface devices, which are able to alter light properties by operating at nano-scale. In the contexte of Maxwell equations, modified to account for nano-scale phenomena, the geometrical properties of materials are optimized to achieve a desired electromagnetic wave response, such as change of polarization, intensity or direction. This task is especially challenging due to the computational cost related to the 3D time-accurate simulations and the difficulty to handle the different geometrical scales in optimization.

A first study, comparing an evolution strategy and a Bayesian optimization algorithm, demonstrates the potentiality of the proposed approach [25], [38].

6.6. Sequential learning of active subspace

Participants: Mickaël Binois, Nathan Wycoff [Virginia Tech], Stefan Wild [ANL].

Continuing a work started at Argonne National Laboratory, in [53] we consider the combination of Gaussian process regression modeling with the active subspace methods (ASMs), which have become a popular means of performing subspace sensitivity analysis on black-box functions. Naively applied, however, ASMs require gradient evaluations of the target function. In the event of noisy, expensive, or stochastic simulators, evaluating gradients via finite differencing may be infeasible. In such cases, often a surrogate model is employed, on which finite differencing is performed. When the surrogate model is a Gaussian process, we show that the ASM estimator is available in closed form, rendering the finite-difference approximation unnecessary. We use our closed-form solution to develop acquisition functions focused on sequential learning tailored to sensitivity analysis on top of ASMs. We also show that the traditional ASM estimator may be viewed as a method of moments estimator for a certain class of Gaussian processes. We demonstrate how uncertainty on Gaussian process hyperparameters may be propagated to uncertainty on the sensitivity analysis, allowing model-based confidence intervals on the active subspace. Our methodological developments are illustrated on several examples.

6.7. The Kalai-Smorodinski solution for many-objective Bayesian optimization

Participants: Mickaël Binois, Victor Picheny [Prowler.io], Abderrahmane Habbal.

Extending the short paper [67] on the use of the game-theoretic Kalai-Smorodinski solution in Bayesian optimization, we have refined the definition of solutions, discussed underlying assumptions, and shown empirically the improved performance of our proposed approach over naive heuristics. A realistic hyperparameter tuning problem with eight objectives as well as an expensive calibration problem with nine objectives have been considered as well.

In parallel, we have substantially improved the efficiency of the implementation, enabled specific treatment of calibration problems as well as handling noise in the `GPGame` package https://cran.r-project.org/web/packages/GPGame.

6.8. Heteroskedastic Gaussian process modeling and sequential design

Participants: Mickaël Binois, Robert Gramacy [Virginia Tech].

An increasing number of time-consuming simulators exhibit a complex noise structure that depends on the inputs. For conducting studies with limited budgets of evaluations, new surrogate methods are required in order to simultaneously model the mean and variance fields. To this end, in [43] we present the `hetGP` package https://cran.r-project.org/web/packages/hetGP, implementing many recent advances in Gaussian process modeling with input-dependent noise. First, we describe a simple, yet efficient, joint modeling framework that relies on replication for both speed and accuracy. Then we tackle the issue of data acquisition leveraging replication and exploration in a sequential manner for various goals, such as for obtaining a globally accurate model, for optimization, or for contour finding. Reproducible illustrations are provided throughout.

6.9. Direct and adaptive approaches to multi-objective optimization

Participants: Jean-Antoine Désidéri, Régis Duvigneau.

We formulate in a unified way the major theoretical results obtained by the authors in the domain of multi-objective differential optimization, discuss illustrative examples, and present a brief discussion of the related software developments made at Inria. The development is split in two connected parts. In Part A, the Multiple Gradient Descent Algorithm (MGDA), referred to as the direct approach, is a general construction of a descent method in the multi-objective optimization context. The algorithm provides a technique for determining Pareto optimal solutions in constrained problems as an extension of the classical steepest-descent method. In Part B, another problematics is posed, referred to as the adaptive approach. It is meant to be developed after a Pareto-optimal solution with respect to a set of primary cost functions subject to constraints has been elected in a first phase of optimization carried out by application of MGDA, or another effective multi-objective optimization technique, possibly an evolutionary strategy. This second phase of optimization permits to construct a continuum of neighboring solutions for which novel cost functions, designated as secondary cost functions, are reduced at the cost of a moderate degradation of the Pareto-stationarity condition of the primary cost functions. In this way, the entire optimization process demonstrates a form of adaptivity to the result of the first phase [42].

6.10. Platform for prioritized multi-objective optimization

Participant: Jean-Antoine Désidéri.

A multi-objective differentiable optimization algorithm had been proposed to solve problems presenting a hierarchy in the cost functions, $\{f_j(\mathbf{x})\}$ $(j = 1, \cdots, M \geq 2;\ \mathbf{x} \in \Omega_a \subseteq \mathsf{R}^n)$. The first cost functions for which $j \in \{1, \cdots, m\}$ $(1 \leq m < M)$ are considered to be of preponderant importance; they are referred to as the "primary cost functions" and are subject to a "prioritized" treatment, in contrast with the tail ones, for which $j \in \{m+1, \cdots, M\}$, referred to as the "secondary cost functions". The problem is subject to the nonlinear constraints, $c_k(\mathbf{x}) = 0$ $(k = 1, \cdots, K)$. The cost functions $\{f_j(\mathbf{x})\}$ and the constraint functions $\{c_k(\mathbf{x})\}$ are all smooth, say $C^2(\Omega_a)$. The algorithm was first introduced in the case of two disciplines ($m = 1$, $M = 2$), and successfully applied to optimum shape design optimization in compressible aerodynamics concurrently with a secondary discipline [101] [105]. An initial admissible point $\mathbf{x}_A^{\star}$ that is Pareto-optimal with respect to the sole primary cost functions (subject to the constraints) is assumed to be known. Subsequently, a small parameter $\varepsilon \in [0, 1]$ is introduced, and it is established that a continuum of Nash equilibria $\{\overline{\mathbf{x}}_\varepsilon\}$ exists for all small enough ε. The continuum originates from $\mathbf{x}_A^{\star}$ $(\overline{\mathbf{x}}_0 = \mathbf{x}_A^{\star})$. Along the continuum: (*i*) the Pareto-stationarity condition exactly satisfied by the primary cost functions at $\mathbf{x}_A^{\star}$ is degraded by a term $O(\varepsilon^2)$ only, whereas (*ii*) the secondary cost functions initially decrease, at least linearly with ε with a negative derivative provided by the theory. Thus, the secondary cost functions are reduced while the primary cost functions are maintained to quasi Pareto-optimality. In this report, we firstly recall the definition of the different steps in the computational Nash-game algorithm assuming the functions all have known first and second derivatives (here without proofs). Then we show how, in the absence of explicitly known derivatives, the continuum of Nash equilibria can be calculated approximately via the construction of quadratic surrogate functions. Numerical examples are provided and commented [41].

6.11. Non-convex multiobjective optimization under uncertainty: a descent algorithm. Application to sandwich plate design and reliability

Participants: Quentin Mercier [Onera DADS, Châtillon], Fabrice Poirion [Onera DADS, Châtillon], Jean-Antoine Désidéri.

A novel algorithm for solving multiobjective design optimization problems with non-smooth objective functions and uncertain parameters is presented. The algorithm is based on the existence of a common descent vector for each sample of the random objective functions and on an extension of the stochastic gradient algorithm. The proposed algorithm is applied to the optimal design of sandwich material. Comparisons with the genetic algorithm NSGA-II and the DMS solver are given and show that it is numerically more efficient due to the fact that it does not necessitate the objective function expectation evaluation. It can moreover be entirely parallelizable. Another simple illustration highlights its potential for solving general reliability problems, replacing each probability constraint by a new objective written in terms of an expectation. Moreover, for this last application, the proposed algorithm does not necessitate the computation of the (small) probability of failure [141].

6.12. Inverse Cauchy-Stokes problems solved as Nash games

Participants: Abderrahmane Habbal, Marwa Ouni [PhD, LAMSIN, Univ. Tunis Al Manar], Moez Kallel [LAMSIN, Univ. Tunis Al Manar].

We extend in two directions our results published in [30] to tackle ill posed Cauchy-Stokes inverse problems as Nash games. First, we consider the problem of detecting unknown pointwise sources in a stationary viscous fluid, using partial boundary measurements. The considered fluid obeys a steady Stokes regime, the boundary measurements are a single compatible pair of Dirichlet and Neumann data, available only on a partial accessible part of the whole boundary. This inverse source identification for the Cauchy-Stokes problem is ill-posed for both the sources and missing data reconstructions, and designing stable and efficient algorithms is challenging. We reformulate the problem as a three-player Nash game. Thanks to a source identifiability result derived for the Cauchy-Stokes problem, it is enough to set up two Stokes BVP, then use them as state equations. The Nash game is then set between 3 players, the two first targeting the data completion while the third one targets the detection of the number, location and magnitude of the unknown sources. We provided the third player with the location and magnitude parameters as strategy, with a cost functional of Kohn-Vogelius type. In particular, the location is obtained through the computation of the topological sensitivity of the latter function. We propose an original algorithm, which we implemented using Freefem++. We present 2D numerical experiments for many different test-cases.The obtained results corroborate the efficiency of our 3-player Nash game approach to solve parameter or shape identification for Cauchy-Stokes problems.

The second direction is dedicated to the solution of the data completion problem for non-linear flows. We consider two kinds of non linearities leading to either a non newtonian Stokes flow or to Navier-Stokes equations. Our recent numerical results show that it is possible to perform a one-shot approach using Nash games : players exchange their respective state information and solve linear systems. At convergence to a Nash equilibrium, the states converge to the solution of the non linear systems. To the best of our knowledge, this is the first time such an approach is applied to solve Inverse problems for nonlinear systems.

6.13. Virtual FFR quantified with a generalized flow model using Windkessel boundary conditions ; Application to a patient-specific coronary tree

Participants: Abderrahmane Habbal, Keltoum Chahour [PhD, ACUMES and EMI, Univ. Mohammed V], Rajae Aboulaich [EMI, Univ. Mohammed V], Nejib Zemzemi [Inria Bordeaux, EPI CARMEN], Mickaël Binois.

Fractional flow reserve (FFR) has proved its efficiency in improving patients diagnosis. From both economical and clinical viewpoints, a realistic simulation of vascular blood flow inside the coronary arteries could be a better alternative to the invasive FFR. In this view, we consider a 2D reconstructed left coronary tree with two artificial lesions of different degrees. We use a generalized fluid model with a Carreau law and use a coupled multidomain method to implement Windkessel boundary conditions at the outlets. We introduce our methodology to quantify the virtual FFR, and lead several numerical experiments. We compare FFR results from Navier Stokes versus generalized flow model, and for Windkessel versus traction free outlets boundary conditions or mixed outlets boundary conditions. We also investigate some sources of uncertainty that the FFR index might encounter during the invasive procedure, in particular the arbitrary position of the distal sensor. The computational FFR results show that the degree of stenosis is not enough to classify a lesion, while there is a good agreement between Navier Stokes and the non Newtonian flow model adopted in classifying coronary lesions. Furthermore, we highlight that the lack of standardization while making FFR measurement might be misleading regarding the significance of stenosis [76].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- **Etic Data** (2019-2020): Acumes has set up a 12 months research and development contract with the company Etic Data on "Predictive modeling and proactive driving of customers behaviour in massive data BtoC context".

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

- **Project OPERA** (2019-2021): Adaptive planar optics
  This project is composed of Inria teams NACHOS, ACUMES and HIEPACS, CNRS CRHEA lab. and company NAPA. Its objective is the characterization and design of new meta-surfaces for optics (opera web site).

8.2. European Initiatives

8.2.1. Collaborations in European Programs, Except FP7 & H2020

Program: COST

Project acronym: CA18232

Project title: Mathematical models for interacting dynamics on networks

Duration: October 2019 - September 2013

Coordinator: University of Ljubljana (Prof. Marjeta Kramar Fijavz)

Other partners: see https://www.cost.eu/actions/CA18232/#tabs|Name:parties

Abstract: Many physical, biological, chemical, financial or even social phenomena can be described by dynamical systems. It is quite common that the dynamics arises as a compound effect of the interaction between sub-systems in which case we speak about coupled systems. This Action shall study such interactions in particular cases from three points of view:

- the abstract approach to the theory behind these systems,
- applications of the abstract theory to coupled structures like networks, neighbouring domains divided by permeable membranes, possibly non-homogeneous simplicial complexes, etc.,
- modelling real-life situations within this framework.

The purpose of this Action is to bring together leading groups in Europe working on a range of issues connected with modelling and analysing mathematical models for dynamical systems on networks. It aims to develop a semigroup approach to various (non-)linear dynamical systems on networks as well as numerical methods based on modern variational methods and applying them to road traffic, biological systems, and further real-life models. The Action also explores the possibility of estimating solutions and long time behaviour of these systems by collecting basic combinatorial information about underlying networks.

8.3. International Initiatives

8.3.1. PHC Utique

Program: Program Hubert Curien PHC Utique (Tunisia)

Project acronym: NAMReD

Project title: Novel Algorithms and Models for Data Reconstruction

Duration: January 2018 - December 2020

Coordinator: A. Habbal and M. Kallel (Univ. Tunis al Manar)

Abstract: The project goal is the design of new and efficient algorithms tailored for data reconstruction involving ill-posed problems. We rely on an original use of game theory and p-Kirchhoff methods. We apply these approaches for missing data recovery and image restoration.

8.3.2. PHC Procope

Program: Program Hubert Curien Procope (Germany)

Project title: Non-local conservation laws for engineering applications

Duration: January 2019 - December 2020

Coordinator: P. Goatin and S. Göttlich (Univ. Mannheim)

Abstract: This project tackles theoretical and numerical issues arising in the mathematical study of conservation laws with non-local flux functions. These equations appear in a variety of applications, ranging from traffic flows to industrial processes and biology, and are intended to model macroscopically the action of non-local interactions occurring at the microscopic level. The team, bi-located in France and Germany, has complementary skills covering the analysis, numerical approximation and optimization of non-linear hyperbolic systems of conservation laws, and their application to the modeling of vehicular and pedestrian traffic flows, manufacturing systems and other industrial problems. Based on the members expertise and on the preliminary results obtained by both teams, the project will focus on the following interconnected aspects: The treatment of boundary conditions, both from the analytical and the numerical point of views, in order to provide a sound basis to address specific problems arising in the applications. The development of efficient, high-order finite volume numerical schemes for the computation of approximate solutions of non-local equations. The investigation of optimal control problems with corresponding optimality systems and the design of appropriate and adaptive optimization algorithms. Targeted applications include vehicular traffic (mainly in connection with vehicle-to-vehicle communication and consumption/pollution estimation), crowd motion (in connection with safe building evacuation procedures), and manufacturing systems (intelligent production). The impact of the project is therefore twofold: while addressing major mathematical advances in the theory and numerical approximation of highly non-standard problems, it puts the basis for innovative tools to handle modern applications in engineering sciences.

8.3.3. Inria International Labs

Inria Chile

Associate Team involved in the International Lab:

8.3.3.1. NOLOCO

Title: Efficient numerical schemes for non-local transport phenomena

International Partner (Institution - Laboratory - Researcher):

Universidad del Bio-Bio (Chile) - Luis Miguel Villada Osorio

Start year: 2018

See also: https://team.inria.fr/acumes/assoc-team/noloco/

This project tackles theoretical and numerical issues arising in the mathematical study of conservation laws with non-local flux functions. These equations include in a variety of applications, ranging from traffic flows to industrial processes and biology, and are intended to model macroscopically the action of non-local interactions occurring at the microscopic level.

The team, bi-located in France and Chile, has complementary skills covering the analysis, numerical approximation and optimization of non-linear hyperbolic systems of conservation laws, and their application to the modeling of vehicular and pedestrian traffic flows, sedimentation and other industrial problems.

Based on the members' expertise and on the preliminary results obtained by the team, the project will focus on the following aspects:

- The development of efficient, high-order finite volume numerical schemes for the computation of approximate solutions of non-local equations.
- The sensitivity analysis of the solutions on model parameters or initial conditions.

The impact of the project is therefore twofold: while addressing major mathematical advances in the theory and numerical approximation of highly non-standard problems, it puts the basis for innovative tools to handle modern applications in engineering sciences.

8.3.4. Inria International Partners

8.3.4.1. ORESTE

Title: Optimal REroute Strategies for Traffic managEment

International Partner (Institution - Laboratory - Researcher):

University of California Berkeley (United States) - Electrical Engineering and Computer Science (EECS) (EECS) - Alexandre M. Bayen

Duration: 2018 - 2022

Start year: 2018

See also: https://team.inria.fr/acumes/assoc-team/oreste

The rapidly changing transportation ecosystem opens new challenges in traffic modeling and optimization approaches. We will focus in particular on the two following aspects:

Route choice apps impact. The vast use of personal route choice systems through phone applications or other devices is modifying the traditional flow of networks, requiring new models for accounting of the guidance impact. Indeed, routing apps have changed traffic patterns in the US and Europe, leading to new congestion patterns where previously no traffic was observed. Over the last decade, GPS enabled smart phones and connected personal navigation devices have disrupted the mobility landscape. Initially, the availability of traffic information led to better guidance of a small portion of motorists in the system. But as the majority of the driving public started to use apps, the systematic broadcasting of “selfish” best routes led to the worsening of traffic in numerous places, ultimately leading to the first lawsuit against one specific company in particular (Waze) accused to be the cause of these problems. This is just the beginning of an evolution, which, if not controlled and regulated, will progressively asphyxiate urban landscapes (already nearly hundreds of occurrences of this phenomenon are noticed by the popular media, which indicates the presence of probably thousands of such issues in the US alone). Traffic managers are typically not equipped to fix these problems, and typically do not fund this research, as in order to be able to regulate and fix the problem, fundamental science needs to be advanced, modeling and game theory in particular, so remediation can happen (for which the traffic managers are equipped). In this project, we will mainly focus on the development and study of new macroscopic dynamical models to describe the aforementioned phenomena, and we will explore control strategies to mitigate their impact.

Autonomous vehicles. Besides, the foreseen deployment of connected and autonomous vehicles (CAVs) opens new perspectives both in traffic modeling and control. Indeed, CAVs are expected to modify the classical macroscopic traffic dynamics due to their peculiar motion laws, which are more uniform than human drivers’ and follow different rules. Besides, due to their extended information on neighboring traffic conditions, the resulting dynamics would have a non-local character, justifying the use of rapidly developing non-local models. In any case, the different behavior of autonomous vehicles requires the design of new multi-class models capable of accounting for different vehicle classes characteristics and mutual interactions. Moreover, CAVs could be used as endogenous variable speed limiters, thus providing new action points to control traffic flow. Preliminary results show that the presence of few controlled vehicles can positively affect traffic conditions. In this setting, the interaction of AVs with the surrounding traffic can be described by strongly coupled PDE-ODE systems, which have been largely studied by the ACUMES team. Yet, the study of CAVs impact in realistic situations requires further research, in particular towards model validation, for which the Berkeley team will provide the necessary data.

8.3.4.2. Informal International Partners

University of Milano Bicocca, Mathematics and Applications (M. Garavello: https://sites.google.com/site/maurogaravello/)

University of Rutgers - Camden, Department of Mathematical Science (B. Piccoli: https://piccoli.camden.rutgers.edu/)

Argonne National Laboratory, Mathematics and Computer Science Division (Jonathan Ozik: https://www.anl.gov/profile/jonathan-ozik, Stefan Wild: https://www.anl.gov/profile/stefan-m-wild)

Virginia Polytechnic Institute and State University (Robert B. Gramacy: https://www.stat.vt.edu/people/stat-faculty/gramacy-robert.html)

University of Texas Arlington (S. Roy, https://mentis.uta.edu/explore/profile/souvik-roy)

8.4. International Research Visitors

8.4.1. Visits of International Scientists

- J. Friedrich (January, June-July, November 2019, Univ. Mannheim, Germany): non-local traffic flow models.
- J. Kotz (November 2019, Univ. Mannheim, Germany): augmented macroscopic traffic flow models at junctions.
- L.M. Villada (November 2019, University of Bio-Bio): finite volume schemes for non-local systems of conservation laws.
- R. Ordonez (November-December 2019, Univ. Concepcion, Chile): finite volume schemes for non-local systems of conservation laws.

- R. Bürger (December 2019, Univ. Concepcion, Chile): finite volume schemes for non-local systems of conservation laws.
- M. Kallel (December 2019, Univ. Tunis al Manar, Tunisia): Game theory for inverse problems.

8.4.2. Visits to International Teams

8.4.2.1. Research Stays Abroad

- F.A. Chiarello visited Mannheim University (S. Göttlich) for 3 months in March-May 2019.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events: Organisation

9.1.1.1. General Chair, Scientific Chair

- P. Goatin is member of the the scientific committee of the annual seminar CEA-GAMNI *"Numerical fluid-mechanics"*.
- P. Goatin was member of the scientific committee of the CIRM conference *"Crowds: models and control"*, Marseille (France), 2019.

9.1.1.2. Member of the Organizing Committees

- R. Duvigneau and A. Habbal are members of the Organizing Committee for the FGS French-German-Swiss Conference on Optimization, Nice, September 2019.
- A. Habbal co-organized the mini-symposium *Game Theory Approaches in Inverse Problems and Control*, French-German-Swiss Conference on Optimization, Nice, September 2019.
- P. Goatin co-organized the mini-symposium *"Numerical methods for traffic flow problems"*, WONAPDE 2019 - 6th Chilean Workshop on Numerical Analysis of Partial Differential Equations, Conception (Chile), 2019 (with L.M. Villada).
- P. Goatin was member of the organizing committee of the IPAM (UCLA) workshop *"Autonomous Vehicles"*, Los Angeles (USA), 2019.
- P. Goatin and E. Rossi co-organized the mini-symposium *"Non Local Balance Laws and their applications"*, ICIAM2019 - 9th International Congress on Industrial and Applied Mathematics, Valencia (Spain), 2019.

9.1.2. Scientific Events: Selection

9.1.2.1. Member of the Conference Program Committees

A. Habbal was program committee member of The 3rd International Conference on Information Technology & Electrical Engineering - ITEE'19 El Jadida - Morocco, 2019. (http://www.ucd.ac.ma/ITEE19/)

9.1.2.2. Reviewer

- M. Binois reviewed for the following conferences: AISTATS 2020, NeurIPS 2019, and Winter Simulation Conference 2019.
- P. Goatin reviewed for the 11th IFAC Symposium on Nonlinear Control Systems.
- A. Habbal reviewed for the FGS French-German-Swiss Conference on Optimization, Nice, September 2019.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- P. Goatin is Managing Editor of *Networks and Heterogeneous Media*.
- P. Goatin is Guest Editor for the special issue "Mathematical Modeling with Measures" of *Mathematical and Bioscience Engineering*.

9.1.3.2. Reviewer - Reviewing Activities

- M. Binois is a reviewer for the following international journals: Aerospace Science and Technology, Annals of Applied Statistics, Journal of Aerospace Engineering, Computational Optimization and Applications, Computational Statistics and Data Analysis, Informs Computing, International Journal on Artificial Intelligence Tools, Integrating Materials and Manufacturing Innovation, Optimization and Engineering, The Computer Journal
- R. Duvigneau is reviewer for the following international journals: Computers & Fluids, International Journal for Numerical Methods in Fluids, Journal of Fluid & Structures, Computer Methods for Applied Mechanics Engineering, Computer Aided Geometric Design, Applied Mathematics & Mechanics, Engineering Optimization, Ocean Engineering
- P. Goatin reviewed for the following international journals: Acta Applicandae Mathematicae; Communications of the Korean Mathematical Society; ESAIM: Mathematical Modelling and Numerical Analysis; IEEE Transactions on Automatic Control; Nonlinear Differential Equations and Applications NoDEA; SIAM Journal on Mathematical Analysis; Transportmetrica A: Transport Science.
- J.-A. Désidéri has made reviews for: Mathematical Problems in Engineering; Numerical Algorithms; Algorithms; Operations Research and Decisions; Journal of Computational Design and Engineering; AIAA Journal.
- A. Habbal is a reviewer for the AMS Math Reviews, and for the following international journals: SIAM Scientific Computing ; Eur. Journal of Operation Research ; Systems & Control Letters.

9.1.4. Invited Talks

- M. Binois: Séminaire LJK-Probabilités & Statistique, Grenoble (France), April 2019.
  Invited talk: *"Heteroskedastic Gaussian Processes for Simulation Experiments"*.
- M. Binois: SRC 2019 - 2019 IMS/ASA Spring Research Conference, Blacksburg (VA, USA), May 2019.
  Invited talk: *"Sequential Learning of Active Subspaces"*.
- M. Binois: ICIAM 2019 - 9th International Congress on Industrial and Applied Mathematics, Valencia (Spain), July 2019. Mini-symposium: "Mathematical Optimization for Industrial and Scientific Applications".
  Invited talk: *"Bayesian Optimization and Dimension Reduction with Active Subspaces"*.
- P. Goatin: Program on "Data Assimilation: Theory, Algorithms, and Applications", Montreal (Canada), May 2019.
  Workshop "Data Assimilation: Methodology and Applications".
  Invited talk: *"Data driven traffic flow models"*.

- P. Goatin: Workshop “Nonlinear Hyperbolic Problems: modeling, analysis, and numerics", Mathematisches Forschungsinstitut, Oberwolfach (Germany), May 2019.
  Invited talk: *“Regularity results for the solutions of a non-local model of traffic flow”*.
- P. Goatin: “30 Years of SIMAI: status and perspectives of applied and industrial mathematics in Italy and in Europe”, Milano (Italy), July 2019.
  Invited talk: *“Traffic management by macroscopic models: present and future challenges”*.
- P. Goatin: ICIAM 2019 - 9th International Congress on Industrial and Applied Mathematics, Valencia (Spain), July 2019. Mini-symposium: “Modelling and calibration in pedestrian dynamics: analysis and numerics”.
  Invited talk: *“Non-local macroscopic models for crowd motion”*.
- P. Goatin: Workshop “Resilient Control of Infrastructure Networks”, Politecnico di Torino (Italy), September 2019.
  Invited talk: *“Macroscopic traffic flow models on road networks”*.
- A. Habbal: ICIAM 2019 - 9th International Congress on Industrial and Applied Mathematics, Valencia (Spain), July 2019. Mini-symposium: “Geometric inverse problems and parameter estimation”.
  Invited talk: *“Fractional Flow Reserve in a stenosed coronary artery”*.
- A. Habbal: MYRPAM 2019 - First Maghrebian Young Researchers in Pure and Applied Mathematics, Hammamet (Tunisia), December 2019. Plenary talk: *“Game Strategies to Solve and Model PDE-constrained Problems”*.

9.1.5. Scientific Expertise

- P. Goatin is member of the advisory board of DISMA Excellence Project of Politecnico di Torino (2018-2022).
- A. Habbal was member of the evaluation panel of the SiRIC CURAMUS Project (Integrated Research in Cancerology) https://curamus-cancer.fr/

9.1.6. Research Administration

- P. Goatin is member of the board of the Doctoral School of Fundamental and Applied Sciences (ED SFA) of Université Côte D’Azur.
- P. Goatin was vice-president of the local selection committee for Inria Sophia Antipolis competitive selection of young graduate scientists (CRCN) (2019).
- R. Duvigneau is member of CSD (“Comité Suivi Doctoral) at Inria Sophia Antipolis Méditerranée.
- R. Duvigneau is head of the Scientific Steering Committee of Platforms (cluster and immersive space) at Inria Sophia Antipolis Méditerranée.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master: M. Binois, Design of experiments, 6 hrs, M2, Ecole Nationale Supérieure des Mines de Saint-Étienne, Saint-Étienne.

Master: R. Duvigneau, Advanced Optimization, 40 hrs, M2, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis.

Master: R. Duvigneau & A. Habbal, Numerical Methods for Partial Differential Equations, 66 hrs, M1, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis.

Master: J.-A. Désidéri, Multidisciplinary Optimization, 22.5 hrs, joint *Institut Supérieur de l’Aéronautique et de l’Espace* (ISAE Supaéro, "Complex Systems") and M2 (Mathematics), Toulouse.

Master: A. Habbal, Optimization, 66 hrs, M1, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis.

Master: A. Habbal, Stochastic Processes, 24 hrs, M1, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis.

Master: A. Habbal, Combinatorial optimization, 15 hrs, M1, Mohammed VI Polytechnic University, Morocco.

Licence (L3): A. Habbal, Implement and Experiment PSO, 48 hrs, L3 Semester Project, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis.

9.2.2. Supervision

PhD in progress: S. Pezzano, *Isogeometric analysis with moving grids*, Univ. Nice Sophia-Antipolis. Supervisor: R. Duvigneau.

PhD defended in September 2019: Nicolas Laurent-Brouty (ENPC), *Macroscopic traffic flow models for pollution estimation and control*, September 2016. Supervisor: P. Goatin.

PhD defended in October 2019: Nikodem Dymski (Maria Curie Sklodowska University & Université de Nice Sophia Antipolis), *Conservation laws in the modeling of collective phenomena*, October 2016. Supervisors: P. Goatin and M.D. Rosini (UMCS).

PhD defended in December 2019: Felisia Angela Chiarello (Université de Nice Sophia Antipolis), *Conservation laws with non- local flux*, October 2016. Supervisor: P. Goatin.

PhD in progress: S. Chabbar, *Modeling and simulation of tumor growth ; the case of prostate cancer*, Jan 2019, Supervisors: A. Habbal, Rajae Aboulaich (LERMA, EMI, Rabat), A. Ratnani (UM6P, Benguerir, Morocco).

PhD in progress: Marwa Ouni, *Solving inverses problems in fluid mechanics with game strategies*, October 2016, Supervisors: A. Habbal, Moez Kallel (LAMSIN, ENIT, Tunis).

PhD defended in December 2019: Rabeb Chamekh, *Game strategies to solve some inverse problems*, Jan 2015, Supervisors: A. Habbal, Moez Kallel (LAMSIN, ENIT, Tunis).

PhD defended in December 2019: Keltoum Chahour, *Modeling coronary blood flow using a non newtonian fluid model : fractional flow reserve estimation*, Nov 2015, Supervisors: A. Habbal, Rajae Aboulaich (LERMA, EMI, Rabat).

9.2.3. Juries

- R. Duvigneau was member of the committee of David Gaudrie's PhD thesis *"High-dimensional multi-objective Gaussian optimization"*, Ecole des Mines de St Etienne, October 28th, 2019.
- P. Goatin was reviewer of D. Inzunza's PhD thesis *"Implicit-explicit methods for nonlinear and nonlocal convection-diffusion-reaction problems"*, Universidad de Concepción, December 2019.

9.3. Popularization

9.3.1. Articles and contents

- "On the optimal shape of a wing", R. Duvigneau, Interstices, September 2019.
- A.S. Ackleh, R.M. Colombo, P. Goatin, S. Hille and A. Muntean, *Mathematical modeling with measures*, Nieuw Archief voor Wiskunde, Part 20 n. 3, September 2019.

9.3.2. Interventions

- R. Duvigneau gave three talks on "Modeling and simulation: when engineering becomes numerical" at Lycée Jules Ferry, Cannes, March 2019.
- P. Goatin gave the talk *"Le trafic routier en équations"* in Biot (Alpes Maritimes, France) on January 31, 2019, as part of the conference cycle "Science pour Tous 06".
- A. Habbal contributed to Cafe'In talks on *"Tumoral Angiogenesis"*, June 2019.

10. Bibliography

Major publications by the team in recent years

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[2] L. ALMEIDA, P. BAGNERINI, A. HABBAL, S. NOSELLI, F. SERMAN.*A Mathematical Model for Dorsal Closure*, in "Journal of Theoretical Biology", January 2011, vol. 268, n^o 1, p. 105-119 [*DOI :* 10.1016/J.JTBI.2010.09.029], http://hal.inria.fr/inria-00544350/en

[3] B. ANDREIANOV, P. GOATIN, N. SEGUIN.*Finite volume schemes for locally constrained conservation laws*, in "Numer. Math.", 2010, vol. 115, n^o 4, p. 609–645, With supplementary material available online

[4] S. BLANDIN, P. GOATIN.*Well-posedness of a conservation law with non-local flux arising in traffic flow modeling*, in "Numerische Mathematik", 2015 [*DOI :* 10.1007/S00211-015-0717-6], https://hal.inria.fr/hal-00954527

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[7] M. L. DELLE MONACHE, J. REILLY, S. SAMARANAYAKE, W. KRICHENE, P. GOATIN, A. BAYEN.*A PDE-ODE model for a junction with ramp buffer*, in "SIAM J. Appl. Math.", 2014, vol. 74, n^o 1, p. 22–39

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[9] A. HABBAL, M. KALLEL.*Neumann-Dirichlet Nash strategies for the solution of elliptic Cauchy problems*, in "SIAM J. Control Optim.", 2013, vol. 51, n^o 5, p. 4066–4083

[10] M. KALLEL, R. ABOULAICH, A. HABBAL, M. MOAKHER.*A Nash-game approach to joint image restoration and segmentation*, in "Appl. Math. Model.", 2014, vol. 38, n^o 11-12, p. 3038–3053, http://dx.doi.org/10.1016/j.apm.2013.11.034

[11] M. MARTINELLI, R. DUVIGNEAU.*On the use of second-order derivative and metamodel-based Monte-Carlo for uncertainty estimation in aerodynamics*, in "Computers and Fluids", 2010, vol. 37, n^o 6

[12] S. ROY, A. BORZÌ, A. HABBAL.*Pedestrian motion modelled by Fokker–Planck Nash games*, in "Royal Society open science", 2017, vol. 4, n^o 9, 170648

[13] M. TWAROGOWSKA, P. GOATIN, R. DUVIGNEAU.*Macroscopic modeling and simulations of room evacuation*, in "Appl. Math. Model.", 2014, vol. 38, n^o 24, p. 5781–5795

[14] G. XU, B. MOURRAIN, A. GALLIGO, R. DUVIGNEAU.*Constructing analysis-suitable parameterization of computational domain from CAD boundary by variational harmonic method*, in "J. Comput. Physics", November 2013, vol. 252

[15] B. YAHYAOUI, M. AYADI, A. HABBAL.*Fisher-KPP with time dependent diffusion is able to model cell-sheet activated and inhibited wound closure*, in "Mathematical biosciences", 2017, vol. 292, p. 36–45

Publications of the year

Doctoral Dissertations and Habilitation Theses

[16] K. CHAHOUR.*Modeling coronary blood flow using a non newtonian fluid model : fractional flow reserve estimation*, Université Nice Sophia Antipolis, December 2019, https://hal.inria.fr/tel-02430901

Articles in International Peer-Reviewed Journal

[17] F. BERTHELIN, P. GOATIN.*Regularity results for the solutions of a non-local model of traffic*, in "Discrete and Continuous Dynamical Systems - Series A", 2019, vol. 39, n° 6, p. 3197-3213, https://hal.archives-ouvertes.fr/hal-01813760

[18] E. BERTINO, R. DUVIGNEAU, P. GOATIN.*Uncertainty quantification in a macroscopic traffic flow model calibrated on GPS data*, in "Mathematical Biosciences and Engineering", 2019, forthcoming, https://hal.archives-ouvertes.fr/hal-02379540

[19] K. CHAHOUR, R. ABOULAICH, A. HABBAL, N. ZEMZEMI, C. ABDELKHIRANE.*Virtual FFR quantified with a generalized flow model using Windkessel boundary conditions ; Application to a patient-specific coronary tree*, in "Computational and Mathematical Methods in Medicine", 2020, forthcoming, https://hal.inria.fr/hal-02427411

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Project-Team AROMATH

AlgebRe gèOmétrie Modelisation et AlgoriTHmes

IN PARTNERSHIP WITH:
National & Kapodistrian University of Athens

RESEARCH CENTER
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THEME
Algorithmics, Computer Algebra and Cryptology

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Project-Team AROMATH

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Other Research Topics and Application Domains:

B9.5.1. - Computer science

B9.5.2. - Mathematics

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2. Overall Objectives

2.1. Overall Objectives

Our daily life environment is increasingly interacting with digital information. An important amount of this information is of geometric nature. It concerns the representation of our environment, the analysis and understanding of "real" phenomena, the control of physical mechanisms or processes. The interaction between physical and digital worlds is two-way. Sensors are producing digital data related to measurements or observations of our environment. Digital models are also used to "act" on the physical world. Objects that we use at home, at work, to travel, such as furniture, cars, planes, ... are nowadays produced by industrial processes which are based on digital representation of shapes. CAD-CAM (Computer Aided Design – Computer Aided Manufacturing) software is used to represent the geometry of these objects and to control the manufacturing processes which create them. The construction capabilities themselves are also expanding, with the development of 3D printers and the possibility to create daily-life objects "at home" from digital models.

The impact of geometry is also important in the analysis and understanding of phenomena. The 3D conformation of a molecule explains its biological interaction with other molecules. The profile of a wing determines its aeronautic behavior, while the shape of a bulbous bow can decrease significantly the wave resistance of a ship. Understanding such a behavior or analyzing a physical phenomenon can nowadays be achieved for many problems by numerical simulation. The precise representation of the geometry and the link between the geometric models and the numerical computation tools are closely related to the quality of these simulations. This also plays an important role in optimisation loops where the numerical simulation results are used to improve the "performance" of a model.

Geometry deals with structured and efficient representations of information and with methods to treat it. Its impact in animation, games and VAMR (Virtual, Augmented and Mixed Reality) is important. It also has a growing influence in e-trade where a consumer can evaluate, test and buy a product from its digital description. Geometric data produced for instance by 3D scanners and reconstructed models are nowadays used to memorize old works in cultural or industrial domains.

Geometry is involved in many domains (manufacturing, simulation, communication, virtual world...), raising many challenging questions related to the representations of shapes, to the analysis of their properties and to the computation with these models. The stakes are multiple: the accuracy in numerical engineering, in simulation, in optimization, the quality in design and manufacturing processes, the capacity of modeling and analysis of physical problems.

3. Research Program

3.1. High order geometric modeling

The accurate description of shapes is a long standing problem in mathematics, with an important impact in many domains, inducing strong interactions between geometry and computation. Developing precise geometric modeling techniques is a critical issue in CAD-CAM. Constructing accurate models, that can be exploited in geometric applications, from digital data produced by cameras, laser scanners, observations or simulations is also a major issue in geometry processing. A main challenge is to construct models that can capture the geometry of complex shapes, using few parameters while being precise.

Our first objective is to develop methods, which are able to describe accurately and in an efficient way, objects or phenomena of geometric nature, using algebraic representations.

The approach followed in CAGD, to describe complex geometry is based on parametric representations called NURBS (Non Uniform Rational B-Spline). The models are constructed by trimming and gluing together high order patches of algebraic surfaces. These models are built from the so-called B-Spline functions that encode a piecewise algebraic function with a prescribed regularity at knots. Although these models have many advantages and have become the standard for designing nowadays CAD models, they also have important drawbacks. Among them, the difficulty to locally refine a NURBS surface and also the topological rigidity of NURBS patches that imposes to use many such patches with trims for designing complex models, with the consequence of the appearing of cracks at the seams. To overcome these difficulties, an active area of research is to look for new blending functions for the representation of CAD models. Some examples are the so-called T-Splines, LR-Spline blending functions, or hierarchical splines, that have been recently devised in order to perform efficiently local refinement. An important problem is to analyze spline spaces associated to general subdivisions, which is of particular interest in higher order Finite Element Methods. Another challenge in geometric modeling is the efficient representation and/or reconstruction of complex objects, and the description of computational domains in numerical simulation. To construct models that can represent efficiently the geometry of complex shapes, we are interested in developing modeling methods, based on alternative constructions such as skeleton-based representations. The change of representation, in particular between parametric and implicit representations, is of particular interest in geometric computations and in its applications in CAGD.

We also plan to investigate adaptive hierarchical techniques, which can locally improve the approximation of a shape or a function. They shall be exploited to transform digital data produced by cameras, laser scanners, observations or simulations into accurate and structured algebraic models.

The precise and efficient representation of shapes also leads to the problem of extracting and exploiting characteristic properties of shapes such as symmetry, which is very frequent in geometry. Reflecting the symmetry of the intended shape in the representation appears as a natural requirement for visual quality, but also as a possible source of sparsity of the representation. Recognizing, encoding and exploiting symmetry requires new paradigms of representation and further algebraic developments. Algebraic foundations for the exploitation of symmetry in the context of non linear differential and polynomial equations are addressed. The intent is to bring this expertise with symmetry to the geometric models and computations developed by AROMATH.

3.2. Robust algebraic-geometric computation

In many problems, digital data are approximated and cannot just be used as if they were exact. In the context of geometric modeling, polynomial equations appear naturally, as a way to describe constraints between the unknown variables of a problem. *An important challenge is to take into account the input error in order to develop robust methods for solving these algebraic constraints.* Robustness means that a small perturbation of the input should produce a controlled variation of the output, that is forward stability, when the input-output map is regular. In non-regular cases, robustness also means that the output is an exact solution, or the most coherent solution, of a problem with input data in a given neighborhood, that is backward stability.

Our second long term objective is to develop methods to robustly and efficiently solve algebraic problems that occur in geometric modeling.

Robustness is a major issue in geometric modeling and algebraic computation. Classical methods in computer algebra, based on the paradigm of exact computation, cannot be applied directly in this context. They are not designed for stability against input perturbations. New investigations are needed to develop methods, which integrate this additional dimension of the problem. Several approaches are investigated to tackle these difficulties.

One relies on linearization of algebraic problems based on “elimination of variables” or projection into a space of smaller dimension. Resultant theory provides strong foundation for these methods, connecting the geometric properties of the solutions with explicit linear algebra on polynomial vector spaces, for families of polynomial systems (e.g., homogeneous, multi-homogeneous, sparse). Important progresses have been made in the last two decades to extend this theory to new families of problems with specific geometric properties. Additional advances have been achieved more recently to exploit the syzygies between the input equations. This approach provides matrix based representations, which are particularly powerful for approximate geometric computation on parametrized curves and surfaces. They are tuned to certain classes of problems and an important issue is to detect and analyze degeneracies and to adapt them to these cases.

A more adaptive approach involves linear algebra computation in a hierarchy of polynomial vector spaces. It produces a description of quotient algebra structures, from which the solutions of polynomial systems can be recovered. This family of methods includes Gröbner Basis, which provides general tools for solving polynomial equations. Border Basis is an alternative approach, offering numerically stable methods for solving polynomial equations with approximate coefficients. An important issue is to understand and control the numerical behavior of these methods as well as their complexity and to exploit the structure of the input system.

In order to compute “only” the (real) solutions of a polynomial system in a given domain, duality techniques can also be employed. They consist in analyzing and adding constraints on the space of linear forms which vanish on the polynomial equations. Combined with semi-definite programming techniques, they provide efficient methods to compute the real solutions of algebraic equations or to solve polynomial optimization problems. The main issues are the completness of the approach, their scalability with the degree and dimension and the certification of bounds.

Singular solutions of polynomial systems can be analyzed by computing differentials, which vanish at these points. This leads to efficient deflation techniques, which transform a singular solution of a given problem into a regular solution of the transformed problem. These local methods need to be combined with more global root localisation methods.

Subdivision methods are another type of methods which are interesting for robust geometric computation. They are based on exclusion tests which certify that no solution exists in a domain and inclusion tests, which certify the uniqueness of a solution in a domain. They have shown their strength in addressing many algebraic problems, such as isolating real roots of polynomial equations or computing the topology of algebraic curves and surfaces. The main issues in these approaches is to deal with singularities and degenerate solutions.

4. Application Domains

4.1. Geometric modeling for Design and Manufacturing.

The main domain of applications that we consider for the methods we develop is Computer Aided Design and Manufacturing.

Computer-Aided Design (CAD) involves creating digital models defined by mathematical constructions, from geometric, functional or aesthetic considerations. Computer-aided manufacturing (CAM) uses the geometrical design data to control the tools and processes, which lead to the production of real objects from their numerical descriptions.

CAD-CAM systems provide tools for visualizing, understanding, manipulating, and editing virtual shapes. They are extensively used in many applications, including automotive, shipbuilding, aerospace industries, industrial and architectural design, prosthetics, and many more. They are also widely used to produce computer animation for special effects in movies, advertising and technical manuals, or for digital content creation. Their economic importance is enormous. Their importance in education is also growing, as they are more and more used in schools and educational purposes.

CAD-CAM has been a major driving force for research developments in geometric modeling, which leads to very large software, produced and sold by big companies, capable of assisting engineers in all the steps from design to manufacturing.

Nevertheless, many challenges still need to be addressed. Many problems remain open, related to the use of efficient shape representations, of geometric models specific to some application domains, such as in architecture, naval engineering, mechanical constructions, manufacturing ...Important questions on the robustness and the certification of geometric computation are not yet answered. The complexity of the models which are used nowadays also appeals for the development of new approaches. The manufacturing environment is also increasingly complex, with new type of machine tools including: turning, 5-axes machining and wire EDM (Electrical Discharge Machining), 3D printer. It cannot be properly used without computer assistance, which raises methodological and algorithmic questions. There is an increasing need to combine design and simulation, for analyzing the physical behavior of a model and for optimal design.

The field has deeply changed over the last decades, with the emergence of new geometric modeling tools built on dedicated packages, which are mixing different scientific areas to address specific applications. It is providing new opportunities to apply new geometric modeling methods, output from research activities.

4.2. Geometric modeling for Numerical Simulation and Optimization

A major bottleneck in the CAD-CAM developments is the lack of interoperability of modeling systems and simulation systems. This is strongly influenced by their development history, as they have been following different paths.

The geometric tools have evolved from supporting a limited number of tasks at separate stages in product development and manufacturing, to being essential in all phases from initial design through manufacturing.

Current Finite Element Analysis (FEA) technology was already well established 40 years ago, when CAD-systems just started to appear, and its success stems from using approximations of both the geometry and the analysis model with low order finite elements (most often of degree ≤ 2).

There has been no requirement between CAD and numerical simulation, based on Finite Element Analysis, leading to incompatible mathematical representations in CAD and FEA. This incompatibility makes interoperability of CAD/CAM and FEA very challenging. In the general case today this challenge is addressed by expensive and time-consuming human intervention and software developments.

Improving this interaction by using adequate geometric and functional descriptions should boost the interaction between numerical analysis and geometric modeling, with important implications in shape optimization. In particular, it could provide a better feedback of numerical simulations on the geometric model in a design optimization loop, which incorporates iterative analysis steps.

The situation is evolving. In the past decade, a new paradigm has emerged to replace the traditional Finite Elements by B-Spline basis element of any polynomial degree, thus in principle enabling exact representation of all shapes that can be modeled in CAD. It has been demonstrated that the so-called isogeometric analysis approach can be far more accurate than traditional FEA.

It opens new perspectives for the interoperability between geometric modeling and numerical simulation. The development of numerical methods of high order using a precise description of the shapes raises questions on piecewise polynomial elements, on the description of computational domains and of their interfaces, on the construction of good function spaces to approximate physical solutions. All these problems involve geometric considerations and are closely related to the theory of splines and to the geometric methods we are investigating. We plan to apply our work to the development of new interactions between geometric modeling and numerical solvers.

5. New Results

5.1. Truncated Normal Forms for Solving Polynomial Systems: Generalized and Efficient Algorithms

Participant: Bernard Mourrain.

In [16], we consider the problem of finding the isolated common roots of a set of polynomial functions defining a zero-dimensional ideal I in a ring R of polynomials over $\mathbb{C}$. Normal form algorithms provide an algebraic approach to solve this problem. The framework presented in Telen et al. (2018) uses truncated normal forms (TNFs) to compute the algebra structure of R/I and the solutions of I. This framework allows for the use of much more general bases than the standard monomials for R/I. This is exploited in this paper to introduce the use of two special (non-monomial) types of basis functions with nice properties. This allows, for instance, to adapt the basis functions to the expected location of the roots of I. We also propose algorithms for efficient computation of TNFs and a generalization of the construction of TNFs in the case of non-generic zero-dimensional systems. The potential of the TNF method and usefulness of the new results are exposed by many experiments.

This is a joint work with Simon Telen and Marc Van Barel, Department of Computer Science - K.U.Leuven.

5.2. Implicit representations of high-codimension varieties

Participants: Ioannis Emiris, Clément Laroche, Christos Konaxis.

In [8], we study implicitization, which usually focuses on plane curves and (hyper)surfaces, in other words, varieties of codimension 1. We shift the focus on space curves and, more generally, on varieties of codimension larger than 1, and discuss approaches that are not sensitive to base points. Our first contribution is a direct generalization of an implicitization method based on interpolation matrices for objects of high codimension given parametrically or as point clouds. Our result shows the completeness of this approach which, furthermore, reduces geometric operations and predicates to linear algebra computations. Our second, and main contribution is an implicitization method of parametric space curves and varieties of codimension > 1, which exploits the theory of Chow forms to obtain the equations of conical (hyper)surfaces intersecting precisely at the given object. We design a new, practical, randomized algorithm that always produces correct output but possibly with a non-minimal number of surfaces. For space curves, which is the most common case, our algorithm returns 3 surfaces whose polynomials are of near-optimal degree; moreover, computation reduces to a Sylvester resultant. We illustrate our algorithm through a series of examples and compare our Maple code with other methods implemented in Maple. Our prototype is not faster but yields fewer equations and is more robust than Maple's implicitize. Although not optimized, it is comparable with Gröbner bases and matrix representations derived from syzygies, for degrees up to 6.

5.3. Saturation of Jacobian ideals: Some applications to nearly free curves, line arrangements and rational cuspidal plane curves

Participant: Alexandru Dimca.

In [6] we describe the minimal resolution of the ideal I_f, the saturation of the Jacobian ideal of a nearly free plane curve $(C : f) = 0$. In particular, it follows that this ideal I_f can be generated by at most 4 polynomials. Some applications to rational cuspidal plane curves are given, and a natural related question is raised.

This is a joint work with Gabriel Sticlaru (Ovidius University of Constanta).

5.4. Matrix formulae for Resultants and Discriminants of Bivariate Tensor-product Polynomials

Participants: Laurent Busé, Angelos Mantzaflaris.

The construction of optimal resultant formulae for polynomial systems is one of the main areas of research in computational algebraic geometry. However, most of the constructions are restricted to formulae for unmixed polynomial systems, that is, systems of polynomials which all have the same support. Such a condition is restrictive, since mixed systems of equations arise frequently in many problems. Nevertheless, resultant formulae for mixed polynomial systems is a very challenging problem. In [5], we introduce a square, Koszul-type, matrix, the determinant of which is the resultant of an arbitrary (mixed) bivariate tensor-product polynomial system. The formula generalizes the classical Sylvester matrix of two univariate polynomials, since it expresses a map of degree one, that is, the elements of the corresponding matrix are up to sign the coefficients of the input polynomials. Interestingly, the matrix expresses a primal-dual multiplication map, that is, the tensor product of a univariate multiplication map with a map expressing derivation in a dual space. In addition we prove an impossibility result which states that for tensor-product systems with more than two (affine) variables there are no universal degree-one formulae, unless the system is unmixed. Last but not least, we present applications of the new construction in the efficient computation of discriminants and mixed discriminants.

This is joint work with Elias Tsigaridas (Ouragan, Inria).

5.5. Implicitizing rational curves by the method of moving quadrics

Participants: Laurent Busé, Clément Laroche, Fatmanur Yildirim.

In [4], a new technique for finding implicit matrix-based representations of rational curves in arbitrary dimension is introduced. It relies on the use of moving quadrics following curve parameterizations, providing a high-order extension of the implicit matrix representations built from their linear counterparts, the moving planes. The matrices we obtain offer new, more compact, implicit representations of rational curves. Their entries are filled by linear and quadratic forms in the space variables and their ranks drop exactly on the curve. Typically, for a general rational curve of degree d we obtain a matrix whose size is half of the size of the corresponding matrix obtained with the moving planes method. We illustrate the advantages of these new matrices with some examples, including the computation of the singularities of a rational curve.

5.6. Separation bounds for polynomial systems

Participants: Ioannis Emiris, Bernard Mourrain.

In [9] we rely on aggregate separation bounds for univariate polynomials to introduce novel worst-case separation bounds for the isolated roots of zero-dimensional, positive-dimensional, and overdetermined polynomial systems. We exploit the structure of the given system, as well as bounds on the height of the sparse (or toric) resultant, by means of mixed volume, thus establishing adaptive bounds. Our bounds improve upon Canny's Gap theorem [9]. Moreover, they exploit sparseness and they apply without any assumptions on the input polynomial system. To evaluate the quality of the bounds, we present polynomial systems whose root separation is asymptotically not far from our bounds. We apply our bounds to three problems. First, we use them to estimate the bit-size of the eigenvalues and eigenvectors of an integer matrix; thus we provide a new proof that the problem has polynomial bit complexity. Second, we bound the value of a positive polynomial over the simplex: we improve by at least one order of magnitude upon all existing bounds. Finally, we asymptotically bound the number of steps of any purely subdivision-based algorithm that isolates all real roots of a polynomial system.

This is a joint work with E. Tsigaridas (Ouragan).

5.7. Sparse polynomial interpolation: sparse recovery, super resolution, or Prony?

Participant: Bernard Mourrain.

In [12], we show that the sparse polynomial interpolation problem reduces to a discrete super-resolution problem on the n-dimensional torus. Therefore the semidefinite programming approach initiated by Candès & Fernandez-Granda in the univariate case can be applied. We extend their result to the multivariate case, i.e., we show that exact recovery is guaranteed provided that a geometric spacing condition on the supports holds and the number of evaluations are sufficiently many (but not many). It also turns out that the sparse recovery LP-formulation of $\ell 1$-norm minimization is also guaranteed to provide exact recovery *provided that* the evaluations are made in a certain manner and even though the Restricted Isometry Property for exact recovery is not satisfied. (A naive sparse recovery LP-approach does not offer such a guarantee.) Finally we also describe the algebraic Prony method for sparse interpolation, which also recovers the exact decomposition but from less point evaluations and with no geometric spacing condition. We provide two sets of numerical experiments, one in which the super-resolution technique and Prony's method seem to cope equally well with noise, and another in which the super-resolution technique seems to cope with noise better than Prony's method, at the cost of an extra computational burden (i.e. a semidefinite optimization).

This is a joint work with Cédric Josz and Jean-Bernard Lasserre (Équipe Méthodes et Algorithmes en Commande, LAAS).

5.8. Computing minimal Gorenstein covers

Participant: Bernard Mourrain.

In [7], we analyze and present an effective solution to the minimal Gorenstein cover problem: given a local Artin k–algebra $A = k[[x_1, ..., x_n]]/I$, compute an Artin Gorenstein k–algebra $G = k[[x_1, ..., x_n]]/I$ such that $\ell(G) - \ell(A)$ is minimal. We approach the problem by using Macaulay's inverse systems and a modification of the integration method for inverse systems to compute Gorenstein covers. We propose new characterizations of the minimal Gorenstein cover and present a new algorithm for the effective computation of the variety of all minimal Gorenstein covers of A for low Gorenstein colength. Experimentation illustrates the practical behavior of the method.

This is a joint work with Juan Elias and Roser Homs (Dep. de Matematiques i Informatica, Universitat de Barcelona).

5.9. Symmetry Preserving Interpolation

Participants: Erick David Rodriguez Bazan, Evelyne Hubert.

In [22], we address multivariate interpolation in the presence of symmetry. Interpolation is a prime tool in algebraic computation while symmetry is a qualitative feature that can be more relevant to a mathematical model than the numerical accuracy of the parameters. The article shows how to exactly preserve symmetry in multivariate interpolation while exploiting it to alleviate the computational cost. We revisit minimal degree and least interpolation with symmetry adapted bases, rather than monomial bases.This allows to construct bases of invariant interpolation spaces in blocks, capturing the inherent redundancy in the computations.We show that the so constructed symmetry adapted interpolation bases alleviate the computational cost of any interpolation problem and automatically preserve any equivariance of their interpolation problem might have.

5.10. Skew-Symmetric Tensor Decomposition

Participant: Bernard Mourrain.

In [2], we introduce the "skew apolarity lemma" and we use it to give algorithms for the skew-symmetric rank and the decomposition of tensors in $\wedge^d V_{\mathbb{C}}$ with $d \leq 3$ and $\dim V_{\mathbb{C}} \leq 8$. New algorithms to compute the rank and a minimal decomposition of a tri-tensor are also presented.

This is a joint work with Enrique Arrondo (UCM - Universidad Complutense de Madrid, Spain), Alessandra Bernardi (Department of Mathematics, University of Trento, Italy) Pedro Macias Marques (Departamento de Matemática da Universidade de Évora, Spain).

5.11. On the maximal number of real embeddings of minimally rigid graphs in $\mathbb{R}^2$, $\mathbb{R}^3$ and $\mathbb{S}^2$

Participants: Ioannis Emiris, Evangelos Bartzos.

In [3], we study the Rigidity theory studies the properties of graphs that can have rigid embeddings in the d-dimensional Euclidean space, or on a sphere and other manifolds which in addition satisfy certain edge length constraints. One of the major open problems in this field is to determine lower and upper bounds on the number of realizations with respect to a given number of vertices. This problem is closely related to the classification of rigid graphs according to their maximal number of real embeddings. In this paper, we are interested in finding edge lengths that can maximize the number of real embeddings of minimally rigid graphs in the plane, space, and on the sphere. We use algebraic formulations to provide upper bounds. To find values of the parameters that lead to graphs with a large number of real realizations, possibly attaining the (algebraic) upper bounds, we use some standard heuristics and we also develop a new method inspired by coupler curves. We apply this new method to obtain embeddings in $\mathbb{R}^3$. One of its main novelties is that it allows us to sample efficiently from a larger number of parameters by selecting only a subset of them at each iteration. Our results include a full classification of the 7-vertex graphs according to their maximal numbers of real embeddings in the cases of the embeddings in $\mathbb{R}^2$ and $\mathbb{R}^3$, while in the case of $\mathbb{S}^2$ we achieve this classification for all 6-vertex graphs. Additionally, by increasing the number of embeddings of selected graphs, we improve the previously known asymptotic lower bound on the maximum number of realizations.

This is a joint work with E. Tsigaridas (Ouragan), and J. Legersky (JK University, Linz, Austria).

5.12. Voronoï diagram of orthogonal polyhedra in two and three dimensions

Participants: Ioannis Emiris, Christina Katsamaki.

In [20], we study Voronoï diagrams, which are a fundamental geometric data structure for obtaining proximity relations. We consider collections of axis-aligned orthogonal polyhedra in two and three-dimensional space under the max-norm, which is a particularly useful scenario in certain application domains. We construct the exact Voronoï diagram inside an orthogonal polyhedron with holes defined by such polyhedra. Our approach avoids creating full-dimensional elements on the Voronoï diagram and yields a skeletal representation of the input object. We introduce a complete algorithm in 2D and 3D that follows the subdivision paradigm relying on a bounding-volume hierarchy; this is an original approach to the problem. The complexity is adaptive and comparable to that of previous methods. Under a mild assumption it is $O(n/D)$ in 2D or $O(na^2/D^2)$ in 3D, where n is the number of sites, namely edges or facets resp., D is the maximum cell size for the subdivision to stop, and a bounds vertex cardinality per facet. We also provide a numerically stable, open-source implementation in Julia, illustrating the practical nature of our algorithm.

The software was developed during Katsamaki's internship in 2018 at Sophia-Antipolis under the supervision of Bernard Mourrain. The problem has been proposed by our industrial collaborator ANSYS Hellas. The paper is based on Katsamaki's MSc thesis.

5.13. Near-Neighbor Preserving Dimension Reduction for Doubling Subsets of L_1

Participants: Ioannis Emiris, Ioannis Psarros.

In [21], we study randomized dimensionality reduction which has been recognized as one of the fundamental techniques in handling high-dimensional data. Starting with the celebrated Johnson-Lindenstrauss Lemma, such reductions have been studied in depth for the Euclidean (L_2) metric, but much less for the Manhattan (L_1) metric. Our primary motivation is the approximate nearest neighbor problem in L_1. We exploit its reduction to the decision-with-witness version, called approximate near neighbor, which incurs a roughly logarithmic overhead. In 2007, Indyk and Naor, in the context of approximate nearest neighbors, introduced the notion of nearest neighbor-preserving embeddings. These are randomized embeddings between two metric spaces with guaranteed bounded distortion only for the distances between a query point and a point set. Such embeddings are known to exist for both L_2 and L_1 metrics, as well as for doubling subsets of L_2. The case that remained open were doubling subsets of L_1. In this paper, we propose a dimension reduction by means of a near neighbor-preserving embedding for doubling subsets of L_1. Our approach is to represent the pointset with a carefully chosen covering set, then randomly project the latter. We study two types of covering sets: c-approximate r-nets and randomly shifted grids, and we discuss the tradeoff between them in terms of preprocessing time and target dimension. We employ Cauchy variables: certain concentration bounds derived should be of independent interest.

This is joint work with Vassilis Margonis (NKUA), and is based on his MSc thesis.

5.14. On the cross-sectional distribution of portfolio returns

Participants: Ioannis Emiris, Apostolos Chalkis.

The aim of the paper [24] is to study the distribution of portfolio returns across portfolios, and for given asset returns. We focus on the most common type of investment, considering portfolios whose weights are non-negative and sum up to 1. We provide algorithms and formulas from computational geometry and the literature on splines to compute the exact values of the probability density function, and of the cumulative distribution function, at any point. We also provide closed form solutions for the computation of its first four moments, and an algorithm to compute the higher moments. All algorithms and formulas allow also for equal asset returns.

This is a joint work with Ludovic Calès (JRC - European Commission - Joint Research Centre, Ispra).

5.15. Enumerating the morphologies of non-degenerate Darboux cyclides

Participant: Bernard Mourrain.

In [19] we provide an enumeration of all possible morphologies of non-degenerate Darboux cyclides. Based on the fact that every Darboux cyclide in $\mathbb{R}^3$ is the stereographic projection of the intersection surface of a sphere and a quadric in $\mathbb{R}^4$, we transform the enumeration problem of morphologies of Darboux cyclides to the enumeration of the algebraic sequences that characterize the intersection of a sphere and a quadric in $\mathbb{R}^4$.

This is a joint work with Mingyang Zhao, Xiaohong Jia (KLMM - Key Laboratory of Mathematics Mechanization, Beijing, China), Changhe Tu (Shandong University, China), Wenping Wang (Computer Graphics Group, Department of Computer Science, Hong Kong, China).

5.16. Anisotropic convolution surfaces

Participants: Alvaro Fuentes Suarez, Evelyne Hubert.

Convolution surfaces with 1D skeletons have been limited to close-to-circular normal sections. The new formalism and method presented in [10] allows for ellipsoidal normal sections. Anisotropy is prescribed on G^1 skeletal curves, chosen as circular splines, by a rotation angle and the three radii of an ellipsoid at each extremity. This lightweight model creates smooth shapes that previously required tweaking the skeleton or supplementing it with 2D pieces. The scale invariance of our formalism achieves excellent radii control and thus lends itself to approximate a variety of shapes. The construction of a scaffold is extended to skeletons with G^1 branches. It projects onto the convolution surface as a quad mesh with skeleton bound edge-flow.

This is a joint work with Cédric Zanni (MFX Inria NGE).

5.17. A non-iterative method for robustly computing the intersections between a line and a curve or surface

Participant: Laurent Busé.

The need to compute the intersections between a line and a high-order curve or surface arises in a large number of finite element applications. Such intersection problems are easy to formulate but hard to solve robustly. In [18], we introduce a non-iterative method for computing intersections by solving a matrix singular value decomposition (SVD) and an eigenvalue problem. That is, all intersection points and their parametric coordinates are determined in one-shot using only standard linear algebra techniques available in most software libraries. As a result, the introduced technique is far more robust than the widely used Newton-Raphson iteration or its variants. The maximum size of the considered matrices depends on the polynomial degree q of the shape functions and is $2q \times 3q$ for curves and $6q^2 \times 8q^2$ for surfaces. The method has its origin in algebraic geometry and has here been considerably simplified with a view to widely used high-order finite elements. In addition, the method is derived from a purely linear algebra perspective without resorting to algebraic geometry terminology. A complete implementation is available from http://bitbucket.org/nitro-project/.

This is joint work with Xiao Xiao and Fehmi Cirak (Cambridge, UK).

5.18. Cooperative Visual-Inertial Sensor Fusion: the Analytic Solution

Participant: Bernard Mourrain.

In [15], we analyze the visual–inertial sensor fusion problem in the cooperative case of two agents, and proves that this sensor fusion problem is equivalent to a simple polynomial equations system that consists of several linear equations and three polynomial equations of second degree. The analytic solution of this polynomial equations system is easily obtained by using an algebraic method. In other words, this letter provides the analytic solution to the visual–inertial sensor fusion problem in the case of two agents. The power of the analytic solution is twofold. From one side, it allows us to determine the relative state between the agents (i.e., relative position, speed, and orientation) without the need of an initialization. From another side, it provides fundamental insights into all the theoretical aspects of the problem. This letter mainly focuses on the first issue. However, the analytic solution is also exploited to obtain basic structural properties of the problem that characterize the observability of the absolute scale and the relative orientation. Extensive simulations and real experiments show that the solution is successful in terms of precision and robustness.

This is a joint work with Agostino Martinelli and Alexander Oliva (CHROMA, Inria Grenoble).

5.19. Overlapping Multi-Patch Structures in Isogeometric Analysis

Participant: Angelos Mantzaflaris.

In isogeometric analysis (IGA) the domain of interest is usually represented by B-spline or NURBS patches, as they are present in standard CAD models. Complex domains can often be represented as a union of simple overlapping subdomains, parameterized by (tensor-product) spline patches. Numerical simulation on such overlapping multi-patch domains is a serious challenge in IGA. To obtain non-overlapping subdomains one would usually reparameterize the domain or trim some of the patches. Alternatively, one may use methods that can handle overlapping subdomains. In [13] we propose a non-iterative, robust and efficient method defined directly on overlapping multi-patch domains. Consequently, the problem is divided into several sub-problems, which are coupled in an appropriate way. The resulting system can be solved directly in a single step. We compare the proposed method with iterative Schwarz domain decomposition approaches and observe that our method reduces the computational cost significantly, especially when handling subdomains with small overlaps. Summing up, our method significantly simplifies the domain parameterization problem, since we can represent any domain of interest as a union of overlapping patches without the need to introduce trimming curves/surfaces. The performance of the proposed method is demonstrated by several numerical experiments for the Poisson problem and linear elasticity in two and three dimensions.

This is a joint work with S. Kargaran, B. Jüttler, S. Kleiss and T. Takacs. (RICAM - Johann Radon Institute for Computational and Applied Mathematics and Institute of Applied Geometry, Linz, Austria)

5.20. First Order Error Correction for Trimmed Quadrature in Isogeometric Analysis

Participant: Angelos Mantzaflaris.

In [23] we develop a specialized quadrature rule for trimmed domains , where the trimming curve is given implicitly by a real-valued function on the whole domain. We follow an error correction approach: In a first step, we obtain an adaptive subdivision of the domain in such a way that each cell falls in a pre-defined base case. We then extend the classical approach of linear approximation of the trimming curve by adding an error correction term based on a Taylor expansion of the blending between the linearized implicit trimming curve and the original one. This approach leads to an accurate method which improves the convergence of the quadrature error by one order compared to piecewise linear approximation of the trimming curve. It is at the same time efficient, since essentially the computation of one extra one-dimensional integral on each trimmed cell is required. Finally, the method is easy to implement, since it only involves one additional line integral and refrains from any point inversion or optimization operations. The convergence is analyzed theoretically and numerical experiments confirm that the accuracy is improved without compromising the computational complexity.

This is joint work with B. Jüttler and F. Scholz. (Institute of Applied Geometry, Linz, Austria).

5.21. Consistent discretization of higher-order interface models for thin layers and elastic material surfaces, enabled by isogeometric cut-cell methods

Participant: Angelos Mantzaflaris.

Many interface formulations, e.g. based on asymptotic thin interphase models or material surface theories, involve higher-order differential operators and discontinuous solution fields. In [11] we are taking first steps towards a variationally consistent discretization framework that naturally accommodates these two challenges by synergistically combining recent developments in isogeometric analysis and cut-cell finite element methods. Its basis is the mixed variational formulation of the elastic interface problem that provides access to jumps in displacements and stresses for incorporating general interface conditions. Upon discretization with smooth splines, derivatives of arbitrary order can be consistently evaluated, while cut-cell meshes enable discontinuous solutions at potentially complex interfaces. We demonstrate via numerical tests for three specific nontrivial interfaces (two regimes of the Benveniste–Miloh classification of thin layers and the Gurtin–Murdoch material surface model) that our framework is geometrically flexible and provides optimal higher-order accuracy in the bulk and at the interface.

This is joint work with Zhilin Han, Changzheng Cheng, (HFUT - Hefei University of Technology, China), Chien-Ting Wu, S. Stoter, S. Mogilevskaya, and D. Schillinger (Department of Civil, Environmental and Geo-Engineering, University of Minnesota, USA).

5.22. Design of Self-Supporting Surfaces with Isogeometric Analysis

Participant: Angelos Mantzaflaris.

Self-supporting surfaces are widely used in contemporary architecture, but their design remains a challenging problem. This paper aims to provide a heuristic strategy for the design of complex self-supporting surfaces. In our method, presented in [17] non-uniform rational B-spline (NURBS) surfaces are used to describe the smooth geometry of the self-supporting surface. The equilibrium state of the surface is derived with membrane shell theory and Airy stresses within the surfaces are used as tunable variables for the proposed heuristic design strategy. The corresponding self-supporting shapes to the given stress states are calculated by the nonlinear isogeometric analysis (IGA) method. Our validation using analytic catenary surfaces shows that the proposed method finds the correct self-supporting shape with a convergence rate one order higher than the degree of the applied NURBS basis function. Tests on boundary conditions show that the boundary's influence propagates along the main stress directions in the surface. Various self-supporting masonry structures, including models with complex topology, are constructed using the presented method. Compared with existing methods such as thrust network analysis and dynamic relaxation, the proposed method benefits from the advantages of NURBS-based IGA, featuring smooth geometric description, good adaption to complex shapes and increased efficiency of computation.

This is joint work with Yang Xia, Ping Hu (Dalian University of Technology, China), Bert Jüttler (Institute of Applied Geometry, Linz, Austria), Hao Pan (Microsoft Research Asia, China), Wenping Wang (CSE - Department of Computer Science and Engineering, HKUST, Honk Kong, China).

5.23. Low-rank space-time decoupled isogeometric analysis for parabolic problems with varying coefficients

Participant: Angelos Mantzaflaris.

In [14] we present a space-time isogeometric analysis scheme for the discretization of parabolic evolution equations with diffusion coefficients depending on both time and space variables. The problem is considered in a space-time cylinder in $\mathbb{R}^{d+1}$, with $d=2,3$ and is discretized using higher-order and highly-smooth spline spaces. This makes the matrix formation task very challenging from a computational point of view. We overcome this problem by introducing a low-rank decoupling of the operator into space and time components. Numerical experiments demonstrate the efficiency of this approach.

This work was done jointly with F. Scholz and I. Toulopoulos (RICAM - Johann Radon Institute for Computational and Applied Mathematics, Linz, Austria).

6. Bilateral Contracts and Grants with Industry

6.1. Bilateral Contracts with Industry

• **NURBSFIX: Repairing the topology of a NURBS model in view of its approximation.** We have a research contract with the industrial partner GeometryFactory, in collaboration with the project-team Titane (Pierre Alliez). The post-doc of Xiao Xiao is funded by this research contract together with a PEPS from the labex AMIES.

Because of their flexibility and accuracy, NURBS (Non-Uniform Rational Basis Spline) models have become a standard in the modeling community for generating and representing complex shapes. They are made of several surface patches and a collection of curves that are used for trimming. As a direct consequence of software quirks, designer errors, and representation flaws, these NURBS models have inconsistencies that introduce small gaps and overlaps between surface patches. They are mainly located on the singularity graph of a NURBS model, near the trimming curves, especially near singularities such as sharp edges or corners. Building a correct approximation of a NURBS model in the presence of inconsistencies is a challenging problem. Most of the current approaches are based on the repairing of the geometry of the surface patches. This requires an interactive process which is difficult to control and rarely completely successful. In this project, we develop another approach which consists in repairing the topology of the singularity graph within a tolerance volume. This tolerance volume will be considered as a protected region that will not receive any query of geometric computations. Based on that, three types of approximations will be treated: triangular isotropic surface meshing of NURBS models, volume approximation of multi-domains delimited by NURBS surfaces, and NURBS models approximation within a given tolerance volume.

7. Partnerships and Cooperations

7.1. European Initiatives

7.1.1. FP7 & H2020 Projects

7.1.1.1. ARCADES

Program: Marie Skłodowska-Curie ETN

Project acronym: ARCADES

Project title: Algebraic Representations in Computer-Aided Design for complEx Shapes

Duration: January 2016 - December 2019

Coordinator: I.Z. Emiris (NKUA, Athens, Greece, and ATHENA Research Innovation Center)

Scientist-in-charge at Inria: L. Busé

Other partners: U. Barcelona (Spain), Inria Sophia Antipolis (France), J. Kepler University, Linz (Austria), SINTEF Institute, Oslo (Norway), U. Strathclyde, Glascow (UK), Technische U. Wien (Austria), Evolute GmBH, Vienna (Austria).

Webpage: http://arcades-network.eu/

Abstract: ARCADES aims at disrupting the traditional paradigm in Computer-Aided Design (CAD) by exploiting cutting-edge research in mathematics and algorithm design. Geometry is now a critical tool in a large number of key applications; somewhat surprisingly, however, several approaches of the CAD industry are outdated, and 3D geometry processing is becoming increasingly the weak link. This is alarming in sectors where CAD faces new challenges arising from fast point acquisition, big data, and mobile computing, but also in robotics, simulation, animation, fabrication and manufacturing, where CAD strives to address crucial societal and market needs. The challenge taken up by ARCADES is to invert the trend of CAD industry lagging behind mathematical breakthroughs and to build the next generation of CAD software based on strong foundations from algebraic geometry, differential geometry, scientific computing, and algorithm design. Our game-changing methods lead to real-time modelers for architectural geometry and visualisation, to isogeometric and design-through-analysis software for shape optimisation, and marine design and hydrodynamics, and to tools for motion design, robot kinematics, path planning, and control of machining tools.

7.1.1.2. POEMA

Program: Marie Skłodowska-Curie ITN

Project acronym: POEMA

Project title: Polynomial Optimization, Efficiency through Moments and Algebra

Duration: January 2019 - December 2022 (48 months)

Coordinator: B. Mourrain (Aromath, Inria Sophia Antipolis)

Other partners: LAAS - CNRS, Toulouse (France), Sorbonne Université, Paris (France), Centrum Wiskunde & Informatica, Amsterdam (The Netherlands), Stichting Katholieke Universiteit Brabant, Tilburd (The Netherlands), Universität Konstanz (Germany), Università degli Studi di Firenze (Italy), University of Birmingham (United Kingdom), Friedrich Alexander University Erlangen-Nuremberg (Germany), Universitet I Tromsø (Norway), ARTELYS SAS, Paris (France).

Webpage: http://poema-network.eu/

Abstract: Non-linear optimization problems are present in many real-life applications and in scientific areas such as operations research, control engineering, physics, information processing, economy, biology, etc. However, efficient computational procedures, that can provide the guaranteed global optimum, are lacking for them. The project will develop new polynomial optimization methods, combining moment relaxation procedures with computational algebraic tools to address this type of problems. Recent advances in mathematical programming have shown that the polynomial optimization problems can be approximated by sequences of Semi-Definite Programming problems. This approach provides a powerful way to compute global solutions of non-linear optimization problems and to guarantee the quality of computational results. On the other hand, advanced algebraic algorithms to compute all the solutions of polynomial systems, with efficient implementations for exact and approximate solutions, were developed in the past twenty years. The network combines the expertise of active European teams working in these two domains to address important challenges in polynomial optimization and to show the impact of this research on practical applications.

POEMA aims to train scientists at the interplay of algebra, geometry and computer science for polynomial optimization problems and to foster scientific and technological advances, stimulating interdisciplinary and intersectoriality knowledge exchange between algebraists, geometers, computer scientists and industrial actors facing real-life optimization problems.

7.1.1.3. GRAPES

Program: Marie Skłodowska-Curie ETN

Project acronym: GRAPES

Project title: Learning, Processing and Optimising Shapes

Duration: December 2019 - November 2023

Coordinator: I.Z. Emiris (NKUA, Athens, and ATHENA Research Center, Greece)

Scientist-in-charge at Inria: L. Busé

Other partners: U. Barcelona (Spain), Inria Sophia-Antipolis (France), J. Kepler University, Linz (Austria), SINTEF Institute, Oslo (Norway), U. Strathclyde, Glascow (UK), RWTH Aachen (Germany), U. Svizzera Italiana (Switzerland), U. Tor Vergata (Italy), Vilnius U. (Lithuania), GeometryFactory SARL (France).

Webpage: http://grapes-network.eu/

Abstract: GRAPES aims at advancing the state of the art in Mathematics, Computer-Aided Design, and Machine Learning in order to promote game changing approaches for generating, optimising, and learning 3D shapes, along with a multisectoral training for young researchers. Recent advances in the above domains have solved numerous tasks concerning multimedia and 2D data. However, automation of 3D geometry processing and analysis lags severely behind, despite their importance in science, technology and everyday life, and the well-understood underlying mathematical principles. GRAPES spans the spectrum from Computational Mathematics, Numerical Analysis, and Algorithm Design, up to Geometric Modelling, Shape Optimisation, and Deep Learning. This allows the 15 PhD candidates to follow either a theoretical or an applied track and to gain knowledge from both research and innovation through a nexus of intersectoral secondments and Network-wide workshops. Horizontally, our results lead to open-source, prototype implementations, software integrated into commercial libraries as well as open benchmark datasets. These are indispensable for dissemination and training but also to promote innovation and technology transfer. Innovation relies on the active participation of SMEs, either as a beneficiary hosting an ESR or as associate partners hosting secondments. Concrete applications include simulation and fabrication, hydrodynamics and marine design, manufacturing and 3D printing, retrieval and mining, reconstruction and visualisation, urban planning and autonomous driving.

7.2. International Initiatives

7.2.1. Participation in Other International Programs

7.2.1.1. PHC Alliance

- Program: PHC Alliance
- Project title: High-order methods for computational design and data-driven engineering
- Duration: 01/2020–12/2021
- Coordinator: Angelos Mantzaflaris
- Other partners: Swansea University, UK
- Abstract: The aim of this project is to develop a mathematical framework for the integration of geometric modeling and simulation using spline-based finite elements of high degree of smoothness. High-order methods are known to provide a robust and efficient methodology to tackle complex challenges in multi-physics simulations, shape optimization, and the analysis of large-scale datasets arising in data-driven engineering and design. However, the analysis and design of high-order methods is a daunting task requiring a concurrent effort from diverse fields such as applied algebraic geometry, approximation theory and splines, topological data analysis, and computational mathematics. Our strategic vision is to create a research team combining a uniquely broad research expertise in these areas by establishing a link between the team AROMATH at Inria Sophia-Antipolis and Swansea University.

7.2.1.2. NSFC

- Program: NSFC
- Project title: "Research on theory and method of time-varying parameterization for dynamic isogeometric analysis",
- Duration: 2018-2021.
- Collaboration project with Gang Xu, Hangzhou Dianzi University, China.

7.3. International Research Visitors

7.3.1. Visits of International Scientists

Gang Xu, Hangzhou Dianzi University, China, visited AROMATH team (9 - 20 Oct.) to work on Isogeometric Analysis and Geometric Modeling.

Ibrahim Adamou, Univ. Dan Dicko Dankoulodo de Maradi, Niger, visited B. Mourrain (28 Oct. - 21 Dec.) to work on medial axes of curve arcs.

7.3.1.1. Internships

Martin Jalard (L3, Ecole normale supérieure de Rennes) for his *introduction to research* internship explored during 6 weeks (May 13th to June 21st) the application of Norton's lemma to the computation of isotypic decompositions.

7.3.2. Visits to International Teams

7.3.2.1. Research Stays Abroad

Evelyne Hubert was awarded a Simons fellowship within the program *Geometry, compatibility and structure preservation in computational differential equations*, from July to December 2019, at the Isaac Newton Institute in Cambridge (UK).

For the month of April, Evelyne Hubert was a guest professor a the University of the Arctic for *Pure Mathematics in Norway*.

Angelos Mantzaflaris visited in April the Computational Foundry, Swansea University, UK in the frame of the College of Science International Visitor Scheme.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events: Organisation

8.1.1.1. General Chair, Scientific Chair

Laurent Busé organized a CIMPA school at Joao Pessoa, Brazil, November 4-13, on the topic "Syzygies: from theory to applications". Six courses delivered by international experts of this topic were scheduled during this school that hosted about 40 international PhD students and young researchers. For more details, see http://www-sop.inria.fr/members/Laurent.Buse/CimpaSchoolBrazil/.

8.1.1.2. Member of the Organizing Committees

Laurent Busé co-organized with C. D'Andrea and Y. Cid Ruiz a mini-symposium on «Syzygies and Applications to Geometry » at the SIAM Conference on Applied Algebraic Geometry, Bern, Switzerland, July 9-13, 2019.

Angelos Mantzaflaris and Bernard Mourrain co-organized with E. Tsigaridas a mini-symposium on "Symbolic-numeric methods for non-linear equations: Algorithms and applications" at the SIAM Conference on Applied Algebraic Geometry, Bern, Switzerland, July 9-13, 2019.

8.1.2. Scientific Events: Selection

8.1.2.1. Member of the Conference Program Committees

Laurent Busé was a member of the international program committee of the 2019 Symposium on Physical and Solid Modeling (SPM), Vancouver, Canada, June 17-19. He was also a member of the scientific committee fro the conference "Ideals, Varieties, Applications" celebrating the influence of David Cox, Amherst, USA, June 10-14.

Angelos Mantzaflaris served in the PC of the 2019 Solid and Physical Modeling (SPM), https://project.inria.fr/spm2019/.

8.1.2.2. Reviewer

Laurent Busé reviewed for *Symposium on Physical and Solid Modeling conference*, *SIGGRAPH conference*, *ISSAC conference* and *MEGA conference*.

Ioannis Emiris reviewed for the *Symposium of Computational Geometry*, *ICALP: Intern. Conf. Automata, Logic & Programming* and *MEGA: Méthodes Effectives en Géométrie Algébrique*.

Angelos Mantzaflaris reviewed for the *Symposium on Physical and Solid Modeling*.

Bernard Mourrain reviewed for *Symposium on Physical and Solid Modeling conference*, *ISSAC conference* and *MEGA conference*.

8.1.3. Journal

8.1.3.1. Member of the Editorial Boards

Ioannis Emiris is editorial board member of *J. Symbolic Computation (Elsevier)* and *Mathematics for Computer Science (Springer)*.

Evelyne Hubert is on the editorial board of Foundation of Computational Mathematics (since 2017) and the Journal of Symbolic Computation (since 2007).

Bernard Mourrain is associate editor of the Journal of Symbolic Computation (since 2007) and of the SIAM Journal on Applied Algebra and Geometry (since 2016).

8.1.3.2. Reviewer - Reviewing Activities

Laurent Busé reviewed for *Graphical Models journal*, *Advances in Applied Mathematics journal*, *SIAM SIAGA journal*, *International Mathematics Research Notices*, *Journal of Algebra*, *Applicable Algebra in Engineering, Communication and Computing journal*, *Computer-Aided Design journal*, *Computer Aided Geometric Design journal*, *Journal of Computer Science and Technology*, *AMS Mathematics of Computations journal*, *Israel Journal of Mathematics* and *Journal of Symbolic Computation*.

Evelyne Hubert reviewed for Journal für die reine und angewandte Mathematik, Proceedings of the American Mathematical Society, Advances in Applied Mathematics, Foundation of Computational Mathematics, SIAM Journal on Applied Algebra and Geometry, Journal of Symbolic Computation, and Computer Aided Geometric Design.

Bernard Mourrain reviewed for *Annales Henri Lebesgue*, *Collectanea Mathematica journalComputer-Aided Design journal*, *Computer Aided Geometric Design journal*, *Journal of Global Optimization*, *Journal of Symbolic Computation*, and *Mathematics of Computations journal*,

Angelos Mantzaflaris reviewed for Computer Methods in Applied Mechanics and Engineering, Computer Aided Geometric Design, Computers & Mathematics with Applications, and Journal of Symbolic Computation.

8.1.4. Invited Talks

Ahmed Blidia was an invited speaker in the minisymposium *Multivariate spline approximation and algebraic geometry* at SIAM Applied Algebraic Geometry meeting, Bern, Switzerland in June 2019.

Laurent Busé was invited to give two lectures at the "27th National School on Algebra: Graded modules over polynomial rings with applications to free divisors", Bucarest, Romania, May 19-25; he was invited to give a plenary talk at the conference "Ideals, Varieties, Applications", in honor of David Cox, Amherst, USA, June 10-14; he gave an invited course during the school "TIME2019: Curves and Surfaces, a History of Shapes", Levico Terme, Italy, Septembre 2-6.

Ioannis Emiris was an invited speaker at KAUST, Visual computing center, Saudi Arabia in February 2019, and SIAM Applied Algebraic Geometry meeting, Bern, Switzerland in June 2019.

Alvaro Fuentes Suarez gave a seminar talk in the MFX team at Inria NGE in February 2019.

Evelyne Hubert presented a series of lectures at the national conference *Equations Fonctionnelles et Interactions* (Anglet). She was invited to give talks at the A^3 - *Arctic Applied Algebra* conference (Tromsø, Norway, April 2019) and the conference *A celebration of Symmetry and Comptutation* (Canterburry, UK). She delivered seminar talks at the University of the Arctic (Tromsø, Norway) and at the Isaac Newton Institute (Cambridge, UK).

Angelos Mantzaflaris gave an invited talk at the 4th Workshop of the ERC project CHANGE, Centro Congressi dell'Annunziata, Sestri Levante, Italy (November 2019) and at the Schloss Dagstuhl – Leibniz Center for Informatics seminar on Interactive Design and Simulation, Germany (December 2019). He also delivered a mini-symposium presentation at the annual conference on Isogeometric Analysis (IGA 2019, Munich, Germany, September 2019).

Both Angelos Mantzaflaris and Bernard Mourrain were invited at the meeting on ”Isogeometric Splines: Theory and Applications“ of the Banff International Research Station for Mathematical Innovation and Discovery (BIRS, February 2019), at the Oberwolfach Mini-Workshop on Mathematical Foundations of Isogeometric Analysis (July 2019), and at the Algebraic Spline Geometry Meeting in Swansea, UK (August 2019).

Bernard Mourrain was invited to give a talk at the conference A^3 - *Arctic Applied Algebra* (Tromsø, Norway, April 1-4); an invited speaker of the conference MEGA (Madrid, Spain, June), to talk at the minisymposium *The algebra and geometry of tensors* of SIAM Applied Algebraic Geometry meeting, (Bern, Switzerland, June 2019), at the conference *Multivariate Approximation and Interpolation with Applications* (Vienna, Austria, Aug. 26-30), at the Italian Mathematical Union conference (Pavia, Sept. 2-5).

He was also invited to give two courses on splines at the University of Montpellier, (October 23-24, 2019).

Erick Rodriguez Bazan was an invited speaker in the minisymposium *Symmetry in algorithmic questions of real algebraic geometry* at SIAM Applied Algebraic Geometry meeting, Bern, Switzerland in June 2019.

Fatmanur Yildirim was an invited speaker in the minisymposium *Syzygies and applications to geometry* at SIAM Applied Algebraic Geometry meeting, Bern, Switzerland in June 2019.

8.1.5. Leadership within the Scientific Community

Ioannis Emiris is member of the Scientific Board of Hellenic Foundation for Research & Innovation (http://www.elidek.gr), representing Informatics and Mathematics.

Bernard Mourain has been elected vice chair of the SIAM Algebraic Geometry group.

8.1.6. Scientific Expertise

Evelyne Hubert was on the hiring committee for Junior Research Scientists at Inria NGE.

8.1.7. Research Administration

Bernard Mourrain is member of the BCEP (Bureau du Comité des Equipes Projet) of the center Inria- Sophia Antipolis.

Evelyne Hubert was a member of Inria Evaluation committee (until June 2019).

Laurent Busé is a member of the admnistrative and scientific committee of the labex AMIES. He is also member of the CDT at Inria Sophia-Antipolis and the CPRH of the Mathematics Laboratory Jean-Alexandre Dieudonné of the University of Nice.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

- Licence : Ioannis Emiris, Discrete Math, 52 h (L1), NKU Athens
- Licence : Ioannis Emiris, Software development, 26 h (L3), NKU Athens
- Master : Ioannis Emiris, Geometric data science, 52 h (M2), NKU Athens
- Master : Ioannis Emiris, Structural bioinformatics, 39 h (M2), NKU Athens
- Master : Laurent Busé, Geometric Modeling, 18h (M2), engineer school of the University of Nice Sophia-Antipolis (EPU).
- Undergraduate: Angelos Mantzaflaris ”Fondements mathématiques 2 (L1 - TD Partie analyse), University of Côte d’Azur, spring semester 2019.

8.2.2. Supervision

- PhD in progress: Lorenzo Baldi, Structure of moment problems and applications to polynomial optimization. POEMA Marie Skłodowska-Curie ITN, started in October 2019, supervised by Bernard Mourrain.
- PhD in progress: Ahmed Blidia, New geometric models for the design and computation of complex shapes. ARCADES Marie Skłodowska-Curie ITN, started in September 2016, supervised by Bernard Mourrain.
- PhD in progress: Rima Khouja, Tensor decomposition, best approximations, algorithms and applications. Cotutelle Univ. Liban, started in November 2018, cosupervised by Houssam Khalil and Bernard Mourrain.
- PhD: Ioannis Psarros, Proximity problems for high-dimensional data. Greek scholarships foundation. Defended in Jun. 2019, NKUA, supervised by Ioannis Emiris.
- PhD in progress: Evangelos Bartzos, Algebraic elimination and Distance graphs. ARCADES Marie Skłodowska-Curie ITN, started in June 2016, NKUA, supervised by Ioannis Emiris.

- PhD in progress: Clément Laroche, Algebraic representations of geometric objects. ARCADES Marie Skłodowska-Curie ITN, started in Nov. 2016, NKUA, supervised by Ioannis Emiris.
- PhD in progress: Apostolos Chalkis, Sampling in high-dimensional convex regions, Google Summer of Code, started in June 2018, NKUA, supervised by Ioannis Emiris.
- PhD in progress: Emmanouil Christoforou, Geometric approximation algorithms for clustering, Structural Bioinformatics national infrastructure "Inspire", started in Jan. 2018, NKUA, supervised by Ioannis Emiris.
- PhD in progress: Tobias Metzlaff. Multivariate orthogonal polynomials and applications to global optimization. POEMA Marie Skłodowska-Curie ITN, started in December 2019, supervised by Evelyne Hubert.
- PhD in progress: Erick Rodriguez Bazan, Symmetry in Algebraic Computations. Inria. Started in November 2017, supervised by Evelyne Hubert.
- PhD : Alvaro Fuentes Suarez defended September 2019 [1]. Modeling shapes with skeletons: scaffolds & anisotropic convolution. ARCADES Marie Skłodowska-Curie ITN, started October 2016 and supervised by Evelyne Hubert.
- PhD in progress: Thomas Laporte, Towards a 4D model of the respiratory system. Fellowship from ED SFA/UCA. Started on October 2019, co-supervised by Benjamin Mouroy (UCA) and Angelos Mantzaflaris.
- PhD in progress: Riccardo Di Dio, Building a diagnosis tool to detect broncho-constrictions, BoostUrCAreer Marie Skłodowska-Curie COFUND fellowship. Started on November 2019, co-supervised by Benjamin Mouroy (UCA) and Angelos Mantzaflaris.

8.2.3. Juries

Bernard Mourrain was a member of the PhD committee of Matias R. Bender *Algorithms for sparse polynomial systems : Gröbner basis and resultants*, Sorbonne Université, Paris, June 3rd; a reviewer and member of the committee of the HDR of Frédéric Holweck entitled *On the projective geometry of entanglement and contextuality*, University Bourgogne Franche-Comté, Belfort, France, September 11th.

Evelyne Hubert was a reviewer for the Habilitation thesis of Georg Regensbuger, Johannes Kepler University (Austria): *Algebraic and algorithmic Approached to Analysis: Integro-differential equations, positive steady states, and wavelets*

Laurent Busé was a reviewer and member of the committee the PhD thesis of Navid Nemati, *Syzygies: Algebra, Combinatorics and Geometry*, Sorbonne Université, Paris, May 28; he was also a member of the PhD committee of Matias R. Bender, *Algorithms for sparse polynomial systems : Gröbner basis and resultants*, Sorbonne Université, Paris, June 3rd.

8.3. Popularization

8.3.1. Interventions

Ioannis Emiris was an invited speaker at “From Open Access to Science", Athens, May 2019. and “30 years celebration of ATHENA Research Center", Athens, November 2019.

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Project-Team ATHENA

Computational Imaging of the Central Nervous System

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Computational Neuroscience and Medicine

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Creation of the Team: 2010 January 01, updated into Project-Team: 2010 July 01

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1. Team, Visitors, External Collaborators

Research Scientists

Rachid Deriche [Team leader, Inria, Senior Researcher, HDR]
Maureen Clerc [Inria, Senior Researcher, until Nov 2019, HDR]
Samuel Deslauriers-Gauthier [Inria, Starting Research Position]
Théodore Papadopoulo [Inria, Senior Researcher, HDR]
Mauro Zucchelli [Inria, Starting Research Position]

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Patryk Filipiak [Inria, Engineer]
Sofiane Guebba [Univ Côte d'Azur, Engineer, until Nov 2019]
Romain Lacroix [Inria, Engineer, until Jan 2019]

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Administrative Assistant

Claire Senica [Inria, Administrative Assistant]

2. Overall Objectives

2.1. Presentation

The main objective of ATHENA is to develop rigorous mathematical models and computational tools for analyzing and modeling the complex Central Nervous System structure and function. These models and tools will help to better understand the structure and the functioning of the human brain and address pressing and challenging clinical and neuroscience questions. Exploring new directions to solve these challenging problems will push forward the state-of-the-art in Structural and Functional Computational Brain Connectivity Mapping.

The relationship between brain structure and function is fundamental in neuroscience. Developing computational models and techniques that recover the structural and functional connectivities of the brain in vivo is thus of utmost importance: it will definitely improve the understanding of the brain and its mechanisms. On the basis of our expertise and contributions to the field of computational neuroimaging and in order to have an impact on this field, our research focusses mainly on the structural and functional Imaging of the brain with a particular emphasis on signal and image recording from diffusion Magnetic Resonance Imaging (dMRI), Magneto-Encephalography (MEG) and Electro-Encephalography (EEG).

In order to further increase the impact of our research, we also aim to push our contributions towards some applications related to brain diseases with characteristic abnormalities in the micro-structure of brain tissues that are not apparent and cannot be revealed reliably by standard imaging techniques. Diffusion MRI, a non invasive imaging modality based on the measurement of the random thermal movement (diffusion) of water molecules within samples can make visible these co-lateral damages to the fibers of the brain white matter and can also help in the development of new biomarkers related to the progression of certain types of neurodegenerative disease. Diffusion MRI is the imaging modality that we will primarly consider to recover the structural brain connectivity.

Connectivity represents the network infrastructure of the brain. Electric activity corresponds to communications over this network. MEG and EEG (jointly as M/EEG), two non-invasive techniques, reveal part of the cortical electric activity and are instrumental in better understanding the brain functional connectivity and in diagnosing diseases linked to anomalous brain function - that in some cases structural or other functional MR images do not reveal. MEG and EEG are the imaging modalities that we will primarly consider to recover the functional brain connectivity.

In some CNS injuries (medullar injuries, strokes, AMS), the peripheral nervous system may not be able to execute commands that are issued by the brain. Brain Computer Interfaces (BCI) use brain signals such as measured through EEG, and translate in real-time the electrical activity of the brain in commands to control external devices. While BCI is advocated as a means to communicate and help restore mobility or autonomy for very severe cases of disabled patients, it is also a new tool for interactively probing and training the human brain.

These considerations support the need to do research on new models and computational tools to analyse brain signals and imaging data. Our main objective is to push forward the state-of-the-art in Structural and Functional Computational Brain Connectivity Mapping to better understand the structure and function of the brain.

In order to tackle these long term and challenging objectives, our strategy is based on the following road map:

- Develop rigorous mathematical and computational tools for the analysis and interpretation of Diffusion MRI and M/EEG data.
- Improve acquisition and processing techniques and push forward the state-of-the-art in Computational brain imaging.
- Use our expertise to address with collaborators clinical and neuroscience questions.

This is implemented through:

- Publications in international conferences and journals dedicated to promoting advances in computational methods for Diffusion MRI and M/EEG analysis and/or use of Diffusion MRI and M/EEG in clinical and neuroscience applications.
- A dense network of collaborations with national as well as international neuroimaging laboratories through which we have access equipment and data and with whom we will jointly contribute to solve common crucial problems of interest.
- Software packages developed to be used in a first stage by our national and international collaborators and then made available to other partners.

3. Research Program

3.1. Computational diffusion MRI

Diffusion MRI (dMRI) provides a non-invasive way of estimating in-vivo CNS fiber structures using the average random thermal movement (diffusion) of water molecules as a probe. It's a relatively recent field of research with a history of roughly three decades. It was introduced in the mid 80's by Le Bihan et al [63], Merboldt et al [68] and Taylor et al [78]. As of today, it is the unique non-invasive technique capable of describing the neural connectivity in vivo by quantifying the anisotropic diffusion of water molecules in biological tissues.

3.1.1. Diffusion Tensor Imaging & High Angular Resolution Diffusion Imaging

In dMRI, the acquisition and reconstruction of the diffusion signal allows for the reconstruction of the water molecules displacement probability, known as the Ensemble Average Propagator (EAP) [77], [47]. Historically, the first model in dMRI is the 2nd order diffusion tensor (DTI) [45], [44] which assumes the EAP to be Gaussian centered at the origin. DTI (Diffusion Tensor Imaging) has now proved to be extremely useful to study the normal and pathological human brain [64], [55]. It has led to many applications in clinical diagnosis of neurological diseases and disorder, neurosciences applications in assessing connectivity of different brain regions, and more recently, therapeutic applications, primarily in neurosurgical planning. An important and very successful application of diffusion MRI has been brain ischemia, following the discovery that water diffusion drops immediately after the onset of an ischemic event, when brain cells undergo swelling through cytotoxic edema.

The increasing clinical importance of diffusion imaging has driven our interest to develop new processing tools for Diffusion Tensor MRI. Because of the complexity of the data, this imaging modality raises a large amount of mathematical and computational challenges. We have therefore developed original and efficient algorithms relying on Riemannian geometry, differential geometry, partial differential equations and front propagation techniques to correctly and efficiently estimate, regularize, segment and process Diffusion Tensor MRI (DT-MRI) (see [66] and [65]).

In DTI, the Gaussian assumption over-simplifies the diffusion of water molecules. While it is adequate for voxels in which there is only a single fiber orientation (or none), it breaks for voxels in which there are more complex internal structures and limitates the ability of the DTI to describe complex, singular and intricate fiber configurations (U-shape, kissing or crossing fibers). To overcome this limitation, so-called Diffusion Spectrum Imaging (DSI) [81] and High Angular Resolution Diffusion Imaging (HARDI) methods such as Q-ball imaging [79] and other multi-tensors and compartment models [74], [76], [38], [37], [71] were developed to resolve the orientationnality of more complicated fiber bundle configurations.

Q-Ball imaging (QBI) has been proven very successful in resolving multiple intravoxel fiber orientations in MR images, thanks to its ability to reconstruct the Orientation Distribution Function (ODF, the probability of diffusion in a given direction). These tools play a central role in our work related to the development of a robust and linear spherical harmonic estimation of the HARDI signal and to our development of a regularized, fast and robust analytical QBI solution that outperforms the state-of-the-art ODF numerical technique developed by Tuch [79]. Those contributions are fundamental and have already started to impact on the Diffusion MRI, HARDI and Q-Ball Imaging community [54]. They are at the core of our probabilistic and deterministic tractography algorithms devised to best exploit the full distribution of the fiber ODF (see [51], [3] and [52], [4]).

3.1.2. Beyond DTI with high order tensors

High Order Tensors (HOT) models to estimate the diffusion function while overcoming the shortcomings of the 2nd order tensor model have also been proposed such as the Generalized Diffusion Tensor Imaging (G-DTI) model developed by Ozarslan et al [85], [86] or 4th order Tensor Model [43]. For more details, we refer the reader to our articles in [57], [74] where we review HOT models and to our articles in [65], co-authored with some of our close collaborators, where we review recent mathematical models and computational methods for the processing of Diffusion Magnetic Resonance Images, including state-of-the-art reconstruction of diffusion models, cerebral white matter connectivity analysis, and segmentation techniques. We also worked on Diffusion Kurtosis Imaging (DKI), of great interest for the company OLEA MEDICAL(https://www.olea-medical.com/en). Indeed, DKI is fastly gaining popularity in the domain for characterizing the diffusion propagator or EAP by its deviation from Gaussianity. Hence it is an important clinical tool for characterizing the white-matter's integrity with biomarkers derived from the 3D 4th order kurtosis tensor (KT) [60].

All these powerful techniques are of utmost importance to acquire a better understanding of the CNS mechanisms and have helped to efficiently tackle and solve a number of important and challenging problems [37], [38]. They have also opened up a landscape of extremely exciting research fields for medicine and neuroscience. Hence, due to the complexity of the CNS data and as the magnetic field strength of scanners increases, as the strength and speed of gradients increase and as new acquisition techniques appear [2], these imaging modalities raise a large amount of mathematical and computational challenges at the core of the research we develop at ATHENA [59], [74].

3.1.3. Improving dMRI acquisitions

One of the most important challenges in diffusion imaging is to improve acquisition schemes and analyse approaches to optimally acquire and accurately represent diffusion profiles in a clinically feasible scanning time. Indeed, a very important and open problem in Diffusion MRI is related to the fact that HARDI scans generally require many times more diffusion gradient than traditional diffusion MRI scan times. This comes at the price of longer scans, which can be problematic for children and people with certain diseases. Patients are usually unable to tolerate long scans and excessive motion of the patient during the acquisition process can force a scan to be aborted or produce useless diffusion MRI images. We have developed novel methods for the acquisition and the processing of diffusion magnetic resonance images, to efficiently provide, with just few measurements, new insights into the structure and anatomy of the brain white matter in vivo.

First, we contributed developing real-time reconstruction algorithm based on the Kalman filter [50]. Then, we started to explore the utility of Compressive Sensing methods to enable faster acquisition of dMRI data by reducing the number of measurements, while maintaining a high quality for the results. Compressed Sensing (CS) is a relatively recent technique which has been proved to accurately reconstruct sparse signals from undersampled measurements acquired below the Shannon-Nyquist rate [69].

We have contributed to the reconstruction of the diffusion signal and its important features as the orientation distribution function and the ensemble average propagator, with a special focus on clinical setting in particular for single and multiple Q-shell experiments. Compressive sensing as well as the parametric reconstruction of the diffusion signal in a continuous basis of functions such as the Spherical Polar Fourier basis, have been proved through our contributions to be very useful for deriving simple and analytical closed formulae for many important dMRI features, which can be estimated via a reduced number of measurements [69], [48], [49].

We have also contributed to design optimal acquisition schemes for single and multiple Q-shell experiments. In particular, the method proposed in [2] helps generate sampling schemes with optimal angular coverage for multi-shell acquisitions. The cost function we proposed is an extension of the electrostatic repulsion to multi-shell and can be used to create acquisition schemes with incremental angular distribution, compatible with prematurely stopped scans. Compared to more commonly used radial sampling, our method improves the angular resolution, as well as fiber crossing discrimination. The optimal sampling schemes, freely available for download[0], have been selected for use in the HCP (Human Connectome Project)[0].

We think that such kind of contributions open new perspectives for dMRI applications including, for example, tractography where the improved characterization of the fiber orientations is likely to greatly and quickly help tracking through regions with and/or without crossing fibers [58].

[0] http://www.emmanuelcaruyer.com/
[0] http://humanconnectome.org/documentation/Q1/imaging-protocols.html

3.1.4. dMRI modelling, tissue microstructures features recovery & applications

The dMRI signal is highly complex, hence, the mathematical tools required for processing it have to be commensurate in their complexity. Overall, these last twenty years have seen an explosion of intensive scientific research which has vastly improved and literally changed the face of dMRI. In terms of dMRI models, two trends are clearly visible today: the parametric approaches which attempt to build models of the tissue to explain the signal based on model-parameters such as CHARMED [39], AxCaliber [40] and NODDI [82] to cite but a few, and the non-parametric approaches, which attempt to describe the signal in useful but generic functional bases such as the Spherical Polar Fourier (SPF) basis [42], [41], the Solid Harmonic (SoH) basis [53], the Simple Harmonic Oscillator based Reconstruction and Estimation (SHORE) basis [83] and more recent Mean Apparent Propagator or MAP-MRI basis [84].

We propose to investigate the feasibility of using our new models and methods to measure extremely important biological tissue microstructure quantities such as axonal radius and density in white matter. These parameters could indeed provide new insight to better understand the brain's architecture and more importantly could also provide new imaging bio-markers to characterize certain neurodegenerative diseases. This challenging scientific problem, when solved, will lead to direct measurements of important microstructural features that will be integrated in our analysis to provide much greater insight into disease mechanisms, recovery and development. These new microstructural parameters will open the road to go far beyond the limitations of the more simple bio-markers derived from DTI that are clinically used to this date – such as MD (Mean Diffusivity) and FA (Fractional Anisotropy) which are known to be extremely sensitive to confounding factors such as partial volume and axonal dispersion, non-specific and not able to capture any subtle effects that might be early indicators of diseases [5].

3.1.5. Towards microstructural based tractography

In order to go far beyond traditional fiber-tracking techniques, we believe that first order information, i.e. fiber orientations, has to be superseeded by second and third order information, such as microstructure details, to improve tractography. However, many of these higher order information methods are relatively new or unexplored and tractography algorithms based on these high order based methods have to be conceived and designed. In this aim, we propose to work with multiple-shells to reconstruct the Ensemble Average Propagator (EAP), which represents the whole 3D diffusion process and use the possibility it offers to deduce valuable insights on the microstructural properties of the white matter. Indeed, from a reconstructed EAP one can compute the angular features of the diffusion in an diffusion Orientation Distribution Function (ODF), providing insight in axon orientation, calculate properties of the entire diffusion in a voxel such as the Mean Squared Diffusivity (MSD) and Return-To-Origin Probability (RTOP), or come forth with bio-markers detailing diffusion along a particular white matter bundle direction such as the Return-to-Axis or Return-to-Plane Probability (RTAP or RTPP). This opens the way to a ground-breaking computational and unified framework for tractography based on EAP and microstructure features [6]. Using additional a priori anatomical and/or functional information, we could also constrain the tractography algorithm to start and terminate the streamlines only at valid processing areas of the brain.

This development of a computational and unified framework for tractography, based on EAP, microstructure and a priori anatomical and/or functional features, will open new perspectives in tractography, paving the way to a new generation of realistic and biologically plausible algorithms able to deal with intricate configurations of white matter fibers and to provide an exquisite and intrinsic brain connectivity quantification.

3.1.6. Going beyond the state-of-the-art dMRI

Overall, these last twenty years have seen an explosion of intensive scientific research which has vastly improved and literally changed the face of dMRI.

However, although great improvements have been made, major improvements are still required primarily to optimally acquire dMRI data, better understand the biophysics of the signal formation, recover high order invariant and intrinsic microstructure features, identify bio-physically important bio-markers and improve tractography.

Therefore, there is still considerable room for improvement when it comes to the concepts and tools able to efficiently acquire, process and analyze the complex structure of dMRI data. Develop ground-breaking dMRI tools and models for brain connectomics is one of the major objective we would like to achieve in order to take dMRI from the benchside to the bedside and lead to a decisive advance and breakthrough in this field.

3.2. MEG and EEG

Electroencephalography (EEG) and Magnetoencephalography (MEG) are two non-invasive techniques for measuring (part of) the electrical activity of the brain. While EEG is an old technique (Hans Berger, a German neuropsychiatrist, measured the first human EEG in 1929), MEG is a rather new one: the first measurements of the magnetic field generated by the electrophysiological activity of the brain were made in 1968 at MIT by D. Cohen. Nowadays, EEG is relatively inexpensive and is routinely used to detect and qualify neural activities (epilepsy detection and characterisation, neural disorder qualification, BCI, ...). MEG is, comparatively, much more expensive as SQUIDS (Superconducting QUantum Interference Device) only operate under very challenging conditions (at liquid helium temperature) and as a specially shielded room must be used to separate the signal of interest from the ambient noise. However, as it reveals a complementary vision to that of EEG and as it is less sensitive to the head structure, it also bears great hopes and an increasing number of MEG machines are being installed throughout the world. Inria and ODYSSÉE/ATHENA have participated in the acquisition of one such machine installed in the hospital "La Timone" in Marseille.

MEG and EEG can be measured simultaneously (M/EEG) and reveal complementary properties of the electrical fields. The two techniques have temporal resolutions of about the millisecond, which is the typical granularity of the measurable electrical phenomena that arise within the brain. This high temporal resolution makes MEG and EEG attractive for the functional study of the brain. The spatial resolution, on the contrary, is somewhat poor as only a few hundred data points can be acquired simultaneously (about 300-400 for MEG and up to 256 for EEG). MEG and EEG are somewhat complementary with fMRI (Functional MRI) and SPECT (Single-Photon Emission Computed Tomography) in that those provide a very good spatial resolution but a rather poor temporal resolution (of the order of a second for fMRI and a minute for SPECT). Also, contrarily to fMRI, which "only" measures an haemodynamic response linked to the metabolic demand, MEG and EEG measure a direct consequence of the electrical activity of the brain: it is acknowledged that the signals measured by MEG and EEG correspond to the variations of the post-synaptic potentials of the pyramidal cells in the cortex. Pyramidal neurons compose approximately 80% of the neurons of the cortex, and it requires at least about 50,000 active such neurons to generate some measurable signal.

While the few hundred temporal curves obtained using M/EEG have a clear clinical interest, they only provide partial information on the localisation of the sources of the activity (as the measurements are made on or outside of the head). Thus the practical use of M/EEG data raises various problems that are at the core of the ATHENA research in this topic:

- First, as acquisition is continuous and is run at a rate up to 1kHz, the amount of data generated by each experiment is huge. Data selection and reduction (finding relevant time blocks or frequency bands) and pre-processing (removing artifacts, enhancing the signal to noise ratio, ...) are largely done manually at present. Making a better and more systematic use of the measurements is an important step to optimally exploit the M/EEG data [1].
- With a proper model of the head and of the sources of brain electromagnetic activity, it is possible to simulate the electrical propagation and reconstruct sources that can explain the measured signal. Proposing better models [62], [7] and means to calibrate them [80] so as to have better reconstructions are other important aims of our work.
- Finally, we wish to exploit the temporal resolution of M/EEG and to apply the various methods we have developed to better understand some aspects of the brain functioning, and/or to extract more subtle information out of the measurements. This is of interest not only as a cognitive goal, but it also serves the purpose of validating our algorithms and can lead to the use of such methods in the field of Brain Computer Interfaces. To be able to conduct such kind of experiments, an EEG lab has been set up at ATHENA.

3.3. Combined M/EEG and dMRI

dMRI provides a global and systematic view of the long-range structural connectivity within the whole brain. In particular, it allows the recovery of the fiber structure of the white matter which can be considered as the wiring connections between distant cortical areas. These white matter based tractograms are analyzed e.g. to explore the differences in structural connectivity between pathological and normal populations. Moreover, as a by-product, the tractograms can be processed to reveal the nodes of the brain networks, i.e. by segregating together gray matter that share similar connections to the rest of the white matter. But dMRI does not provide information on:

- the cortico-cortical pathways (not passing through white matter) and to some extent, on the short-range connections in the white matter,
- the actual use of connections over time during a given brain activity.

On the opposite, M/EEG measures brain activation over time and provides, after source reconstruction (solving the so-called inverse problem of source reconstruction), time courses of the activity of the cortical areas. Unfortunately, deep brain structures have very little contribution to M/EEG measurements and are thus difficult to analyze. Consequently, M/EEG reveals information about the nodes of the network, but in a more blurry (because of the inverse problem) and fragmented view than dMRI (since it can only reveal brain areas measurable in M/EEG whose activity varies during the experimental protocol). Given its very high temporal resolution, the signal of reconstructed sources can be processed to reveal the functional connectivity between the nodes [75].

While dMRI and M/EEG have been the object of considerable research separately, there have been very few studies on combining the information they provide. Some existing studies deal with the localization of abnormal MEG signals, particularly in the case of epilepsy, and on studying the white matter fibers near the detected abnormal source [67], [70], but to our knowledge there are very few studies merging data coming both from M/EEG and dMRI at the analysis level [72], [56], [46], [73].

Combining the structural and functional information provided by dMRI and M/EEG is a difficult problem as the spatial and temporal resolutions of the two types of measures are extremely different. Still, combining the measurements obtained by these two types of techniques has the great potential of providing a detailed view both in space and time of the functioning brain at a macroscopic level. Consequently, it is a timely and extremely important objective to develop innovative computational tools and models that advance the dMRI and M/EEG state-of-the-art and combine these imaging modalities to build a comprehensive dynamical structural-functional brain connectivity network to be exploited in brain connectivities diseases.

The CoBCoM ERC project aims to develop a joint dynamical structural-functional brain connectivity network built on advanced and integrated dMRI and M/EEG ground-breaking methods. To this end, CoBCoM will provide new generation of computational dMRI and M/EEG models and methods for identifying and characterizing the connectivities on which the joint network is built. Capitalizing on the strengths of dMRI & M/EEG and building on the bio-physical and mathematical foundations of our models, CoBCoM will contribute to create a joint and solid network which will be exploited to identify and characterize white matter abnormalities in some high-impact brain diseases such as Multiple Sclerosis (MS), Epilepsy and mild Traumatic Brain Injury (mTBI).

4. Application Domains

4.1. Applications of diffusion MRI

Clinical domain: Diagnosis of neurological disorder

Various examples of CNS diseases as Alzheimer's and Parkinson's diseases and others like multiple sclerosis, traumatic brain injury and schizophrenia have characteristic abnormalities in the micro-structure of brain tissues that are not apparent and cannot be revealed reliably by standard imaging techniques. Diffusion MRI can make visible these co-lateral damages to the fibers of the CNS white matter that connect different brain regions. This is why in our research, Diffusion MRI is the structural imaging modality that will be considered to recover the CNS connectivity.

4.2. Applications of M/EEG

Clinical domain: Diagnosis of neurological disorders
The dream of all M/EEG researchers is to alleviate the need for invasive recordings (electrocorticograms or intracerebral electrodes), which are often necessary prior to brain surgery, in order to precisely locate both pathological and vital functional areas. We are involved in this quest, particularly through our collaborations with the La Timone hospital in Marseille.
Subtopics include:

- Diagnosis of neurological disorders such as epilepsy, schizophrenia, tinnitus, ...
- Presurgical planning of brain surgery.
- Collaboration with the *Institut de Neurosciences des Systèmes* on these topics http://ins.univ-amu.fr/fr/.

Cognitive research

- Aims at better understanding the brain spatio-temporal organisation.
- Collaboration with the *Laboratory for Neurobiology of Cognition* in order to develop methods that suit their needs for sophisticated data analysis.

Brain Computer Interfaces (BCI) aim to allow direct control of external devices using brain signals such as measured through EEG. In our project, BCI can be seen as an application of EEG processing techniques, but also as an object of fundamental and applied research as they open the way for more dynamical and active brain cognitive protocols.

We develop a research collaboration with the eemagine/ANT-Neuro company. We collaborate with Nice University Hospital on the usage of BCI-based communication for ALS[0] patients.

5. Highlights of the Year

5.1. Highlights of the Year

Maureen Clerc left the group and took up her new position as new Director and Head of the Inria Sophia Antipolis - Méditerranée research centre on 8 November 2019.

5.1.1. Awards

The European Association for Signal Processing (EURASIP) elevated on Sept. 2019 Rachid DERICHE to EURASIP FELLOW, the Association's most prestigious honour in recognition of outstanding achievements in the broad field of Signal Processing and in particular in Computational Brain Imaging.

November 22nd 2019, Université Côte d'Azur officially launched its new Institute of artificial intelligence *3IA Côte d'Azur*. Rachid Deriche and Maureen Clerc are among the 27 awarded 3IA chairs.

[0]Nice University Hospital hosts a regional reference center for patients suffering from Amyotrophic Lateral Sclerosis

6. New Software and Platforms

6.1. Dmipy

Diffusion MRI Multi-Compartment Modeling and Microstructure Recovery Made Easy

KEYWORDS: Diffusion MRI - Multi-Compartment Modeling - Microstructure Recovery

FUNCTIONAL DESCRIPTION: Non-invasive estimation of brain microstructure features using diffusion MRI (dMRI) – known as Microstructure Imaging – has become an increasingly diverse and complicated field over the last decades. Multi-compartment (MC)-models, representing the measured diffusion signal as a linear combination of signal models of distinct tissue types, have been developed in many forms to estimate these features. However, a generalized implementation of MC-modeling as a whole, providing deeper insights in its capabilities, remains missing. To address this fact, we present Diffusion Microstructure Imaging in Python (Dmipy), an open-source toolbox implementing PGSE-based MC-modeling in its most general form. Dmipy allows on-the-fly implementation, signal modeling, and optimization of any user-defined MC-model, for any PGSE acquisition scheme. Dmipy follows a “building block”-based philosophy to Microstructure Imaging, meaning MC-models are modularly constructed to include any number and type of tissue models, allowing simultaneous representation of a tissue’s diffusivity, orientation, volume fractions, axon orientation dispersion, and axon diameter distribution. In particular, Dmipy is geared toward facilitating reproducible, reliable MC-modeling pipelines, often allowing the whole process from model construction to parameter map recovery in fewer than 10 lines of code. To demonstrate Dmipy’s ease of use and potential, we implement a wide range of well-known MC-models, including IVIM, AxCaliber, NODDI(x), Bingham-NODDI, the spherical mean-based SMT and MC-MDI, and spherical convolution-based single- and multi-tissue CSD. By allowing parameter cascading between MC-models, Dmipy also facilitates implementation of advanced approaches like CSD with voxel-varying kernels and single-shell 3-tissue CSD. By providing a well-tested, user-friendly toolbox that simplifies the interaction with the otherwise complicated field of dMRI-based Microstructure Imaging, Dmipy contributes to more reproducible, high-quality research.

- Authors: Rutger Fick, Demian Wassermann and Rachid Deriche
- Contact: Rachid Deriche

6.2. High Performance Diffusion MRI

KEYWORDS: Health - Neuroimaging - Medical imaging

FUNCTIONAL DESCRIPTION: This library has been developed and transferred to the Cie Olea Medical currently in charge of its validation and inclusion in its Olea Sphere platform. We have been closely involved in pushing the frontiers of the diffusion MRI (dMRI) in the recent years, especially in the mathematical modelling and processing of the dMRI signal and have developed state-of-the-art software implementations in the form of a C++ library that can be effectively used to infer the complex microstructure of the cerebral white matter. The algorithms and software transfered to Olea Medical fall into four categories : (i) local tissue modelling, which includes both popular 2nd order models and advanced higher than 2nd order models such as DTI, higher order Cartesian tensors (HOTs), ODF, FOD, EAP, maxima extraction, regularization and segmentation, (ii) generation of scalar indices (or biomarkers), which include DTI biomarkers, Diffusion Kurtosis Imaging (DKI) and invariants of 4th order tensors, (iii) global structure estimation, which includes deterministic and probabilistic tractography, and (iv) data visualisation for scalar indices, local models and global structures.

- Participants: Aurobrata Ghosh, Rachid Deriche and Théodore Papadopoulo
- Partner: Olea Medical
- Contact: Rachid Deriche

6.3. OpenMEEG

KEYWORDS: Health - Neuroimaging - Medical imaging

SCIENTIFIC DESCRIPTION: OpenMEEG provides a symmetric boundary element method (BEM) implementation for solving the forward problem of electromagnetic propagation over heterogeneous media made of several domains of homogeneous and isotropic conductivities. OpenMEEG works for the quasistatic regime (frequencies < 100Hz and medium diameter < 1m).

FUNCTIONAL DESCRIPTION: OpenMEEG provides state-of-the art tools for modelling bio-electromagnetic propagation in the quasi-static regime. It is based on the symmetric BEM for the EEG/MEG forward problem, with a distributed source model. OpenMEEG has also been used to model the forward problem of ECoG, for modelling nerves or the cochlea. OpenMEEG is a free, open software written in C++ with python bindings. OpenMEEG is used through a command line interface, but is also interfaced in graphical interfaces such as BrainStorm, FieldTrip or SPM.

RELEASE FUNCTIONAL DESCRIPTION: OpenMEEG has had a large update including notably the parallelisation of some operators and bug corrections. The new version allows in addition the use of non-nested domains.

NEWS OF THE YEAR: OpenMEEG has had a large update including notably the parallelisation of some operators and bug corrections. The new version allows in addition the use of non-nested domains. These improvements have been ditributed with the two new releases (2.4.0 and 2.4.1) made in 2018.

- Participants: Alexandre Gramfort, Emmanuel Olivi, Geoffray Adde, Jan Kybic, Kai Dang, Maureen Clerc, Perrine Landreau, Renaud Keriven and Théodore Papadopoulo
- Contact: Théodore Papadopoulo
- Publications: inria-00467061v2 - inria-00584205v1 - hal-01278377v1
- URL: http://openmeeg.github.io/

6.4. OpenVIBE

KEYWORDS: Neurosciences - Interaction - Virtual reality - Health - Real time - Neurofeedback - Brain-Computer Interface - EEG - 3D interaction

FUNCTIONAL DESCRIPTION: OpenViBE is a free and open-source software platform devoted to the design, test and use of Brain-Computer Interfaces (BCI). The platform consists of a set of software modules that can be integrated easily and efficiently to design BCI applications. The key features of OpenViBE software are its modularity, its high-performance, its portability, its multiple-users facilities and its connection with high-end/VR displays. The designer of the platform enables to build complete scenarios based on existing software modules using a dedicated graphical language and a simple Graphical User Interface (GUI). This software is available on the Inria Forge under the terms of the AGPL licence, and it was officially released in June 2009. Since then, the OpenViBE software has already been downloaded more than 60000 times, and it is used by numerous laboratories, projects, or individuals worldwide. More information, downloads, tutorials, videos, documentations are available on the OpenViBE website.

- Participants: Cedric Riou, Thierry Gaugry, Anatole Lécuyer, Fabien Lotte, Jussi Tapio Lindgren, Laurent Bougrain, Maureen Clerc and Théodore Papadopoulo
- Partners: INSERM - GIPSA-Lab
- Contact: Anatole Lécuyer
- URL: http://openvibe.inria.fr

6.5. BCI-VIZAPP

BCI visual applications

KEYWORDS: Health - Brain-Computer Interface - GUI (Graphical User Interface)

SCIENTIFIC DESCRIPTION: Bci-Vizapp is a library that allows (in interaction with OpenViBE) to build BCI (Brain Computer Interfaces) applications based on the P300 speller principle. Bci-Vizapp provides a library that allows you to create the BCI's stimulation part as part of the Qt toolkit. Being able to use a standard toolkit to make BCI applications is a strong Bci-Vizapp originality. Indeed, in general the use of such toolkits is prohibited by the need for a very precise control of the display timings, which generally eliminates high-level graphic toolkits such as Qt.

FUNCTIONAL DESCRIPTION: BCI-VIZAPP includes a virtual keyboard for typing text, a photodiode monitoring application for checking timing issues. It communicates with the OpenViBE acquisition server for signal acquisition and with the OpenViBE designer for signal processing. The configuration is performed through a wizard.

This software is a new version following the CoAdapt P300 stimulator software.

NEWS OF THE YEAR: Bci-Vizapp is undergoing a profound transmutation with the help of CRISAM's SED in ADT BciBrowser (part of the AMDT). This change aims at integrating the functionality of Bci-Vizapp in third-party applications such as a web browsers.

- Participants: Nathanaël Foy, Romain Lacroix, Maureen Clerc and Théodore Papadopoulo
- Contact: Théodore Papadopoulo

7. New Results

7.1. Computational Diffusion MRI

7.1.1. Coarse-Grained Spatiotemporal Acquisition Design for Diffusion MRI

Participants: Patryk Filipiak, Rutger Fick [TheraPanacea, Paris], Alexandra Petiet [ICM, CENIR, Paris], Mathieu Santin [ICM, CENIR, Paris], Anne-Charlotte Philippe [ICM, CENIR, Paris], Stéphane Lehericy [ICM, CENIR, Paris], Demian Wassermann [Inria Parietal], Rachid Deriche.

Acquisition protocols that allow to capture time-dependent changes in diffusion signal require long imaging time. We address this issue through an optimized subsampling scheme that maximizes accuracy of the spatiotemporal diffusion signal representation, qτ-dMRI, for given time constraints. Our proposed coarse-grained variant of the problem reduces the space of feasible acquisition parameters compared to the fine-grained approach causing no significant deterioration of a reconstruction accuracy in most of the studied cases.

This work has been published in [25].

7.1.2. A Computational Framework For Generating Rotation Invariant Features And Its Application In Diffusion MRI

Participants: Mauro Zucchelli, Samuel Deslauriers-Gauthier, Rachid Deriche.

In this work, we present a novel computational framework for analytically generating a complete set of algebraically independent Rotation Invariant Features (RIF) given the Laplace-series expansion of a spherical function. Our computational framework provides a closed-form solution for these new invariants, which are the natural expansion of the well known spherical mean, power-spectrum and bispectrum invariants. We highlight the maximal number of algebraically independent invariants which can be obtained from a truncated Spherical Harmonic (SH) representation of a spherical function and show that most of these new invariants can be linked to statistical and geometrical measures of spherical functions, such as the mean, the variance and the volume of the spherical signal. Moreover, we demonstrate their application to dMRI signal modeling including the Apparent Diffusion Coefficient (ADC), the diffusion signal and the fiber Orientation Distribution Function (fODF). In addition, using both synthetic and real data, we test the ability of our invariants to estimate brain tissue microstructure in healthy subjects and show that our framework provides more flexibility and open up new opportunities for innovative development in the domain of microstructure recovery from diffusion MRI.

This work has been published in [20].

7.1.3. A Novel Characterization of Traumatic Brain Injury in White Matter with Diffusion MRI Spherical-Harmonics Rotation Invariants

Participants: Mauro Zucchelli, Samuel Deslauriers-Gauthier, Drew Parker [Penn Applied Connectomics and Imaging Group, Philadelphia], Junghoon John Kim [Department of Molecular, Cellular & Biomedical Sciences, New York], Ragini Verma [Penn Applied Connectomics and Imaging Group, Philadelphia], Rachid Deriche.

The current DTI-based markers of traumatic brain injury are able to capture affected WM in the brain, but missthe areas of crossing fibers and complex WM due to the simplicity of the model. In this work, we use a novelset of spherical-harmonics rotation invariant indices, recently proposed in the literature. We demonstrate thatthese 12 invariants capture all the information provided by DTI. But in addition, they capture differences incomplex WM, beyond DTI measures. This combined with the clinical feasibility of the method, paves the wayfor them to be used as better markers of brain injury.

This work has been published in [31].

7.1.4. The Dmipy Toolbox: Diffusion MRI Multi-Compartment Modeling and Microstructure Recovery Made Easy

Participants: Rutger Fick [TheraPanacea, Paris], Demian Wassermann [Inria Parietal], Rachid Deriche.

Non-invasive estimation of brain microstructure features using diffusion MRI (dMRI)—known as Microstructure Imaging—has become an increasingly diverse and complicated field over the last decades. Multi-compartment (MC)-models, representing the measured diffusion signal as a linear combination of signal models of distinct tissue types, have been developed in many forms to estimate these features. However, a generalized implementation of MC-modeling as a whole, providing deeper insights in its capabilities, remains missing. To address this fact, we present Diffusion Microstructure Imaging in Python (Dmipy), an open-source toolbox implementing PGSE-based MC-modeling in its most general form. Dmipy allows on-the-fly implementation, signal modeling, and optimization of any user-defined MC-model, for any PGSE acquisition scheme. Dmipy follows a “building block”-based philosophy to Microstructure Imaging, meaning MC-models are modularly constructed to include any number and type of tissue models, allowing simultaneous representation of a tissue’s diffusivity, orientation, volume fractions, axon orientation dispersion, and axon diameter distribution. In particular, Dmipy is geared toward facilitating reproducible, reliable MC-modeling pipelines, often allowing the whole process from model construction to parameter map recovery in fewer than 10 lines of code. To demonstrate Dmipy’s ease of use and potential, we implement a wide range of well-known MC-models, including IVIM, AxCaliber, NODDI(x), Bingham-NODDI, the spherical mean-based SMT and MC-MDI, and spherical convolution-based single- and multi-tissue CSD. By allowing parameter cascading between MC-models, Dmipy also facilitates implementation of advanced approaches like CSD with voxel-varying kernels and single-shell 3-tissue CSD. By providing a well-tested, user-friendly toolbox that simplifies the interaction with the otherwise complicated field of dMRI-based Microstructure Imaging, Dmipy contributes to more reproducible, high-quality research.

This work has been published in [12].

7.1.5. Effects of tractography filtering on the topology and interpretability of connectomes.

Participants: Matteo Frigo, Samuel Deslauriers-Gauthier, Drew Parker [Penn Applied Connectomics and Imaging Group, Philadelphia], Abdol Aziz Ould Ismail [Penn Applied Connectomics and Imaging Group, Philadelphia], Junghoon John Kim [Department of Molecular, Cellular & Biomedical Sciences, New York], Ragini Verma [Penn Applied Connectomics and Imaging Group, Philadelphia], Rachid Deriche.

The analysis of connectomes and their associated network metrics forms an important part of clinical studies. These connectomes are based on tractography algorithms to estimate the structural connectivity between brain regions. However, tractography algorithms, are prone to false positive connections and this affects the quality of the connectomes. Several tractography filtering techniques (TFTs) have been proposed to alleviate this issue in studies, but their effect on connectomic analyses of pathology has not been investigated. The aim of this work is to investigate how TFTs affect network metrics and their interpretation in the context of clinical studies.

This work has been published in [29]

7.1.6. Spherical convolutional neural network for fiber orientation distribution function and micro-structure parameter estimation from dMRI

Participants: Sara Sedlar, Samuel Deslauriers-Gauthier, Théodore Papadopoulo, Rachid Deriche.

Convolutional neural networks (CNNs) are proven to be a powerful tool for many computer vision problems where the data is acquired on a regular grid in Euclidean space. As the dMRI signals used in our experiments are acquired on spheres, we have investigated spherical CNN model (S2-CNN). In regular CNNs, during convolution, kernels are translated over the input feature maps with equidistant steps. In S2-CNN, both kernels and feature maps are represented in the 3D rotation group - SO(3) manifold. A rotation in SO(3) is analogous to a translation in Euclidean space. However, there is no regular equidistant grid in SO(3). As a consequence, the convolution is performed in the rotational harmonics (Fourier) domain. In this work, we investigate how the S2-CNN can be adapted to properties of dMRI data, such as antipodal symmetry, the presence of Rician noise, multiple sampling shells, etc.

This work currently in progress.

7.1.7. Adaptive phase correction of diffusion-weighted images

Participants: Marco Pizzolato [Signal Processing Lab (LTS5), EPFL, Lausanne], Guillaume Gilbertb [MR Clinical Science, Philips Healthcare Canada, Markham, ON], Jean-Philippe Thiran [Signal Processing Lab (LTS5), EPFL, Lausanne], Maxime Descoteaux [Université de Sherbrooke, Sherbrooke], Rachid Deriche.

Phase correction (PC) is a preprocessing technique that exploits the phase of images acquired in Magnetic Resonance Imaging (MRI) to obtain real-valued images containing tissue contrast with additive Gaussian noise, as opposed to magnitude images which follow a non-Gaussian distribution, e.g. Rician. PC finds its natural application to diffusion-weighted images (DWIs) due to their inherent low signal-to-noise ratio and consequent non-Gaussianity that induces a signal overestimation bias that propagates to the calculated diffusion indices. PC effectiveness depends upon the quality of the phase estimation, which is often performed via a regularization procedure. We show that a suboptimal regularization can produce alterations of the true image contrast in the real-valued phase-corrected images. We propose adaptive phase correction (APC), a method where the phase is estimated by using MRI noise information to perform a complex-valued image regularization that accounts for the local variance of the noise. We show, on synthetic and acquired data, that APC leads to phase-corrected real-valued DWIs that present a reduced number of alterations and a reduced bias. The substantial absence of parameters for which human input is required favors a straightforward integration of APC in MRI processing pipelines.

This work has been published in [17].

7.1.8. Towards validation of diffusion MRI tractography: bridging the resolution gap with 3D Polarized Light Imaging

Participants: Abib Olushola Yessouffou Alimi, Samuel Deslauriers-Gauthier, Rachid Deriche.

Three-dimensional Polarized Light Imaging (3D-PLI) is an optical approach presented as a good candidate for validation of diffusion Magnetic Resonance Imaging (dMRI) results such as orientation estimates (fiber Orientation Distribution Functions) and tractography. We developed an anlytical approach to reconstruct fiber ODFs from 3D-PLI datasets. From these fODFs, here we compute brain fiber tracts via dMRI-based probabilistic tractography algorithm. Reconstructed fODFs at different scales proves the ability to bridge the resolution gap between 3D-PLI and dMRI, demonstrating, therefore, a great promise to validate diffusion MRI tractography thanks to multi-scale fiber tracking based on 3D-PLI.

This work has been published in [21].

7.1.9. Analytical Fiber ODF Reconstruction in 3D Polarized Light Imaging: Performance Assessment

Participants: Abib Olushola Yessouffou Alimi, Samuel Deslauriers-Gauthier, Felix Matuschke [INM-1 - Institute of Neuroscience and Medicine, Jülich], Daniel Schmitz [INM-1 - Institute of Neuroscience and Medicine, Jülich], Markus Axer [INM-1 - Institute of Neuroscience and Medicine, Jülich], Rachid Deriche.

Three dimensional Polarized Light Imaging (3D-PLI) allows to map the spatial fiber structure of postmortem tissue at a sub-millimeter resolution, thanks to its birefringence property. Different methods have been recently proposed to reconstruct the fiber orientation distribution function (fODF) from high-resolution vector data provided by 3D-PLI. Here, we focus on the analytical fODF computation approach, which uses the spherical harmonics to represent the fODF and analytically computes the spherical harmonics coefficients via the spherical Fourier transform. This work deals with the assessment of the performance of this approach on rich synthetic data which simulates the geometry of the neuronal fibers and on human brain dataset. A computational complexity and robustness to noise analysis demonstrate the interest and great potential of the approach.

This work has been published in [22].

7.2. Unveiling brain activity using M/EEG

7.2.1. Fast Approximation of EEG Forward Problem and Application to Tissue Conductivity Estimation

Participants: Kostiantyn Maksymenko, Maureen Clerc, Théodore Papadopoulo.

Bioelectric source analysis in the human brain from scalp electroencephalography (EEG) signals is sensitive to the conductivity of the different head tissues. Conductivity values are subject dependent, so non-invasive methods for conductivity estimation are necessary to fine tune the EEG models. To do so, the EEG forward problem solution (so-called lead field matrix) must be computed for a large number of conductivity configurations. Computing one lead field requires a matrix inversion which is computationally intensive for realistic head models. Thus, the required time for computing a large number of lead fields can become impractical. In this work, we propose to approximate the lead field matrix for a set of conductivity configurations, using the exact solution only for a small set of basis points in the conductivity space. Our approach accelerates the computing time, while controlling the approximation error. Our method is tested for brain and skull conductivity estimation , with simulated and measured EEG data, corresponding to evoked somato-sensory potentials. This test demonstrates that the used approximation does not introduce any bias and runs significantly faster than if exact lead field were to be computed.

This work has been published in [15].

7.2.2. Data-driven cortical clustering to provide a family of plausible solutions to the M/EEG inverse problem

Participants: Maureen Clerc, Kostiantyn Maksymenko, Théodore Papadopoulo.

The Magneto/Electroencephalography (M/EEG) inverse problem consists in reconstructing cortical activity from M/EEG measurements. It is an ill-posed problem. Hence prior hypotheses are needed to constrain the solution space. In this work, we consider that the brain activity which generates the M/EEG signals is supported by single or multiple connected cortical regions. As opposed to methods based on convex optimization, which are forced to select one possible solution, we propose a cortical clustering based approach, which is able to find several candidate regions. These regions are different in term of their sizes and/or positions but fit the data with similar accuracy. We first show that even under the hypothesis of a single active region, several source configurations can similarly explain the data. We then use a multiple signal classification (MUSIC) approach to recover multiple active regions with our method. We validate our method on simulated and measured MEG data. Our results show that our method provides a family of plausible solutions which both accord with the priors and similarly fit the measurements.

This work has been published in [8].

7.2.3. Convolutional autoencoder for waveform learning

Participants: Sara Sedlar, Maureen Clerc, Rachid Deriche, Théodore Papadopoulo.

Electro- or Magneto-encephalographic (M/EEG) signals measured on the scalp can be modeled as a linear combination of source signals occurring in different cortical regions. Analysis of specific recurrent waveforms from measurements can help in the evaluation of several neurological disorders such as epilepsy, Alzheimer's disease, and narcolepsy. In addition, detection of the neural events evoked by certain stimuli is crucial for brain-computer interfaces. Such M/EEG signals are quite faint and inherently affected by an important noise, generated by irrelevant brain activities, by other organs, by external ambient noise or imperfections of the measuring devices. In addition, there are intra- and inter-subject variabilities, meaning that the relevant waveforms vary in terms of amplitudes, shapes, and time delays. This makes waveform learning on such signals a quite complex task. In order to address these problems, a number of dictionary (here waveforms) learning based approaches has been proposed. The common framework behind those approaches is an alternative estimation of data-driven waveforms and their corresponding activations in terms of amplitudes and positions over time. Motivated by the success of these methods and the advances in deep learning, we propose a method based on a convolutional auto-encoder that aims at improving more traditional approaches. Auto-encoders are unsupervised neural network models that have been successfully used for data compression, feature learning, denoising and clustering. Auto-encoders are composed of an encoder which creates a code also known as bottle-neck and decoder that is supposed to reconstruct input signal given the code. By penalizing reconstruction loss function with certain constraints we can guide the auto-encoder to perform compression, denoising, clustering etc. For the moment, the properties of the model are investigated on single-channel synthetic data imitating three types of neurological activities (spikes, short oscillatory and low frequency saw-tooth waveforms) mixed using a realistic leadfield matrix (source space to sensor space transform).

This work is in current progress.

7.2.4. Automatic detection of epileptic seizures by video-EEG

Participants: Mamoudou Sano, Hugo Cadis [IPMC], Fabrice Duprat [IPMC], Massimo Mantegazza [IPMC], Maureen Clerc, Théodore Papadopoulo.

Epilepsy is a serious condition that affects almost 50 million people worldwide. Despite several generations of antiepileptic treatments, the rate of drug-resistant patients remains around 30% and the discovery of new pharmacological targets is therefore a crucial issue.

In order to find pharmacological targets, several animal models make it possible to study the mechanisms of establishment of epileptic disease, or epileptogenesis, and the consequences of repeated spontaneous attacks which characterize epilepsy. Recording an electroencephalogram (EEG) remains the best way to understand these mechanisms. However, the placement of electrodes on small animals such as mice is difficult or even impossible depending on the age of the animal or other used protocols. The use of video recordings over several days, weeks or months makes it possible to observe the animals with a minimum of disturbances and to assess the severity of the crises on a behavioral scale. In both cases, the visual analysis of hundreds of hours of video and/or EEG recordings is very long and error-prone.

The goal of this joint IPMC, ATHENA work was to improve acquisition techniques and develop software tools to automate both EEG and video analysis. EEG analysis was based on the "Adaptive Waveform Learning" that was developed in the group a few years ago [61]. This is work in progress.

7.3. Combined fMRI, M/EEG and dMRI

7.3.1. White Matter Information Flow Mapping from Diffusion MRI and EEG.

Participants: Samuel Deslauriers-Gauthier, Jean-Marc Lina [ETS - Ecole de Technologie Supérieure, Montréal], Russel Butler [Université de Sherbrooke, Sherbrooke], Kevin Whittingstall [Université de Sherbrooke,

Sherbrooke], Pierre-Michel Bernier [Université de Sherbrooke, Sherbrooke], Maxime Descoteaux [Université de Sherbrooke, Sherbrooke], Rachid Deriche.

The human brain can be described as a network of specialized and spatially distributed regions. The activity of individual regions can be estimated using electroencephalography and the structure of the network can be measured using diffusion magnetic resonance imaging. However, the communication between the different cortical regions occurring through the white matter, coined information flow, cannot be observed by either modalities independently. Here, we present a new method to infer information flow in the white matter of the brain from joint diffusion MRI and EEG measurements. This is made possible by the millisecond resolution of EEG which makes the transfer of information from one region to another observable. A subject specific Bayesian network is built which captures the possible interactions between brain regions at different times. This network encodes the connections between brain regions detected using diffusion MRI tractography derived white matter bundles and their associated delays. By injecting the EEG measurements as evidence into this model, we are able to estimate the directed dynamical functional connectivity whose delays are supported by the diffusion MRI derived structural connectivity. We present our results in the form of information flow diagrams that trace transient communication between cortical regions over a functional data window. The performance of our algorithm under different noise levels is assessed using receiver operating characteristic curves on simulated data. In addition, using the well-characterized visual motor network as grounds to test our model, we present the information flow obtained during a reaching task following left or right visual stimuli. These promising results present the transfer of information from the eyes to the primary motor cortex. The information flow obtained using our technique can also be projected back to the anatomy and animated to produce videos of the information path through the white matter, opening a new window into multi-modal dynamic brain connectivity.

This work has been published in [11].

7.3.2. *Structural connectivity to reconstruct brain activation and effective connectivity between brain regions*

Participants: Brahim Belaoucha, Théodore Papadopoulo.

Understanding how brain regions interact to perform a specific task is very challenging. EEG and MEG are two non-invasive imaging modalities that allow the measurement of brain activation with high temporal resolution. Several works in EEG/MEG source reconstruction show that estimating brain activation can be improved by considering spatio-temporal constraints but only few of them use structural information to do so. In this work, we present a source reconstruction algorithm that uses brain structural connectivity, estimated from diffusion MRI (dMRI), to constrain the EEG/MEG source reconstruction. Contrarily to most source reconstruction methods which reconstruct activation for each time instant, the proposed method estimates an initial reconstruction for the first time instants and a multivariate autoregressive model that explains the data in further time instants. This autoregressive model can be thought as an estimation of the effective connectivity between brain regions. We called this algorithm iterative Source and Dynamics reconstruction (iSDR). This paper presents the overall iSDR approach and how the proposed model is optimized to obtain both brain activation and brain region interactions. The accuracy of our method is demonstrated using synthetic data in which it shows a good capability to reconstruct both activation and connectivity. iSDR is also tested with real data (face recognition task). The results are in phase with other works published with the same data and others that used different imaging modalities with the same task showing that the choice of using an autoregressive model gives relevant results.

This work has been submitted to the non-invasive brain imaging special issue of Journal of Neural Engineering.

7.3.3. *Estimation of Axon Conduction Delay, Conduction Speed, and Diameter from Information Flow using Diffusion MRI and MEG.*

Participants: Samuel Deslauriers-Gauthier, Rachid Deriche.

The different lengths and conduction velocities of axons connecting cortical regions of the brain yield information transmission delays which are believed to be fundamental to brain dynamics. While early work on axon conduction velocity was based on ex vivo measurements , more recent work makes use of a combination of diffusion Magnetic Resonance Imaging (MRI) tractography and electroencephalography (EEG) to estimate axon conduction velocity in vivo. An essential intermediary step in this later strategy is to estimate the inter hemispheric transfer time (IHTT) using EEG. The IHTT is estimated by measuring the latency between the peaks or by computing the lag to maximum correlation on contra lateral electrodes. These approaches do not take the subjects anatomy into account and, due to the limited number of electrodes used, only partially leverage the information provided by EEG. In our previous work, we proposed a method, named Connectivity Informed Maximum Entropy on the Mean (CIMEM), to estimate information flow in the white matter of the brain. CIMEM is built around a Bayesian network which represents the cortical regions of the brain and their connections, observed using diffusion MRI tractography. This Bayesian network is used to constrain the EEG inverse problem and estimate which white matter connections are used to transfer information between cortical regions. In our previous work, CIMEM was used to infer the information flow in the white matter by assuming a constant conduction velocity for all connections. In this context, the conduction speed, and thus the delays, were inputs used to help constrain the problem. Here, we instead assume that the connection used to transfer information across the hemispheres is known, due the design of the acquisition paradigm, but that its conduction velocity must be estimated.

This work has been published in [23].

7.3.4. Estimation of Axonal Conduction Speed and the Inter Hemispheric Transfer Time using Connectivity Informed Maximum Entropy on the Mean

Participants: Samuel Deslauriers-Gauthier, Rachid Deriche.

The different lengths and conduction velocities of axons connecting cortical regions of the brain yield information transmission delays which are believed to be fundamental to brain dynamics. A critical step in the estimation of axon conduction speed in vivo is the estimation of the inter hemispheric transfer time (IHTT). The IHTT is estimated using electroencephalography (EEG) by measuring the latency between the peaks of specific electrodes or by computing the lag to maximum correlation on contra lateral electrodes. These approaches do not take the subject's anatomy into account and, due to the limited number of electrodes used, only partially leverage the information provided by EEG. Using the previous published Connectivity Informed Maximum Entropy on the Mean (CIMEM) method, we propose a new approach to estimate the IHTT. In CIMEM, a Bayesian network is built using the structural connectivity information between cortical regions. EEG signals are then used as evidence into this network to compute the posterior probability of a connection being active at a particular time. Here, we propose a new quantity which measures how much of the EEG signals are supported by connections, which is maximized when the correct conduction delays are used. Using simulations, we show that CIMEM provides a more accurate estimation of the IHTT compared to the peak latency and lag to maximum correlation methods.

This work has been published in [24].

7.3.5. A Unified Model for Structure–function Mapping Based on Eigenmodes

Participants: Samuel Deslauriers-Gauthier, Rachid Deriche.

Characterizing the connection between brain structure and brain function is essential for understanding how behaviour emerges from the underlying anatomy. To this end, a common representation of the brain is that of a network, where nodes represent cortical and sub–cortical gray matter volumes and edges represent the strength of structural or functional connectivity. A convenient representation of this network is that of a matrix, where entries represent the strength of the structural connectivity (SC) or functional connectivity (FC) between nodes. A number of studies have shown that the network structure of the white matter shapes functional connectivity, leading to the idea that it should be possible to predict the function given the structure. A strategy is to learn a direct mapping from the SC matrix to the FC matrix. In this work, we show that the mappings currently proposed in the literature can be generalized to a single model and that this model can be used to generate new structure-function mappings. We tested our general model on 40 subjects of the Human Connectome Project and demonstrated that for specific choices of parameters, our model reduces to previously proposed models and yields comparable results. However, by allowing to choose the eigenvalue and eigenvector mapping independently, our models can also produce novel mapping that improve the prediction of FC from SC.

This work is currently under submission to OHBM.

7.3.6. Connectivity-informed spatio-temporal MEG source reconstruction: Simulation results using a MAR model

Participants: Ivana Kojcic, Théodore Papadopoulo, Samuel Deslauriers-Gauthier, Rachid Deriche.

Recovering brain activity from M/EEG measurements is an ill-posed problem and prior constraints need to be introduced in order to obtain unique solution. The majority of the methods use spatial and/or temporal constraints, without taking account of long-range connectivity. In this work, we propose a new connectivity-informed spatio-temporal approach to constrain the inverse problem using supplementary information coming from diffusion MRI. We present results based on simulated brain activity using a Multivariate Autoregressive Model, with realistic subject anatomy obtained from Human Connectome Project dataset.

This work has been published in [35].

7.3.7. Connectivity-informed solution for spatio-temporal M/EEG source reconstruction

Participants: Ivana Kojcic, Théodore Papadopoulo, Samuel Deslauriers-Gauthier, Rachid Deriche.

Recovering brain activity from M/EEG measurements is an ill–posed problem and prior constraints need to be introduced in order to obtain unique solution. The majority of the methods use spatial and/or temporal constraints, without taking account of long–range connectivity. In this work, we propose a new connectivity–informed spatio–temporal approach to constrain the inverse problem using supplementary information coming from difusion MRI. We present results based on simulated brain activity obtained with realistic subject anatomy from Human Connectome Project dataset.

This work has been published in [34].

7.3.8. Deconvolution of fMRI Data using a Paradigm Free Iterative Approach based on Partial Differential Equations

Participants: Isa Costantini, Samuel Deslauriers-Gauthier, Rachid Deriche.

Functional magnetic resonance imaging (fMRI) is a technique which indirectly measures neural activations via the blood oxygenated level dependent (BOLD) signal. So far, few approaches have been proposed to regularize the fMRI data, while recovering the underlying activations at the voxel level. In particular, for task fMRI, voxels time courses are fitted on a given experimental paradigm. To avoid the necessity of a priori information on the pattern, supposing the brain works with blocks of constant activation, Farouj et al. has developed a deconvolution approach which solves the optimizations problem by splitting it into two regularization problems, i.e. spatial and temporal. Starting from this idea, we propose a paradigm-free iterative algorithm based on partial differential equations (PDEs) which minimizes the image variations, while preserving sharp transitions (i.e. brain activations), in the space and the time dimensions at once.

This work has been published in [27].

7.3.9. Novel 4-D Algorithm for Functional MRI Image Regularization using Partial Differential Equations

Participants: Isa Costantini, Samuel Deslauriers-Gauthier, Rachid Deriche.

State-of-the-art techniques for denoising functional MRI (fMRI) images consider the problems of spatial and temporal regularization as decoupled tasks. In this work we propose a partial differential equations (PDEs)-based algorithm that acts directly on the 4-D fMRI image. Our approach is based on the idea that large image variations should be preserved as they occur during brain activation, but small variations should be smoothed to remove noise. Starting from this principle, by means of PDEs we were able to smooth the fMRI image with an anisotropic regularization, thus recovering the location of the brain activations in space and their timing and duration.

This work has been published in [28].

7.3.10. Spatially Varying Monte Carlo Sure for the Regularization of Biomedical Images

Participants: Marco Pizzolato [Signal Processing Lab (LTS5), EPFL, Lausanne], Erick Jorge Canales-Rodríguez [Radiology Department CHUV, Lausanne], Jean-Philippe Thiran [Signal Processing Lab (LTS5), EPFL, Lausanne], Rachid Deriche.

Regularization, filtering, and denoising of biomedical images requires the use of appropriate filters and the adoption of efficient regularization criteria. It has been shown that the Stein's Unbiased Risk Estimate (SURE) can be used as a proxy for the mean squared error (MSE), thus giving an effective criterion for choosing the regularization amount as to that minimizing SURE. Often, due to the complexity of the adopted filters and solvers, this proxy must be calculated with a Monte Carlo method. In practical biomedical applications, however, images are affected by spatially-varying noise distributions, which must be taken into account. We propose a modification to the Monte Carlo method, called svSURE, that accounts for the spatial variability of the noise variance, and show that it correctly estimates the MSE in such cases.

This work has been published in [30].

7.3.11. The visual word form area (VWFA) is part of both language and attention circuitry

Participants: Lang Chen, Demian Wasserman, Daniel Abrams, John Kochalka, Guillermo Gallardo-Diez, Vinod Menon.

While predominant models of visual word form area (VWFA) function argue for its specific role in decoding written language, other accounts propose a more general role of VWFA in complex visual processing. However, a comprehensive examination of structural and functional VWFA circuits and their relationship to behavior has been missing. Here, using high-resolution multimodal imaging data from a large Human Connectome Project cohort ($N = 313$), we demonstrate robust patterns of VWFA connectivity with both canonical language and attentional networks. Brain-behavior relationships revealed a striking pattern of double dissociation: structural connectivity of VWFA with lateral temporal language network predicted language, but not visuo-spatial attention abilities, while VWFA connectivity with dorsal fronto-parietal attention network predicted visuo-spatial attention, but not language abilities. Our findings support a multiplex model of VWFA function characterized by distinct circuits for integrating language and attention, and point to connectivity-constrained cognition as a key principle of human brain organization.

This work has been published in [10].

7.4. Brain Computer Interfaces

7.4.1. Augmenting Motor Imagery Learning for Brain–Computer Interfacing Using Electrical Stimulation as Feedback

Participants: Saugat Bhattacharyya [School of Bio-Science and Engineering, Calcutta], Mitsuhiro Hayashibe [Tohoku University, Sendai], Maureen Clerc.

Brain-computer Interfaces (BCI) and Functional electrical stimulation (FES) contribute significantly to induce cortical learning and to elicit peripheral neuronal activation processes and thus, are highly effective to promote motor recovery. This study aims at understanding the effect of FES as a neural feedback and its influence on the learning process for motor imagery tasks while comparing its performance with a classical visual feedback protocol. The participants were randomly separated into two groups: one group was provided with visual feedback (VIS) while the other received electrical stimulation (FES) as feedback. Both groups performed various motor imagery tasks while feedback was provided in form of a bi-directional bar for VIS group and targeted electrical stimulation on the upper and lower limbs for FES group. The results shown in this paper suggest that the FES based feedback is more intuitive to the participants, hence, the superior results as compared to the visual feedback. The results suggest that the convergence of BCI with FES modality could improve the learning of the patients both in terms of accuracy and speed and provide a practical solution to the BCI learning process in rehabilitation.

This work, obtained in the context of the BCI-LIFT IPL, has been published in [9].

7.4.2. Adaptive parameter setting in a code modulated visual evoked potentials BCI

Participants: Federica Turi, Maureen Clerc.

Code-modulated visual evoked potentials (c-VEPs) BCI are designed for high-speed communication. The setting of stimulus parameters is fundamental for this type of BCI, because stimulus parameters have an influence on the performance of the system. In this work we design a c-VEP BCI for word spelling, in which it is possible to find the optimal stimulus presentation rate per each subject thanks to an adaptive setting parameter phase. This phase takes place at the beginning of each session and allows to define the stimulus parameters that are used during the spelling phase. The different stimuli are modulated by a binary m-sequence circular-shifted by a different time lag and a template matching method is applied for the target detection. We acquired data from 4 subjects in two sessions. The results obtained for the offline spelling show the variability between subjects and therefore the importance of subject-dependent adaptation of c-VEP BCI.

This work has been published in [32].

7.4.3. Participation to the Cybathlon BCI Series

Participants: Karine Leclerc [Centre René Labreuille, Le Cannet], Magali Mambrucchi [Centre René Labreuille, Le Cannet], Amandine Audino, Pierre Giacalone, Federica Turi, Maureen Clerc, Théodore Papadopoulo.

The CYBATHLON is a unique championship in which people with physical disabilities compete against each other to complete everyday tasks using state-of-the-art technical assistance systems. Athena participated in the CYBATHLON BCI Series that took place on September 8th, 2019 as a satellite event of the Graz Brain–Computer Interface Conference. Athena was part of a bigger Inria team which encompassed also the Inria Bordeaux Sud-Ouest Potioc team (participants from Bordeaux are not listed). For both Inria sub-teams, it was a first participation to such a competition : we learned a lot about the practical issues of working with people with physical disabilities and on all the practical issues that can encounter a BCI user out of the lab. The actual competition consisted of driving a car on a track by issuing three types of commands (Left, Right, Lights) using mental imagery. Even though our pilot finished last, she was for each run leading the race till a few seconds before its end. A great satisfaction was to see that the software that we built worked reliably out of the lab (many teams have had troubles in issuing commands and had to redo a race). Yet, this required a lot of last minute work to integrate smoothly in the competition system: we learned a lot in this respect. The poster [36] summarises this effort.

7.4.4. BCI Performance prediction

Participants: Maureen Clerc, Nathalie Gayraud, Laurent Bougrain [NeuroSys Project-Team], Sébastien Rimbert [NeuroSys Project-Team], Stéphanie Fleck [Perseus].

Predicting a subject's ability to use a Brain Computer Interface (BCI) is one of the major issues in the BCI domain. Relevant applications of forecasting BCI performance include the ability to adapt the BCI to the needs and expectations of the user, assessing the efficiency of BCI use in stroke rehabilitation, and finally, homogenizing a research population. A limited number of recent studies have proposed the use of subjective questionnaires, such as the Motor Imagery Questionnaire Revised-Second Edition (MIQ-RS). Our results showed no significant correlation between BCI performance and the MIQ-RS scores. However, we reveal that BCI performance is correlated to habits and frequency of practicing manual activities. This work is an outcome of the BCI-LIFT IPL and was published in [18]. Another joint publication [19] investigated median nerve stimulation as a new approach to detect intraoperative awareness during General Anesthesia.

7.4.5. EEG Classification of Auditory Attention

Participants: Joan Belo, Johann Benerradi, Maureen Clerc, Michel Pascal [Nice Music Conservatory], Daniele Schön [Institut de Neurosciences des Systèmes].

In a Master's thesis [33] in collaboration with Nice Music Conservatory and Institut de Neurosciences des Systèmes, we focused on analyzing auditory attention of human participants who are presented two auditory streams, simultaneously on left and right. By analyzing the EEG signals measured, the problem is to detect to which stream the participant is attending. Auditory Attention is also the topic of the PhD thesis of Joan Belo, funded by a CIFRE with Oticon Medical.

7.4.6. Innovative Brain-Computer Interface based on motor cortex activity to detect accidental awareness during general anesthesia

Participants: Sébastien Rimbert, Philippe Guerci, Nathalie Gayraud, Claude Meistelman, Laurent Bougrain.

Accidental Awareness during General Anesthesia (AAGA) occurs in 1-2% of high-risk practice patients and is responsible for severe psychological trauma, termed post-traumatic stress disorder (PTSD). Currently, monitoring techniques have limited accuracy in predicting or detecting AAGA. Since the first reflex of a patient experiencing AAGA is to move, a passive Brain-Computer Interface (BCI) based on the detection of an intention of movement would be conceivable to alert the anesthetist and prevent this phenomenon. However, the way in which the propofol (an anesthetic drug commonly used for inducing and maintaining general anesthesia) affects the motor brain activity and is reflected by the electroencephalo-graphic (EEG) signal has been poorly investigated and is not clearly understood. The goal of this forward-looking study is to investigate the motor activity behavior with step-wise increase of propofol doses in 4 healthy subjects and provide a proof of concept for such an innovative BCI.

This work has been published in [26].

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ADT

8.1.1.1. ADT BCI-Browser

Participants: Théodore Papadopoulo, Maureen Clerc.

Duration: 1 year

Most often, BCI techniques are demonstrated in simple toy applications made. The only "few" real BCI applications are specific developments and are not used much as they lack of functionality, maintenance, ... The goal of this development contract is to demonstrate a new approach to BCI, in which BCI interactions are integrated in existing applications. Ideally, the original software is not modified and not even recompiled. It is modified by providing either modified GUI libraries or providing extensions as plugins. As a proof of concept, we aim at modifying C++/Qt applications with a focus on web browsing, by redefining some of its basic interactions (mouse clicks, keyboard, ...) using some BCI components. In this manner, it might be possible to drive standard and state-of-the-art application using BCI and at a limited maintenance cost.

This contract is part of the AMDT initiative.

8.1.1.2. ADT OpenMEEG

Participants: Théodore Papadopoulo, Maureen Clerc, Kostiantyn Maksymenko, Alexandre Gramfort [PARIETAL], Joan Massich [PARIETAL].

Duration: *24 months.*

The OpenMEEG ADT aims at improving OpenMEEG along 3 main directions:

1. Offer a user interface for the creation and verification of head models most importantly for a simpler management of non-nested head models.
2. Improve the Python interface (extension and reliability). This will also be useful to develop new research axes (in connection with point 3).
3. Enrich the available operators and refactor the code to offer new possibilities in OpenMEEG and reduce the cost of maintenance.

In addition to the expected gains in code maintenance, these improvements will allow a number of new – more sophisticated – applications as well as open OpenMEEG to a larger audience with a simplified interface for classical use-cases.

This contract is part of the AMDT initiative.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. ERC AdG CoBCoM

Program: H2020-EU.1.1. (ERC-ADG-2015 - ERC Advanced Grant)

Project acronym: COBCOM - **ID:** 694665

Project title: *Computational Brain Connectivity Mapping*

Start date: 2016-09-01, End date: 2021-08-31

P.I. : R. Deriche

Partners: ATHENA project-team

Abstract:

One third of the burden of all the diseases in Europe is due to problems caused by diseases affecting brain. Although exceptional progress has been obtained for exploring it during the past decades, **the brain is still terra-incognita** and calls for specific research efforts to better understand its architecture and functioning.

COBCOM is our response to this great challenge of modern science with the overall goal to **develop a joint Dynamical Structural-Functional Brain Connectivity Network** (DSF-BCN) solidly grounded on advanced and integrated methods for diffusion Magnetic Resonance Imaging (dMRI) and Electro & Magneto-Encephalography (EEG & MEG).

To take up this grand challenge and achieve new frontiers for brain connectivity mapping, we will develop a new generation of computational models and methods for identifying and characterizing the structural and functional connectivities that will be at the heart of the DSF-BCN. Our strategy is to break with the tradition to incrementally and separately contributing to structure or function and develop **a global approach involving strong interactions between structural and functional connectivities.** To solve the limited view of the brain provided just by one imaging modality, our models will be developed under a rigorous computational framework integrating complementary non invasive imaging modalities: dMRI, EEG and MEG.

COBCOM will push far forward the state-of-the-art in these modalities, developing **innovative models and ground-breaking processing tools** to provide in-fine a joint DSF-BCN solidly grounded on a detailed mapping of the brain connectivity, both in space and time.

Capitalizing on the strengths of dMRI, MEG & EEG methodologies and building on the **bio-physical and mathematical foundations** of our new generation of computational models, COBCOM will be applied to high-impact diseases, and its **ground-breaking computational nature and added clinical value** will open new perspectives in neuroimaging.

8.3. International Initiatives

8.3.1. Inria International Partners

8.3.1.1. Declared Inria International Partners

- Sherbrooke University, CA (M. Descoteaux)

- CMRR, University of Minnesota, USA (C. Lenglet)
- Verona University, It (G. Menegaz)
- Department of CISE, the University of Florida, Gainesville, USA (B. C. Vemuri)
- Centre for Medical Image Computing (CMIC), Dept. Computer Science, UCL, UK (D. Alexander)
- SBIA, University of Pennsylvania Medical School, USA (R. Verma).
- EEMagine company on EEG/MEG hardware.

8.3.2. Participation in Other International Programs

- University Houari Boumedienne (USTHB, Algiers) (L. Boumghar) and University of Boumerdes, (D. Cherifi), Algeria.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

- Pr Gloria Menegaz, Department of Computer Science, University of Verona (March 23 - Sept 20, 2019)

8.4.1.1. Internships

- Imogen Den otter-Moore - Queen's University, Kingston, Canada, From early May to late July, 2019
- Federica Cruciani - Department of Computer Science, University of Verona (March 1 - June 30, 2019)
- Enes Albay - Ph.D. student in Computer Engineering (Cont.), Istanbul Technical University, From Nov. 4, 2019 to Oct. 3, 2020.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events: Organisation

9.1.1.1. Member of the Organizing Committees

- M. Zucchelli is one of the organizer of the summer school on Brain Connectomics at the University of Verona, September 2019.

9.1.2. Scientific Events: Selection

9.1.2.1. Member of the Conference Program Committees

- T. Papadopoulo is member of the Program Commitee of GRETSI 2019.
- T. Papadopoulo is member of the Program Commitee of Soph.IA 2019.

9.1.2.2. Reviewer

- M. Clerc serves several international conferences (ISBI, ICASSP, IEEE EMBS, IEEE NER).
- R. Deriche serves several international conferences (ISBI, MICCAI, ISMRM, ...) and international workshops (CD-MRI Miccai, MFCA Miccai...).
- T. Papadopoulo serves several international conferences (GRETSI, ICIP, ISBI, ICASSP, VISAPP).

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- M. Clerc is member of the Editorial Boards of the Journal of Neural Engineering, and of the journal Neurons, Behavior, Data and Theory.

- R. Deriche is member of the Editorial Board of the Journal of Neural Engineering, editorial board member at Springer for the book series entitled Computational Imaging and Vision and member of the Editorial Board of the Medical Image Analysis Journal
- M. Clerc, R. Deriche and T. Papadopoulo serve as Guest Editor for the special issue on Non-invasive brain imaging of the Journal of Neural Engineering.

9.1.3.2. Reviewer - Reviewing Activities

- M. Clerc serves several international journals (Journal of Neural Engineering, NeuroImage, Physics in Medicine and Biology).
- R. Deriche serves several international journals (NeuroImage, IEEE Transactions on Medical Imaging, Magnetic Resonance in Medicine, Journal of Mathematical Imaging and Vision, Medical Image Analysis Journal, ...).
- T. Papadopoulo serves several international journals (Pattern Recognition, NeuroImage, Frontiers in Neuroscience, Brain Topography, Journal of Neural Engneering).
- S. Deslauriers-Gauthier serves several international journals (NeuroImage, IEEE Transactions on Biomedical Engineering, Journal of Neural Engineering).
- M. Zucchelli serves several international journals (NeuroImage, BioMedical Engineering OnLine).

9.1.4. Invited Talks

- M. Clerc gave a talk in front of the French Academy of Sciences on June 21 2019.
- M. Clerc gave a keynote talk at the INCF conference in Warsaw on Sep 2, 2019.
- M. Clerc gave a keynote talk at the ACM Multimedia HealthMedia workshop in Nice on October 21, 2019.
- R. Deriche gave an invited keynote speech at Hassan II Academy of Sciences and Technology, Kingdom of Morocco (Feb. 27, 2019).

9.1.5. Leadership within the Scientific Community

- M. Clerc is vice-president of the CORTICO association https://www.cortico.fr
- M. Clerc is vice-president of the NeuroMod institute of Université Côte d'Azur

9.1.6. Scientific Expertise

- M. Clerc is member of the COERLE and CERNA committees.
- R. Deriche serves several international institutions in reviewing applications : ERC Grants, Swiss National Science Foundation, EPFL, the Netherlands Organisation for Scientific Research (NWO).
- T. Papadopoulo serves several international (Cordis-H2020 for FET-OPEN), national (ANR) and local (NeuroMod in Nice, iSite NExT in Nantes) institutions in reviewing applications.

9.1.7. Research Administration

- M. Clerc was appointed director of the Inria Sophia Antipolis research Center in November 2019.
- M. Clerc was president of the CRCN hiring committee at Inria Bordeaux in 2019.
- M. Clerc was vice-president of the Inria Evaluation committee from September to October 2019.
- R. Deriche is member of the Academic Council of UCA (Université Côte d'Azur).
- R. Deriche is member of the Scientific Council of Academy 2 *Complex Systems*, Université Côte d'Azur and member of the Scientific Council of Olea Medical Company (https://www.olea-medical.com/en).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master: T. Papadopoulo, *Inverse problems for brain functional imaging*, 24 ETD, M2, Mathématiques, Vision et Apprentissage, ENS Cachan, France.

M. Clerc teaches Functional Brain Imaging in the MSc Mod4NeuCog of Université Côte d'Azur (30 hours).

M. Clerc gave two lectures in a summer school on Brain Connectomics at the University of Verona, September 2019.

M. Zucchelli gave one lecture and one hands-on session in a summer school on Brain Connectomics at the University of Verona, September 2019.

9.2.2. Supervision

PhD defended on May 7th, 2019: Thinhinane Megherbi, "HARDI & High Order Tensors", Supervisors: Rachid Deriche & L. Boumghar (USTHB, Algiers)

PhD in progress: Abib Alimi, "Diffusion & PLI" started Nov, 1st, 2016, Université Côte d'Azur. Supervisor: Rachid Deriche.

PhD in progress: Matteo Frigo, "Structure & Function" started Nov, 1st, 2017, Université Côte d'Azur. Supervisor: Rachid Deriche.

PhD in progress: Isa Costantini, "Brain Connectomics" started Oct. 1st, 2016, Université Côte d'Azur.. Supervisor: Rachid Deriche.

PhD defended on Dec. 19th, 2019: Kostiantyn Maksymenko, "Inverse problem in EEG/MEG/SSEG: towards a better consideration of anatomo-functional constraints", Université Côte d'Azur, Supervisors: Théodore Papadopoulo and Maureen Clerc.

PhD in progress: Federica Turi, "User-adapted Brain Computer Interaction", Université Côte d'Azur, started October 2016. Supervisor: Maureen Clerc.

PhD in progress: Sara Sedlar, "Reconstruction and analysis of dynamical functional networks from EEG, MEG and dMRI measurements", Université Côte d'Azur, started October 2018. Supervisors: Théodore Papadopoulo and Maureen Clerc.

PhD in progress: Ivana Kojcic, "Estimation of cortical activity and of the structure–function link using EEG and dMRI", Université Côte d'Azur, started October 2018. Supervisors: Théodore Papadopoulo and Samuel Deslauriers-Gauthier.

PhD in progress: Côme Le Breton, "Non invasive analysis of epileptogenetic networks and their response to neurofeedback", started June 2019. Supervisors: Maureen Clerc and Théodore Papadopoulo.

PhD in progress: Joan Belo, "Electroencephalography analysis of auditory attention when listening to music", started June 2019. Supervisors: Maureen Clerc and Daniele Schön.

9.2.3. Juries

- M. Clerc participated in the PhD Jury of Maria-Carla Piastra at University of Genova in March 2019.
- M. Clerc participated in the PhD Jury of Jelena Mladenovic at University of Bordeaux in September 2019.
- R. Deriche participated in the PhD Jury of L. El Gueddari at University Paris Saclay on Dec. 13th, 2019.
- R. Deriche participated in the PhD Jury of A. Mendoza Quispe at Ecole Normale Supérieure Paris-Saclay on Feb. 5th, 2019.
- R. Deriche participated in the PhD Jury of T. Megherbi at USTHB (Algiers) on May 7th, 2019.
- R. Deriche participated as a reviewer in the PhD Jury of M. Kchaou at ENIT (Tunis) defended on July, 2019.

- T. Papadopoulo participated as a reviewer in the PhD Jury of L. Uro at Sorbonne University Paris 6 on Nov. 25th, 2019.
- T. Papadopoulo participated as a reviewer in the HDR Jury of S. Bonnet at CEA Clinatec, Grenoble on Dec. 2nd, 2019.
- T. Papadopoulo and M. Clerc participated in the PhD Jury of K. Maksymenko at Université Côte d'Azur on Dec. 19th, 2019.

9.3. Popularization

- Demonstration of the P300 speller and of the subject adapted dry EEG cap to the local and national instances, M. Clerc, T. Papadopoulo, F. Turi, S. Guebba.
- Participation to the Cybathlon BCI Series, Graz. September 2019 [36].

9.3.1. Articles and contents

- An article mentioned the BCI projects of Athena in a special issue from magazine Le Point https://www.lepoint.fr/sante/connecter-son-cerveau-a-un-ordinateur-pour-quoi-faire-18-03-2019-2301895_40.php

9.3.2. Interventions

- National events: Brain Awareness Week, two wide audience talks in Biot, Mouans Sartoux, and demonstration of Brain-Computer interfaces, M. Clerc, T. Papadopoulo.

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Major publications by the team in recent years

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Publications of the year

Doctoral Dissertations and Habilitation Theses

[8] K. MAKSYMENKO.*Novel algorithmic approaches for the forward and inverse M/EEG problems*, Université Côte d'Azur, December 2019, https://hal.inria.fr/tel-02404166

Articles in International Peer-Reviewed Journal

[9] S. BHATTACHARYYA, M. CLERC, M. HAYASHIBE.*Augmenting Motor Imagery Learning for Brain–Computer Interfacing Using Electrical Stimulation as Feedback*, in "IEEE Transactions on Medical Robotics and Bionics", November 2019, vol. 1, n^o^ 4, p. 247-255 [*DOI :* 10.1109/TMRB.2019.2949854], https://hal.inria.fr/hal-02401304

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Project-Team BIOCORE

Biological control of artificial ecosystems

IN PARTNERSHIP WITH:
CNRS

INRA

Institut national de recherche pour l'agriculture, l'alimentation et l'environnement

Sorbonne Université (UPMC)

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Modeling and Control for Life Sciences

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Project-Team BIOCORE

Creation of the Project-Team: 2011 January 01

Keywords:

Computer Science and Digital Science:

A1.5.1. - Systems of systems
A6. - Modeling, simulation and control
A6.1.1. - Continuous Modeling (PDE, ODE)
A6.1.3. - Discrete Modeling (multi-agent, people centered)
A6.1.4. - Multiscale modeling
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Other Research Topics and Application Domains:

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B1.1.8. - Mathematical biology
B1.1.10. - Systems and synthetic biology
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1. Team, Visitors, External Collaborators

Research Scientists

Jean-Luc Gouzé [Team leader, Inria, Senior Researcher, HDR]
Valentina Baldazzi [INRA, Researcher]

Olivier Bernard [Team vice-leader, Inria, Senior Researcher, HDR]
Pierre Bernhard [Inria, Senior Researcher, Emeritus]
Madalena Chaves [Inria, Senior Researcher, HDR]
Walid Djema [Inria, Starting Research Position, from Nov 2019]
Frédéric Grognard [Inria, Researcher]
Ludovic Mailleret [INRA, Senior Researcher, HDR]
Antoine Sciandra [CNRS, Senior Researcher, Part time, HDR]
Jean-Philippe Steyer [INRA, Senior Researcher, Part time, HDR]
Suzanne Touzeau [INRA, Researcher]

External Collaborators

Hubert Bonnefond [Inalve]
Frédéric Fabre [INRA]
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Jérémie Roux [CNRS]
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Lucie Chambon [Inria, PhD Student]
Clotilde Djuikem [Inria, PhD Student, from Oct 2019]
Eleni Firippi [Inria, PhD Student]
Luis Gomes Pereira [Inria, PhD Student, until Nov 2019]
Carlos Martinez Von Dossow [Conicyt, Chile, PhD Student, until May 2019]
Samuel Nilusmas [INRA & Région PACA, PhD Student]
Marielle Péré [Inria, PhD Student, from Oct 2019]
Alex Dos Reis de Souza [Inria, PhD Student, Team Valse, from Oct 2018]
Agustin Yabo [Univ Côte d'Azur, PhD Student]

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Ouassim Bara [Inria, Post-Doctoral Fellow, until Apr 2019]
Walid Djema [Inria, Post-Doctoral Fellow, until Oct 2019]
Carlos Martinez Von Dossow [Inria, Post-Doctoral Fellow, from May 2019]
Sofya Maslovskaya [Inria, Post-Doctoral Fellow, from Apr 2019]

Visiting Scientists

Sofia Almeida [Portugal, from Feb 2019 until Jun 2019]
Christopher Castaldello [Univ. of Padova, Italy, from Oct 2019]
Clotilde Djuikem [Univ. of Douala, Cameroon, from Mar 2019 until Jul 2019]
Yves Fotso Fotso [Univ. of Dschang, Cameroon, from Mar 2019 until Jul 2019]
Israël Tankam Chedjou [Univ. of Yaoundé I, Cameroon, from Feb 2019 until Jun 2019]

Administrative Assistant

Marie-Line Meirinho [Inria, Part time]

2. Overall Objectives

2.1. Introduction

BIOCORE is a joint research team between Inria (Centre of Sophia-Antipolis Méditerranée), INRA (ISA - Institut Sophia Agrobiotech and LBE - Laboratory of Environmental Biotechnology in Narbonne) and Sorbonne Université-CNRS (Oceanographic Laboratory of Villefranche-sur-mer - LOV, UMR 7093/ Sorbonne Université, Villefranche sur Mer, Team: Processes in Pelagic Ecosystems - PEPS).

Sustainable growth of living organisms is one of the major challenges of our time. In order to tackle it, the development of new technologies is necessary, and many of these new technologies will need to use modeling and computer tools. BIOCORE contributes to this theme, in the general field of design and control of artificial ecosystems (or biosystems). Its general goal is to design devices, systems and processes containing living cells or individuals and performing some tasks to decrease pollution, use of chemicals, or to produce bioenergy in a sustainable way. We build biological/ecological models in close collaborations with biologists and bioprocess engineers, and validate them with experimental platforms. Our activities are structured in three levels: mathematical and computational methods, a methodological approach to biology, and applications.

Research themes:

Mathematical and computational methods:

- Tools for modeling in biology: model design, validation, parameter identification.
- Mathematical properties of models in biology: mathematical studies of models and of their global behavior.
- Software sensors for biological systems: using the model and on-line measurements to estimate the variables that are not measured directly.
- Control, regulation, and optimization for biological systems; design of laws to maintain a variable at a given level, or to optimize the productivity of the system.

A methodological approach to biology: system study at different scales

- At the intra-individual level: theoretical and experimental study of simple metabolic-genetic networks, coarse grained models of the internal state.
- At the level of interactions between individuals in the population: individual behavior, resource allocation.
- At the scale of interaction between populations: interaction between prey and predator populations in a trophic network or competition between species in a chemostat.
- At the scale of interaction between ecosystems: coupling of two artificial ecosystems as a unique bioprocess or interactions between an artificial ecosystem and the surrounding natural ecosystem.

Fields of application:

- Bioenergy, in particular the production of lipids (which can be used as biofuel), methane and hydrogen by microorganisms (with LOV and LBE).
- CO2 fixation by micro-algae, with the aim of capturing industrial CO2 fluxes (with LOV). This theme can also include artificial ecosystems developed to improve the prediction of carbon fluxes between the ocean and the atmosphere.
- Design and optimization of ecologically friendly protection methods for plants and micro-plants artificial production systems (with ISA and LOV). This theme focuses in particular on biological control programs to control pathogens and pest invasions in crops and bioreactors.
- Biological waste treatment with microorganisms in bioreactors to reduce pollution emission levels (in collaboration with LBE).

Software for biological modeling and supervision of biological processes.

National, international and industrial relations

- National collaborations: IFREMER (Nantes), INRA (MISTEA Montpellier, BIOGER Grignon, IAM Nancy, Agrocampus Ouest, MaIAGE Jouy-en-en-Josas, BioEpAR Nantes), CIRAD Montpellier, Institut Méditerranéen d'Océanologie, LOCEAN (Paris), GIPSA Grenoble, IBIS, ANGE, MCTAO, and VALSE Inria teams.
- Participation in French groups: ModStatSAP (Modélisation et Statistique en Santé des Animaux et des Plantes), GDR Invasions Biologiques.
- Participation to national programmes: ANR projects Phycover, ICycle, and Maximic, Plan Cancer Imodrez, UMT Fiorimed, and Labex SIGNALIFE.
- International collaborations: Université Catholique de Louvain (Belgium), Université de Mons (Belgium), MacMaster University (Canada), University Ben Gurion (Israel), Imperial College (United-Kingdom), Massey University (New Zealand), Universidad Tecnica Federico Santa Maria and Universidad de Chile (Chile), University of Edinburgh (UK), Universities of Douala, Yaoundé I and Dschang (Cameroon).

3. Research Program

3.1. Mathematical and computational methods

BIOCORE's action is centered on the mathematical modeling of biological systems, more particularly of artificial ecosystems, that have been built or strongly shaped by human. Indeed, the complexity of such systems where life plays a central role often makes them impossible to understand, control, or optimize without such a formalization. Our theoretical framework of choice for that purpose is Control Theory, whose central concept is "the system", described by state variables, with inputs (action on the system), and outputs (the available measurements on the system). In modeling the ecosystems that we consider, mainly through ordinary differential equations, the state variables are often population, substrate and/or food densities, whose evolution is influenced by the voluntary or involuntary actions of man (inputs and disturbances). The outputs will be some product that one can collect from this ecosystem (harvest, capture, production of a biochemical product, etc), or some measurements (number of individuals, concentrations, etc). Developing a model in biology is however not straightforward: the absence of rigorous laws as in physics, the presence of numerous populations and inputs in the ecosystems, most of them being irrelevant to the problem at hand, the uncertainties and noise in experiments or even in the biological interactions require the development of dedicated techniques to identify and validate the structure of models from data obtained by or with experimentalists.

Building a model is rarely an objective in itself. Once we have checked that it satisfies some biological constraints (eg. densities stay positive) and fitted its parameters to data (requiring tailor-made methods), we perform a mathematical analysis to check that its behavior is consistent with observations. Again, specific methods for this analysis need to be developed that take advantage of the structure of the model (eg. the interactions are monotone) and that take into account the strong uncertainty that is linked to life, so that qualitative, rather than quantitative, analysis is often the way to go.

In order to act on the system, which often is the purpose of our modeling approach, we then make use of two strong points of Control Theory: 1) the development of observers, that estimate the full internal state of the system from the measurements that we have, and 2) the design of a control law, that imposes to the system the behavior that we want to achieve, such as the regulation at a set point or optimization of its functioning. However, due to the peculiar structure and large uncertainties of our models, we need to develop specific methods. Since actual sensors can be quite costly or simply do not exist, a large part of the internal state often needs to be re-constructed from the measurements and one of the methods we developed consists in integrating the large uncertainties by assuming that some parameters or inputs belong to given intervals. We then developed robust observers that asymptotically estimate intervals for the state variables [83]. Using the directly measured variables and those that have been obtained through such, or other, observers, we then develop control methods that take advantage of the system structure (linked to competition or predation relationships between species in bioreactors or in the trophic networks created or modified by biological control).

3.2. A methodological approach to biology: from genes to ecosystems

One of the objectives of BIOCORE is to develop a methodology that leads to the integration of the different biological levels in our modeling approach: from the biochemical reactions to ecosystems. The regulatory pathways at the cellular level are at the basis of the behavior of the individual organism but, conversely, the external stresses perceived by the individual or population will also influence the intracellular pathways. In a modern "systems biology" view, the dynamics of the whole biosystem/ecosystem emerge from the interconnections among its components, cellular pathways/individual organisms/population. The different scales of size and time that exist at each level will also play an important role in the behavior of the biosystem/ecosystem. We intend to develop methods to understand the mechanisms at play at each level, from cellular pathways to individual organisms and populations; we assess and model the interconnections and influence between two scale levels (eg., metabolic and genetic; individual organism and population); we explore the possible regulatory and control pathways between two levels; we aim at reducing the size of these large models, in order to isolate subsystems of the main players involved in specific dynamical behaviors.

We develop a theoretical approach of biology by simultaneously considering different levels of description and by linking them, either bottom up (scale transfer) or top down (model reduction). These approaches are used on modeling and analysis of the dynamics of populations of organisms; modeling and analysis of small artificial biological systems using methods of systems biology; control and design of artificial and synthetic biological systems, especially through the coupling of systems.

The goal of this multi-level approach is to be able to design or control the cell or individuals in order to optimize some production or behavior at higher level: for example, control the growth of microalgae via their genetic or metabolic networks, in order to optimize the production of lipids for bioenergy at the photobioreactor level.

4. Application Domains

4.1. Bioenergy

Finding sources of renewable energy is a key challenge for our society. We contribute to this topic through two main domains for which a strong and acknowledged expertise has been acquired over the years. First, we consider anaerobic digesters, the field of expertise of the members of the team at the Laboratory of Enviromental Biotechnology (LBE), for the production of methane and/or biohydrogen from organic wastes. The main difficulty is to make these processes more reliable and exploit more efficiently the produced biogas by regulating both its quality and quantity despite high variability in the influent wastes. One of the specific applications that needs to be tackled is the production of biogas in a plant when the incoming organic waste results from the mixing of a finite number of substrates. The development of control laws that optimize the input mix of the substrates as a function of the actual state of the system is a key challenge for the viability of this industry.

The second topic consists in growing microalgae, the field of expertise of the members of the team at the Oceanographic Laboratory of Villefranche-sur-Mer (LOV), to produce biofuel. These microorganisms can synthesize lipids with a much higher productivity than terrestrial oleaginous species. The difficulty is to better understand the involved processes, which are mainly transient, to stimulate and optimize them on the basis of modeling and control strategies. Predicting and optimizing the productivity reached by these promising systems in conditions where light received by each cell is strongly related to hydrodynamics, is a crucial challenge.

Finally, for the energy balance of the process, it is important to couple microalgae and anaerobic digestion to optimize the solar energy that can be recovered from microalgae, as was explored within the ANR Symbiose project (2009-2012) [3].

4.2. CO_2 fixation and fluxes

Phytoplanktonic species, which assimilate CO_2 during photosynthesis, have received a lot of attention in the last years. Microalgal based processes have been developed in order to mitigate industrial CO_2. As for biofuel productions, many problems arise when dealing with microalgae which are more complex than bacteria or yeasts. Several models have been developed within our team to predict the CO_2 uptake in conditions of variable light and nitrogen availability. The first modeling challenge in that context consists in taking temperature effects and light gradient into account.

The second challenge consists in exploiting the microalgal bioreactors which have been developed in the framework of the quantification of carbon fluxes between ocean and atmospheres. The SEMPO platform (simulator of variable environment computer controlled), developed within the LOV team, has been designed to reproduce natural conditions that can take place in the sea and to accurately measure the cells behavior. This platform, for which our team has developed models and control methods over the years, is an original and unique tool to develop relevant models which stay valid in dynamic conditions. It is worth noting that a better knowledge of the photosynthetic mechanisms and improved photosynthesis models will benefit both thematics: CO_2 mitigation and carbon fluxes predictions in the sea.

4.3. Biological control for plants and micro-plants production systems

This research concentrates on the protection of cultures of photosynthetic organisms against their pests or their competitors. The cultures we study are crop and micro-algae productions. In both cases, the devices are more or less open to the outside, depending on the application (greenhouse/field, photobioreactor/raceway), so that they may give access to harmful pathogens and invading species. We opt for protecting the culture through the use of biocontrol in a broad sense.

In crop production, biocontrol is indeed a very promising alternative to reduce pesticide use: it helps protecting the environment, as well as the health of consumers and producers; it limits the development of resistance (in comparison to chemicals). The use of biocontrol agents, which are, generically, natural enemies (predators, parasitoids or pathogens) of crop pests [89], is however not widespread yet because it often lacks efficiency in real-life crop production systems (while its efficiency in the laboratory is much higher) and can fail to be economically competitive. Resistant crops are also used instead of pesticides to control pests and pathogens, but the latter eventually more or less rapidly overcome the resistance, so these crops need to be replaced by new resistant crops. As resistant genes are a potentially limited resource, a challenge is to ensure the durability of crop resistance. Our objective is to propose models that would help to explain which factors are locks that prevent the smooth transition from the laboratory to the agricultural crop, as well as develop new methods for the optimal deployment of the pests natural enemies and of crop resistance.

Microalgae production is faced with exactly the same problems since predators of the produced microalgae (e.g. zooplankton) or simply other species of microalgae can invade the photobioreactors and outcompete or eradicate the one that we wish to produce. Methods need therefore to be proposed for fighting the invading species; this could be done by introducing predators of the pest and so keeping it under control, or by controling the conditions of culture in order to reduce the possibility of invasion; the design of such methods could greatly take advantage of our knowledge developed in crop protection since the problems and models are related.

4.4. Biological depollution

These works will be carried out with the LBE , mainly on anaerobic treatment plants. This process, despite its strong advantages (methane production and reduced sludge production) can have several locally stable equilibria. In this sense, proposing reliable strategies to stabilize and optimise this process is a key issue. Because of the recent (re)development of anaerobic digestion, it is crucial to propose validated supervision algorithms for this technology. A problem of growing importance is to take benefit of various waste sources in order to adapt the substrate quality to the bacterial biomass activity and finally optimize the process. This generates new research topics for designing strategies to manage the fluxes of the various substrate sources meeting at the same time the depollution norms and providing a biogas of constant quality. In the past years, we have developed models of increasing complexity. However there is a key step that must be considered in the future: how to integrate the knowledge of the metabolisms in such models which represent the evolution of several hundreds bacterial species? How to improve the models integrating this two dimensional levels of complexity? With this perspective, we wish to better represent the competition between the bacterial species, and drive this competition in order to maintain, in the process, the species with the highest depollution capability. This approach, initiated in [92] must be extended from a theoretical point of view and validated experimentally.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Highlights

- The patented approach to produce microalgae under a biofilm form was further optimized with gradient based approaches [71] and strategies to still enhance productivities were identified and tested experimentally [26].
- The introduction of resistant plants for the protection against pathogens often leads to the appearance of virulent pathogenic strains that are capable of infecting these resistant plants. We developed a model for the pyramiding of these qualitative resistances with genetically controlled infection bottlenecks, and showed the efficiency of this technique when the fitness cost of Resistance Breaking pathogen variants in susceptible plants is intermediate [36].
- In the context of ANR project ICycle, following the PhD thesis of Sofia Almeida and in collaboration with F. Delaunay's lab (Institut Biologie Valrose, CNRS), a calibrated and validated model of the mammalian circadian clock was published in [13]. The interactions between the circadian clock and the cell cycle were then investigated [44]. The coupled models replicate the oscillators' period-lock response and recover clock to cell cycle period ratios such as 1:1 or 3:2, as observed in F. Delaunay's lab.

5.1.2. Awards

- Lucie Chambon and J.-L. Gouzé won a Best Paper award at the DYCOPS conference in Brazil (April 2019), on original control strategies for the genetic toggle switch.

BEST PAPERS AWARDS :

[46]

L. CHAMBON, J.-L. GOUZÉ.*A new qualitative control strategy for the genetic Toggle Switch*, in "DYCOPS 2019 - 12th IFAC Symposium on Dynamics and Control of Process Systems, including Biosystems", Florianopolis, Brazil, B. CHACHUAT, O. BERNARD, J. E. NORMEY-RICO (editors), IFAC-PapersOnLine, Ifac, 2019, vol. 52, n^{o} 1, p. 532-537 [*DOI :* 10.1016/J.IFACOL.2019.06.117], https://hal.inria.fr/hal-02319873

6. New Software and Platforms

6.1. In@lgae

Numerical simulator of microalgae based processes

KEYWORDS: Simulation - Microalgae system - Productivity

FUNCTIONAL DESCRIPTION: In@lgae simulates the productivity of a microalgae production system, taking into account both the process type and its location and time of the year. The process is mainly defined by its thermal dynamics and by its associated hydrodynamics. For a given microalgal strain, a set of biological parameters describe the response to nitrogen limitation, temperature and light. As a result, the biomass production, CO_2 and nitrogen fluxes, lipid and sugar accumulation are predicted.

RELEASE FUNCTIONAL DESCRIPTION: The In@lgae platform has been optimised to make it faster. Some of the key models have been rewritten in C++ to allow a faster computation. Models have been improved to include, in the growth rate computation, the composition of the light spectrum. The graphical user interface has been enhanced and several sets of parameters describing different microalgal species have been stored.

- Participants: Étienne Delclaux, Francis Mairet, Olivier Bernard and Quentin Béchet
- Contact: Olivier Bernard

6.2. Odin

Platform for advanced monitoring, control and optimisation of bioprocesses

KEYWORDS: Bioinformatics - Biotechnology - Monitoring - Automatic control

SCIENTIFIC DESCRIPTION: This C++ application enables researchers and industrials to easily develop and deploy advanced control algorithms through the use of a Scilab interpreter. It also contains a Scilab-based process simulator which can be harnessed for experimentation and training purposes. ODIN is primarily developed in the C++ programming language and uses CORBA to define component interfaces and provide component isolation. ODIN is a distributed platform, enabling remote monitoring of the controlled processes as well as remote data acquisition.It is very modular in order to adapt to any plant and to run most of the algorithms, and it can handle the high level of uncertainties that characterises the biological processes through explicit management of confidence indexes.

FUNCTIONAL DESCRIPTION: ODIN is a software framework for bioprocess control and supervision. ODIN is a distributed platform, where algorithms are described with a common structure easy to implement. Finally, ODIN can perform remote data acquisition and process these data to compute the signals to be applied to the actuators, together with estimates of state variables or process state. ODIN can handle the high level of uncertainties that characterises the biological processes through explicit management of confidence indexes.

- Participants: Fabien Dilet, Florian Guenn, Francesco Novellis, Mathieu Lacage, Melaine Gautier, Olivier Bernard, Olivier Calabro, Romain Primet and Serigne Sow
- Contact: Olivier Bernard
- URL: https://team.inria.fr/biocore/software/odin/

7. New Results

7.1. Mathematical methods and methodological approach to biology

7.1.1. Mathematical analysis of biogical models

7.1.1.1. Mathematical study of ecological models

Participants: Frédéric Grognard, Ludovic Mailleret, Suzanne Touzeau, Clotilde Djuikem, Israël Tankam Chedjou.

Semi-discrete models. Semi-discrete models have shown their relevance in the modeling of biological phenomena whose nature presents abrupt changes over the course of their evolution [41]. We used such models and analyzed their properties in several practical situations, some of them requiring such a modeling to describe external perturbations of natural systems such as harvest, and others to take seasonality into account. We developed such models in the context of the analysis of the effect of stochasticity and Allee effects on the introduction of populations [14], seasonality in the dynamics of coffee leaf rust [59] and of banana and plantain burrowing nematodes [67], as well as for the protection of plant resistance against root-knot nematodes [66].

Models in plant epidemiology. We developed and analysed dynamical models describing plant-parasite interactions, in order to better understand, predict and control the evolution of damages in crops. We considered several pathosystems, further described in Section 7.2.3, describing and controlling the impact on plants of fungi [59], [39], viruses [36], nematodes [67], [66], and pests [60].

7.1.1.2. Estimation and control

Participants: Frédéric Grognard, Ludovic Mailleret, Suzanne Touzeau, Yves Fotso Fotso, Samuel Nilusmas, Israël Tankam Chedjou.

Parameter identification in complex systems. In complex biological systems, identifying model parameters is a challenge that raises identifiability issues. To fit a within-host immunological model to a large data set of individual viremia profiles, we developed an Approximate Bayesian Computation (ABC)-like method that yielded several parameter sets compatible with the data and reflecting the variability among individuals [25]. This work benefited from the resources and support of NEF computation cluster.

Optimal control and optimisation. We developed several approaches to control the evolution of crop pests. To reduce crop losses due to plant-parasitic nematodes, we optimised (i) rotation strategies between resistant and susceptible cultivars of horticultural crops [76], or (ii) fallow periods between plantain cropping seasons [67]. These optimisation problems were solved on a finite time horizon. They benefited from the resources and support of NEF computation cluster.

We also solved an optimal control problem to limit the damages due to coffee berry borers [60]. It consisted in designing the most cost-efficient application of a biopesticide over time. Using Pontryagin's maximum principle, we determined the existence and structure of the solution. The problem was solved numerically using BOCOP (https://www.bocop.org/).

7.1.1.3. Analysis of multistability and periodic behavior with hybrid models

Participants: Madalena Chaves, Eleni Firippi.

Probabilistic dynamics tool for hybrid models In a collaboration with D. Figueiredo and M.A. Martins from the University of Aveiro, Portugal (project PHC Pessoa), a tool was developed for simulating weighted reactive models [55]. These are essentially discrete models with dynamics described by state transition graphs: each transition has a given weight and the graph has the capacity to alter its accessibility relations.

M. Chaves and M.A. Martins jointly edited a book with selected papers from the Symposium on Molecular Logic and Computational Synthetic Biology [70], gathering work on different formalisms and applications of hybrid models.

Coupling and synchronization of piecewise linear systems This work studies the coupling of N identical positive feedback loops described by piecewise linear differential equations. Under diffusive coupling, and for different conditions on the coupling parameters, the N systems may synchronize or, alternatively, generate a set ofnew steady states that form a specific pattern [49]. An unexpected result is the existence of a special relationship between the number of components N and the maximal concentration-to-activity threshold ratio $(V_1/(\gamma_1\theta_1))$. This relationship implies that, for very specific parameter sets, the N compartments cannot be guaranteed to synchronize.

7.1.1.4. Dynamics of complex feedback architectures

Participants: Madalena Chaves, Jean-Luc Gouzé.

To analyze the closed-loop dynamics of metabolic pathways under gene regulation, we propose a method to construct a state transition graph for a given regulatory architecture consisting of a pathway of arbitrary length, with any number of genetic regulators, and under any combination of positive and negative feedback loops [19]. Using this formalism, we analyze a "metabolator"-like mechanism (a pathway with two metabolites and three enzymes) and prove the existence of two co-existing oscillatory behaviors: damped oscillations towards a fixed point or sustained oscillations along a periodic orbit [20].

7.1.2. Metabolic and genomic models

Participants: Jean-Luc Gouzé, Olivier Bernard, Valentina Baldazzi, Lucie Chambon, Carlos Martinez Von Dossow, Agustin Yabo, Alex Dos Reis de Souza, Walid Djema, Sofya Maslovskaya.

Analysis and reduction of a model of sugar metabolism in peach fruit. Predicting genotype-to-phenotype relationships is a big challenge for plant biology and breeding. A model of sugar metabolism in peach fruit has been recently developed and applied to 10 peach varieties [80]. A reduction pipeline combining several reduction strategies has been developed to reduce both model size and nonlinearity and allow for further application to virtual breeding (collaboration with B. Quilot-Turion and Mohamed Memmah (INRA Avignon) as part of the PhD thesis of Hussein Kanso) [64]. A paper is currently under revision for Mathematical Biosciences.

Analysis of an integrated cell division-endoreduplication and expansion model. The development of a new organ depends on cell-cycle progression and cell expansion, but the interaction and coordination between these processes is still unclear [27]. An integrated model of fruit development has been developed and used to test different interaction schemes, by comparing simulation results to the observed cell size distribution in tomato fruit [15].

Modeling cell growth and resource allocation. In the framework of the Maximic project (collaboration with IBIS team) and as a follow up of our previous work [82], we investigated the impact of energy metabolism on cell's strategy for resource allocation. Preliminary results show that the inclusion of energy costs leads to the emergence of a trade-off between growth rate and yield, as experimentally observed in many bacterial cells .

The allocation of cellular resources can strongly influence not only the rate of cell growth but also the resulting cell size [78]. To better investigate the connection between proteome allocation and cell volume, the original model by Giordano et al. [82] has been connected to a biophysical model of cell growth, explicitly describing cell volume increase as a function of cell's internal pressure and mechanical properties. The resulting model will be used to investigate the mechanisms (control of osmotic pressure or wall mechanics) behind cell size control under different environmental constrains [84].

Optimal allocation of resources in a bacterium. We study by techniques of optimal control the optimal allocation between metabolism and gene expression during growth of bacteria, in collaboration with Inria IBIS and MCTAO project-teams. We developed different versions of the problem, and consider a new problem where the aim is to optimize the production of a product [68], [40], [50], (ANR project Maximic, PhD thesis of A. Yabo). We also study variations of the model, for example in the chemostat [57]. The precise mathematical analysis of the optimal behavior (turnpike property) is under investigation.

A synthetic community of bacteria. In the framework of IPL Cosy, we study the coexistence of two strains of bacteria E. Coli in a bioreactor. The strains have been modified synthetically to achieve some goals. The aim is to obtain a better productivity in the consortium than in a single strain, by control technics. The description of models is in revision for Plos Comp. Biol.

In collaboration with team VALSE (Lille), we also studied several problems of estimation and robust stabilization related to IPL Cosy, for two bacterial species in a bioreactor [53], [54].

Control of a model of synthesis of a virulence factor. In collaboration with J.-A. Sepulchre (UCA), we modeled the production of a virulence factor by a bacterium in a continuous stirred tank reactor. The production of this enzyme is genetically regulated, and degrades a polymeric external substrate into monomers [37]. We also studied the problem of periodic inputs for maximization of some yield [97].

Hybrid control of genetic networks. We designed control strategies based on the measurement and control of a unique gene within positive or negative loops of genetic networks, in order to stabilize the system around its unstable fixed point. The quantized nature of genetic measurements and the new synthetic control approaches available in biology encourage the use of piecewise constant control laws. A specific partitioning of the state space and the study of successive repulsive regions allow to show global convergence and global stability for the resulting system [18]. Several other control strategies are studied [47], [48], [46]. This is part of the PhD thesis of L. Chambon.

7.1.3. Biochemical and signaling models

Participants: Madalena Chaves, Eleni Firippi, Sofia Almeida, Marielle Péré, Luis Gomes Pereira, Jérémie Roux.

7.1.3.1. Analysis and coupling of biological oscillators

Modeling, analysis and coupling of the mammalian cell cycle and clock A transcriptional model of the mammalian circadian clock was developed in [13] and its parameters calibrated against experimental data from F. Delaunay's lab. A cell cycle model was also previously developed by us [77]. The interactions between the two oscillators are investigated under uni- or bi-directional coupling schemes [44]. Numerical simulations replicate the oscillators' period-lock response and recover observed clock to cell cycle period ratios such as 1:1, 3:2 and 5:4 (as observed in experiments, F. Delaunay's lab). This work is in collaboration with F. Delaunay (ANR ICycle) and part of the PhD thesis of Sofia Almeida.

Period-control in a coupled system of two genetic oscillators In the context of ANR project ICycle, we consider two reduced models that mimic the dynamics of the cell cycle and clock oscillators and study the effect of each oscillator on the coupled system, from a synthetic biology perspective [56]. The first observation is that oscillator A is more likely to be the controller of the coupled system period when the dynamis of oscillator B becomes stable due to the coupling strength. Another interesting observation is that the coupled system exhibits oscillatory dynamics over an increased region of the parameter space. This work is part of the PhD thesis of Eleni Firippi (ANR ICycle).

7.1.3.2. Modeling the apoptotic signaling pathway

A detailed model of the death receptor layer In a collaboration with J. Roux and within project Imodrez, he goal is to study the origins of cell-to-cell variability in response to anticancer drugs and provide a link between complex cell signatures and cell response phenotype. In a first approach, we constructed a detailed model to represent the death receptor-ligand binding and subsequent signaling cascade [11]. This model was used to study the effect of intrinsic and extrinsic noise sources, and suggested the need to expand a set of reactions on the model, to account for the observed cell heterogeneity (this was part of the PhD thesis of Luis Pereira).

A basic model to explore the effect of a positive feedback loop Analysis of the detailed apoptosis receptor model uncovered a set of reactions for which the introduction of a positive feedback loop from caspase 8 was able to significantly increase the range of variability in the model in response to extrinsic noise. To better understand this mechanism and the role of positive loop in cell response variability, we are constructing a reduced model representing only the basic components: death ligand and receptor, caspase 8 and two intermediate complexes. This is part of the work of the PhD student Marielle Péré.

7.2. Fields of application

7.2.1. Bioenergy

7.2.1.1. Modelling microalgae production

Participants: Olivier Bernard, Antoine Sciandra, Walid Djema, Ignacio Lopez, David Demory, Ouassim Bara, Jean-Philippe Steyer.

Experimental developments

Running experiments in controlled dynamical environments. The experimental platform made of continuous photobioreactors driven by a set of automaton controlled by the ODIN software is a powerful and unique tool which gave rise to a quantity of very original experiments. Such platform improved knowledge of several biological processes such as lipid accumulation or cell cycle under light fluctuation, etc [69].

This experimental platform was used to control the long term stress applied to a population of microalgae [72]. This Darwinian selection procedure generated several new strains more resistant to oxidative stresses after several months in the so called selectiostats [58].

Experiments were run to understand the interactions in a simplified ecosystem between microalgae and cyanobacteria. The initial idea was to use a nitrogen fixing cyanobacteria providing nitrogen to the microalgae. It turns out that negative interactions appear in this ecosystem, first because of the mutual shadowing of these organisms, and second because of the production of allelopathic substances inhibiting the competitive organisms [79].

On top of this, we carried out outdoor pilot experiments with solar light. We tested the impact of various temperatures, resulting from different shadowing configurations on microalgal growth rate.

Experimental work was also carried out in collaboration with the Inalve startup with microalgal biofilm to determine the impact of light and dark sequences on cell growth and photoacclimation [26], [63]. The architecture of the biofilms was also observed for different species with confocal microscopic techniques [23].

These works have been carried out in collaboration with A. Talec and E. Pruvost (CNRS/Sorbonne Université -Oceanographic Laboratory of Villefranche-sur-Mer LOV).

Metabolism of carbon storage and lipid production. A metabolic model has been set up and validated for the microalgae *Isochrysis luthea*, on the basis of the DRUM framework , in order to simulate autotophic, heterotropic and mixotrophic growth, and to determine how to reduce substrate inhibition. The model was extended for other substrates such as glucose or glycerol. A simplified model was developed by I. Lopez to represent the dynamics of polar lipids, especially when faced to higher oxygen concentration. In particular, this model represents the microalgae growth under different conditions of temperature, light and oxygen.

Modeling photosynthetic biofilms. Several models have been developed to represent the growth of microalgae within a biofilm. A first structured physiological model, extending the one proposed in [95] uses mixture theory to represent the microalgae growth, based on the consideration of intracellular reserves triggering the processes of growth, respiration and excretion. We consider separately the intracellular storage carbon (lipids and carbohydrates) and the functional part of microalgae . Another approach accounts for the dynamics of the light harvesting systems when cells are submitted to rapid successions of light and dark phases [28], [71]. A simpler model was developed and used to identify the optimal working mode of a process based on photosynthetic biofilm growing on a conveyor belt [45]. The model was used to identify the worldwide potential of microalgal biofilms under different climates [26].

Modeling microalgae production processes.

A synthesis has been written on the different aspects for developing models of microalgae in the field of wastewater treatment [38]. The paper is completed by a position paper proposing guidelines for the development of models in biotechnology [31]. A model representing the dynamics of microalgae when growing in suboptimal conditions of light, nitrogen and phosphorus was developed. It consists in an extension of the Droop model accounting for the two quota of nitrogen and phosphorus [65]. This was the topic of the internship of Luis Plaza Alvarez. The model also represents the pigment acclimation to various light intensities. We have studied in [75] the response of a Droop model forced by periodic light or temperature signals. We transformed the model into a planar periodic system generating a monotone dynamical system. Combined with results on periodic Kolmogorov equations, the global dynamics of the system can be described.

Modeling thermal adaptation in microalgae.

Experiments have been carried out in collaboration with A.-C. Baudoux (Biological Station of Roscoff) in order to study growth of various species of the microalgae genus *Micromonas* at different temperatures. After calibration of our models, we have shown that the pattern of temperature response is strongly related to the site where cells were isolated. We derived a relationship to extrapolate the growth response from isolation location. With this approach, we proved that the oceanwide diversity of *Micromonas* species is very similar to the oceanwide diversity of the phytoplankton [22]. We have used Adaptive Dynamics theory to understand how temperature drives evolution in microalgae. We could then predict the evolution of this biodiversity in a warming ocean and show that phytoplankton must be able to adapt within 1000 generation to avoid a drastic reduction in biodiversity [22].

Modeling viral infection in microalgae. In collaboration with A.-C. Baudoux (Biological Station of Roscoff) a model was developed to account for the infection of a *Micromonas* population, with population of susceptible, infected and also free viruses. The model turned out to accurately reproduce the infection experiments at various temperatures, and the reduction of virus production above a certain temperature [22]. The model was then extrapolated to the whole ocean to better understand how the warming will impact the mortality due to viruses.

7.2.1.2. Control and Optimization of microalgae production

Optimization of the bioenergy production systems

A model predictive control algorithm was run based on simple microalgae models coupled with physical models where culture depth influences thermal inertia. Optimal operation in continuous mode for outdoor cultivation was determined when allowing variable culture depth. Assuming known weather forecasts considerably improved the control efficiency [21].

Control of microalgal biofilms.

Determining the optimal operating conditions for a rotating algal biofilm process [63] is a difficult question. A 1D model was developed, and the gradient associated to the productivity at the process scale was computed. Then the conditions maximizing productivity were derived, playing on the conveyer belt velocity and geometry [71].

Interactions between species. We have proposed an optimal control strategy to select in minimal time the microalgal strain with the lowest pigment content [51]. The control takes benefit from photoinhibition to compute light stresses penalizing the strains with a higher pigment content and finally selecting microalgae with lower chlorophyll content. Another optimal control problem was considered for selecting a strain of interest within two species competing for the same substrate, when dynamics is represented by a Droop model [52], [73], [74]. In both cases, the optimal control derived from the Pontryagin maximum principle also exhibit a turnpike behaviour. This is a collaboration with team MCTAO.

Strategies to improve the temperature response have also been studied. We modelled the adaptive dynamics for a population submitted to a variable temperature [58]. This was used at the LOV to design experiments with periodic temperature stresses aiming at enhancing polyunsaturated long chain fatty acids content of *Tisochrysis lutea* [72].

7.2.1.3. Modelling mitochondrial inheritance patterns

Most eukaryotes inherit their mitochondria from only one of their parents. When there are different sexes, it is almost always the maternal mitochondria that are transmitted. Indeed, maternal uniparental inheritance has been reported for the brown alga Ectocarpus but we show in this study [33] that different strains of Ectocarpus can exhibit different patterns of inheritance: Ectocarpus siliculosus strains showed maternal uniparental inheritance, as expected, but crosses using different Ectocarpus species 7 strains exhibited either paternal uniparental inheritance or an unusual pattern of transmission where progeny inherited either maternal or paternal mitochondria, but not both. A possible correlation between the pattern of mitochondrial inheritance and male gamete parthenogenesis was investigated. Moreover, in contrast to observations in the green lineage, we did not detect any change in the pattern of mitochondrial inheritance in mutant strains affected in life cycle progression. Finally, an analysis of field-isolated strains provided evidence of mitochondrial genome recombination in both Ectocarpus species.

7.2.2. Biological depollution

7.2.2.1. Control and optimization of bioprocesses for depollution

Participants: Olivier Bernard, Carlos Martinez Von Dossow, Jean-Luc Gouzé.

We consider artificial ecosystems including microalgae, cyanobacteria and bacteria in interaction. The objective is to more efficiently remove inorganic nitrogen and phosphorus from wastewater, while producing a microalgal biomass which can be used for biofuel or bioplastic production. Models have been developed including predators grazing the microalgae. Experiments with nitrogen fixing cyanobacteria were carried out, and simple models of the ecosystem where developed to assess the potential of such organisms to support the nitrogen need of microalgae [79].

7.2.2.2. Coupling microalgae to anaerobic digestion

Participants: Olivier Bernard, Antoine Sciandra, Jean-Philippe Steyer, Frédéric Grognard, Carlos Martinez Von Dossow.

The coupling between a microalgal pond and an anaerobic digester is a promising alternative for sustainable energy production and wastewater treatment by transforming carbon dioxide into methane using light energy. The ANR Phycover project is aiming at evaluating the potential of this process [96].

We have proposed several models to account for the biodiversity in the microalgal pond and for the interaction between the various species. These models were validated with data from the Saur company. More specifically, we have included in the miroalgae model the impact of the strong turbidity, and derived a theory to better understand the photolimitation dynamics especially when accounting for the photo-inhibition in the illuminated periphery of the reactor [91]. Control strategies playing with the dilution rate, shadowing or modifying depth were then proposed [90].

Finally, a study of the possible sensors which would enhance the monitoring of these process was proposed [30], [29]

7.2.2.3. Life Cycle Assessment

Participants: Olivier Bernard, Jean-Philippe Steyer, Marjorie Alejandra Morales Arancibia.

Environmental impact assessment. To follow up the pioneering life cycle assessment (LCA) work of [87], we identified the obstacles and limitations which should receive specific research efforts to make microalgae production environmentally sustainable [93].
In the Purple Sun ANR-project, we studied a new paradigm to improve the energy balance by combining biofuel production with photovoltaic electricity. The LCA of a greenhouse with, at the same time, photovoltaic panels and low emissivity glasses was carried out. Depending on the period of the year, changing the species can both improve productivity and reduce environmental footprint [34].

We have also studied the environmental impact of protein production from microalgae in an algal biofilm process and compared it to other sources (fisheries, soy,...). This study confirms the interest of microalgae for reducing the environmental impact.

This work is the result of a collaboration with Arnaud Helias of INRA-LBE (Laboratory of Environmental Biotechnology, Narbonne).

7.2.3. Design of ecologically friendly plant production systems

7.2.3.1. Controlling plant arthropod pests

Participants: Frédéric Grognard, Ludovic Mailleret, Suzanne Touzeau, Yves Fotso Fotso.

Optimization of introduction processes. The question of how many and how frequently natural enemies should be introduced into crops to most efficiently fight a pest species is an important issue of integrated pest management. The topic of optimization of natural enemies introductions has been investigated for several years [89], and extends more generally to pulse perturbations in population dynamics.

A central theoretical result concerns the unveiling of the crucial influence of within-predator density dependent processes. To evaluate this theoretical prediction in a more realistic, stochastic and spatially explicit setting, a stochastic individual based model has been built in Python MESA, on the basis of a previous work in NetLogo. Extensive simulatory experiments were performed to assess the effects of density dependent processes as well as spatial structure and stochasticity on augmentative biological control performance and variability [88]. The modelling platform is interactive and can be accessed online at http://popintro.sophia.inra.fr/.

In a more general setting, we studied the impact on the introduction success of a population of the interplay of Allee effects, stochasticity in introduction sizes, and occurrence of catastrophes that temporarily wipe out the population. The mean first passage time (MFPT) for a population to reach a viable size was used as a measure of establishment success for the introduction processes [14].

Characteristics of space and the behavior and population dynamics of biological control agents. We studied the influence of the spatial structure and characteristics of the environment on the establishment and spread of biological control agents through computer simulations and laboratory experiments on parasitoids of the genus Trichogramma. This was the topic of Thibaut Morel Journel [94] and Marjorie Haond's PhD theses [85]. The last article associated with Thibaut Morel Journel's Thesis appeared this year [35]. We explored the influence of different characteristics of the structural connectivity of an invaded habitat on the invading population. We demonstrated how spread was hindered by habitat clusters and accelerated by the presence of hubs. These results highlight the importance of considering the structure of the invaded area to predict the outcome of invasions.

In a different study stemming from Marjorie Haond Thesis, we showed how habitat richness [86] as represented by its local carrying capacity can positively influence the spreading speeed of an expanding population. This work has been published as a preprint recommended by *Peer Community in Ecology* and is on the verge to be submitted to a regular scientific journal. This work has been performed in collaboration with Elodie Vercken (ISA) and Lionel Roques (BioSP, Avignon).

In a different context, we studied how predatory mite population development can be enhanced by the provision of artificial habitats. One paper focused on the influence of different artificial materials on the oviposition and survival of predatory mites appeared this year [16]. This topic was also at the core of the Master 2 intership of Lucas Etienne [81] during which he studied the combined influences of artificial habitats and additional food on the development of a predatory mite and on the control of a phytophagous mite. An article reporting on this study is currently under preparation.

Modelling and control of coffee berry borers. We developed a model describing the coffee berry borer dynamics based on the insect life-cycle and the berry availability during a single cropping season. A control was introduced, based on a biopesticide (entomopathogenic fungus such as *Beauveria bassiana*) that is sprayed and persist on the berries. An optimal control problem was solved (see Section 7.1.1.2). The aim was to maximise the yield at the end of the cropping season, while minimising the borer population for the next cropping season and the control costs. Depending on the initial pest infestation, the optimal solution structure varied [60], [62]. This research pertains to Yves Fotso Fotso's PhD thesis, who visited BIOCORE during 5 months in 2019 through the EPITAG associate team.

7.2.3.2. Controlling plant pathogens

Participants: Frédéric Grognard, Ludovic Mailleret, Suzanne Touzeau, Clotilde Djuikem.

Sustainable management of plant resistance. We studied other plant protection methods dedicated to fight plant pathogens. One such method is the introduction of plant strains that are resistant to one pathogen. This often leads to the appearance of virulent pathogenic strains that are capable of infecting the resistant plants.

We have developed a (spatio-)temporal epidemiological model of the phoma stem canker of oilseed rape, to test and assess the durability of deployment strategies of various cultivars. Based on this model, we aim at developing a user-friendly, upgradeable and efficient simulation tool designed for researchers as well as non academic partners from technical institutes and agriculture cooperatives. We hence applied and obtained the SiDRes AMDT, which will start in 2020.

A stochastic model was developed to help determine the efficiency of pyramiding qualitative resistance and quantitative resistance narrowing population bottlenecks exerted on plant viruses, the latter aiming at slowing down virus adaptation to the qualitative resistance. It showed the efficiency of pyramiding when the fitness cost of RB virus variants in susceptible plants is intermediate [36]. This studiy provide a framework to select plants with appropriate virus-evolution-related traits to avoid or delay resistance breakdown. This was done in collaboration with Frédéric Fabre (INRA Bordeaux) and Benoît Moury (INRA Avignon).

Taking advantage of plant diversity and immunity to minimize disease prevalence. An epidemiological model of gene-for-gene interaction considering a mechanism related to the specific defense response of plants, the systemic acquired resistance (SAR) was developed. SAR provides a sort of immunity to virulent pathogens for resistant plants having undergone an infection attempt by an avirulent pathogen. This model showed that there exists an optimal host mixture that ensures the lowest plant disease prevalence, so as to optimize the crop yield.

It is especially efficient for pathogens with a low or intermediate basic reproduction rate and hosts with a high SAR efficiency [61]. This was done in collaboration with Pauline Clin and Frédéric Hamelin (Agrocampus Ouest).

7.2.3.3. Plant-nematode interactions

Participants: Valentina Baldazzi, Frédéric Grognard, Ludovic Mailleret, Suzanne Touzeau, Israël Tankam Chedjou, Samuel Nilusmas.

Plant-parasitic nematodes are small little-mobile worms that feed and reproduce on plant roots, generating considerable losses in numerous crops all over the world. Most eco-friendly plant protection strategies are based on the use of resistant crops, but agricultural practices also contribute to nematode control.

Based on an interaction model between plantain roots and *Radopholus similis*, we solved an optimisation problem (see Section 7.1.1.2). It aimed at determining the duration between cropping seasons (fallow period) that maximises the farmer's cumulated yield, which is affected by the nematode population, while minimising the costs of nematode control and nursery-bought pest-free suckers, on a fixed time horizon that lasts several cropping seasons. Fallow periods reduce the nematode population in the soil, as these pests need roots to feed on and reproduce. For a relatively long time horizon, deploying one season less than the maximum possible number of cropping seasons resulted in a better multi-seasonal profit. The optimal solution consisted in applying long fallows at the beginning, to drastically reduce the nematode population. The profit was lower for more regular fallows, but the final soil infestation was also lower [67]. This research pertains to Israël Tankam Chedjou's PhD thesis, who visited BIOCORE during 5 months in 2019 through the EPITAG associate team.

We also studied resistance-based root-knot nematode control. As virulent nematodes exhibit a reduced fitness on susceptible crops, alternating resistant and susceptible plants could help increase the efficiency and durability of such control methods. Optimal crop rotations (see Section 7.1.1.2 were characterised by low ratios of resistant plants and were robust to parameter uncertainty. Rotations provided significant gains over resistant-only strategies, especially for intermediate fitness costs and severe epidemic contexts. Switching from the current general deployment of resistant crops to custom rotation strategies could not only maintain or increase crop yield, but also preserve the few and valuable R-genes available. This research pertains to Samuel Nilusmas' PhD thesis. This work has been publisehd as a pre-print [76] and is currently under review. It has also been presented at several national and international conferences this year [66], [42].

7.2.3.4. Optimality/games in population dynamics

Participants: Frédéric Grognard, Ludovic Mailleret, Pierre Bernhard.

Optimal resource allocation. Mycelium growth and sporulation are considered for phytopathogenic fungi. For biotrophic fungi, a flow of resource is uptaken by the fungus without killing its host; in that case, life history traits (latency-sporulation strategy) have been computed based on a simple model considering a single spore initiating the mycelium, several spores in competition and applying optimal resource allocation, and several spores in competition through a dynamic game through the analytico-numerical solution of the Hamilton-Jacobi-Bellman-Isaacs equation [39]. This work is done with Fabien Halkett of INRA Nancy.

Optimal foraging and residence times variations. In this work, we built on our re-analysis of the Marginal Value Theorem (MVT) [4] to study the effect on the optimal foraging strategy of habitat conversion, whereby patches are converted from one existing type to another, hence changing the frequency of each type in the environment. We studied how realized fitness and the average rate of movement should respond to changes in the frequency distribution of patch-types, and how they should covary. We found that the initial pattern of patch-exploitation in a habitat can help predict the qualitative responses of fitness and movement rate following habitat conversion. We conclude that taking into account behavioral responses may help better understand the ecological consequences of habitat conversion [17].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

BioEnTech: the collaboration with the BioEnTech start-up is aiming at developing new functionalities for ODIN in order to improve the advanced monitoring and control of industrial anaerobic digesters.

Inalve: with the Inalve start-up we develop a breakthrough process that we patented, in which microalgae grow within a moving biofilm. The objective of the collaboration is to optimize the process by enhancing productivity, while reducing environmental footprint.

8.2. Bilateral Grants with Industry

Exactcure: in the collaboration with the start-up Exactcure (Nice), the goal of the project is to study pharmacokinetic models. Exactcure and Biocore agreed for a transfer of intellectual property concerning the work of former intern L. Dragoni.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. National programmes

- **ANR-Phycover:** The overall objective of the PHYCOVER project (2014-2018) is to identify a modular wastewater treatment process for the production of biogas. The method combines three modules. First, a high-rate algal pond is dedicated to the treatment of municipal wastewater. Then, an anaerobic digester capable of co-digesting biomass products (and others organic matter resources) to significantly reduce biological and chemical contaminants while producing a sustainable energy as biogas is analysed. A final module transforms the residual carbon, nitrogen and phosphorus into high-value microalgae dedicated to aquaculture and green chemistry.
- **ITE-OPALE:** The goal of the Institut de la Transition Énergétique - OPALE project (2016-2019) is to increase the lipid content of microalgae by specific selection pressure. The project relies on the strain already selected during the Facteur 4 project, whose productivity was 4 times higher than the wild type. We expect to still increase strain performances up to 10 times the productivity of the wild type. This project was unexpectedly arrested by the funding agency on April 2019.
- **ADEME Phytorecolt:** The goal of this project (2017-2019) is to develop an automated and optimized procedure for microalgae harvesting. A project coordinated by H. Bonnefond.
- **ANR-ICycle:** This project (2016-2020) aims at understanding the communication pathways between the cell division cycle and the circadian clock, using mathematical modeling and control theory to construct and implement two coupled synthetic biological oscillators. Project coordinated by M. Chaves.
- **ANR - Maximic:** The goal of the project (2017-2021) is to design and implement control strategies in a bacterium for producing at maximal rate a high value product. It is coordinated by H. de Jong (IBIS Grenoble), and involves members of Biocore and McTao.
- **Plan Cancer - Imodrez:** The objective of this project (2018-2021) is to understand cancer drug response heterogeneity using tumor single-cell dynamics and developing mathematical models and computational approaches. A project coordinated by J. Roux (IRCAN) and funded by Inserm - Plan Cancer.
- **SIGNALIFE:** Biocore is part of this Labex (scientific cluster of excellence) whose objective is to build a network for innovation on Signal Transduction Pathways in life Sciences, and is hosted by the University of Nice Sophia Antipolis.

- **UMT FIORIMED:** FioriMed is a Mixed Technology Unit created in January 2015 to strengthen the production and dissemination of innovation to the benefit of ornamental horticulture. Horticultural greenhouses are seen as a "laboratory" for the actual implementation of agroecology concepts with the possibility of generic outcomes being transfered to other production systems. The main partners of UMT FioriMed are ASTREDHOR (National Institute of Horticulture) and the ISA Joint Research Unit of INRA-CNRS-Univ. Nice.
- **EcoPhyto - CeraTIS Corse:** “Territorial management of the Mediterranean fruit fly in Corsica by the Sterile Insect Technique” (2020-2022). This project is based on a pilot field experiment of sterile male releases and it integrates population dynamics and socio-economic approaches.
- **EcoPhyto - INTERLUDE:** “Territorial innovations to reduce phytoparmaceutical products for the sustainable production of vegetable crops” (2020-2022). BIOCORE members participate in a case study that focuses on the agroecological management of soil pests and pathogens in Provence.

9.1.2. Inria funding

- **Inria Project Lab, Algae** *in silico***:** (2014-2019) The Algae in silico Inria Project Lab, funded by Inria and coordinated by O. Bernard, focuses on the expertise and knowledge of biologists, applied mathematicians and computer scientists to propose an innovative numerical model of microalgal culturing devices. The latest developments in metabolic modeling, hydrodynamic modeling and process control are joined to propose a new generation of advanced simulators in a realistic outdoor environment. The project gathers 5 Inria project teams and 3 external teams.
- **Inria Project Lab, Cosy:** (2017-...) This proposal aims at exploiting the potential of state-of-art biological modeling, control techniques, synthetic biology and experimental equipment to achieve a paradigm shift in control of microbial communities. We will investigate, design, build and apply an automated computer-driven feedback system for control of synthetic microbial communities, not just accounting for but rather leveraging population heterogeneity in the optimal accomplishment of a population-level task. The development of methodologies of general applicability will be driven by and applied to two different applications closely connected with real-world problems in the biomedical and biotechnological industry. The consortium is composed of the four Inria project-teams IBIS, BIOCORE, COMMANDS, VALSE, INBIO, as well as the external partners BIOP (Université Grenoble Alpes, including members of IBIS), MaIAge (INRA), and YoukLAB (TU Delft).

9.1.3. INRA funding

- **MoGeR:** “From knowledge to modeling: towards a user-friendly simulation tool to test crop resistance management scenarios in the Phoma-oilseed rape case study”, INRA Metaprogramme SMaCH, 2017–2019. This is a follow-up of the K-Masstec project, which focused on sustainable strategies for the deployment of genetic resistance in the field, based on molecular knowledge on avirulence genes.
- **ABCD:** INRA SPE is funding the project ABCD "Augmentative Biological Control; optimizing natural ennemies Deployment" (2017-2019) in which Biocore is a partner with INRA Sophia Antipolis.
- **IMMUnE:** INRA SPE is funding the project IMMUnE "Immunité et Modélisation Mathématique pour Unifier l’Epidémiologie" (2019-2021), headed by F. Hamelin (Agrocampus Ouest), in which BIOCORE is a partner.

9.1.4. Networks

- **ModStatSAP:** The objective of this INRA network is to federate researchers in applied mathematics and statistics and to promote mathematical and statistical modeling studies in crop and animal health. S. Touzeau is a member of the scientific committee.
- **Seminar:** BIOCORE organizes a regular seminar “Modeling and control of ecosystems” at the station zoologique of Villefranche-sur-Mer, at INRA-ISA or at Inria.

9.2. European Initiatives

9.2.1. Collaborations in European Programs, Except FP7 & H2020

Program: **PHC-Pessoa** Partenariat Hubert Curien with Portugal, managed by Campus France

Project acronym: **LTSB**

Project title: Logic Tools for Systems Biology

Duration: 01/2019 - 12/2019

Coordinator: M. Chaves

Other partners: M.A. Martins, University of Aveiro

Abstract: This project aims at developing Boolean, piecewise linear and other hybrid tools for analysis of biological networks.

9.2.2. Collaborations with Major European Organizations

Imperial college, Department of Chemical engineering (UK),

Modelling and optimization of microalgal based processes.

University of Padova, Italy.

Modelling and control of microalgal production at industrial scale.

9.3. International Initiatives

9.3.1. Inria International Labs

Inria Chile
Associate Team involved in the International Lab:

9.3.1.1. GREENCORE

Title: Modelling and control for energy producing bioprocesses

International Partners (Institution - Laboratory - Researcher):

PUCV (Chile) - Escuela de Ingenieria Bioquimica (EIB) - David Jeison

UTFSM (Chile) - Departamento de Matematica - Pedro Gajardo

Univ. Chile (Chile) - Centro de modelacion matematica - Hector Ramirez

Inria coordinator: O. Bernard

Start year: 2014

See also: https://team.inria.fr/eagreencore/

The worldwide increasing energy needs together with the ongoing demand for CO2 neutral fuels represent a renewed strong driving force for the production of energy derived from biological resources. In this scenario, the culture of oleaginous microalgae for biofuel and the anaerobic digestion to turn wastes into methane may offer an appealing solution. The main objective of our proposal is to join our expertise and tools, regarding these bioprocesses, in order to implement models and control strategies aiming to manage and finally optimize these key bioprocesses of industrial importance. By joining our expertise and experimental set-up, we want to demonstrate that closed loop control laws can significantly increase the productivity, ensure the bioprocess stability and decrease the environmental footprint of these systems. This project gathers experts in control theory and optimization (BIOCORE, UTFSM) together with experts in bioprocesses (PUCV and CMM) and software development.

International Laboratory for Research in Computer Science and Applied Mathematics
Associate Team involved in the International Lab:

9.3.1.2. EPITAG

Title: Epidemiological Modelling and Control for Tropical Agriculture

International Partner (Institution - Laboratory - Researcher):

Université de Douala (Cameroon) - Département de Mathématique et Informatique - Samuel Bowong

Inria coordinator: S. Touzeau

Start year: 2017

See also: https://team.inria.fr/epitag/

EPITAG gathers French and Cameroonian researchers, with a background in dynamical systems and control and with an interest in crop diseases. Crop pests and pathogens are responsible for considerable yield losses and represent a threat to food security. Their control is hence a major issue, especially in Cameroon, where agriculture is an important sector in terms of revenues and employment. To help design efficient strategies for integrated pest management, mathematical models are particularly relevant. Our main objective is to study the epidemiology and management of tropical crop diseases, with a focus on Cameroon and Sub-Saharan Africa. Our approach consists in developing and analysing dynamical models describing plant-parasite interactions, in order to better understand, predict and control the evolution of damages in crops. To ensure the relevance of our models, field experts and stakeholders need to be closely associated. We will focus on pest and pathogens that affect major staple food and cash crops, such as cocoa plant mirids, plantain and banana plant-parasitic nematodes, coffee berry borers, coffee leaf rust, maize stalk borers, cabbage diamondback moths, papaya mealybugs, etc. To tackle these issues, we jointly supervise master and PhD students.

9.3.2. Inria International Partners

- NTNU (Norwegian University of Science and Technology), Trondheim, Norway. The project involves turning wastes into bioenergy with anaerobic digestion. O. Bernard spent a one year sabbatical at NTNU in the Enersene group working on renewable energy.

9.3.3. Participation in Other International Programs

- Univ. Ben Gurion : Microalgal Biotechnology Lab (Israel), Member of the ESSEM COST Action ES1408 European network for algal-bioproducts (EUALGAE). Modelling of photosynthesis.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

Daniel Figueiredo, University of Aveiro, Portugal, 02-06 Sep. 2019. Visit in the context of PHC-Pessoa project to work on the development of logical tools for systems biology.

Israël Tankam Chedjou, University of Yaoundé 1, Cameroon, Feb.-Jun. 2019. Visit in the context of the EPITAG associate team.

Yves Fotso Fotso, University of Dschang, Cameroon, Mar.-Jul. 2019. Visit in the context of the EPITAG associate team.

Clotilde Djuikem, University of Douala, Cameroon, Mar.-Jul. 2019. Visit in the context of the EPITAG associate team.

9.4.2. Visits to International Teams

9.4.2.1. Sabbatical programme

O. Bernard spent a one year sabbatical at NTNU (Norwegian University of Science and Technology), Trondheim, Norway. He worked on a project to turn wastes into bioenergy with anaerobic digestion.

9.5. Project-team seminar

BIOCORE organized a 3-day seminar in September at Peyresq (Alpes-de-Haute-Provence). On this occasion, every member of the project-team presented his/her recent results and brainstorming sessions were organized.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events: Organisation

10.1.1.1. General Chair, Scientific Chair

O. Bernard was the Co-Chair of the Dycops-CAB conference (CAB 2019 Florianópolis, Brazil, 23rd-26th April).

O. Bernard was the head of the academic scientific committee for the AlgaeEurope conference (Paris, France, 3rd-5th December).

10.1.1.2. Special sessions

M. Chaves together with Laetitia Giraldi (from team McTao, Inria) organized an invited session at the Conf. Decision and Control (Nice, France).

J.-L. Gouzé organized an invited session about control and biology at the FGS Conference (Nice, France).

10.1.1.3. Member of the Organizing Committees

O. Bernard was in the organizing committee of the workshop "Growing microalgae for aquaculture in a Nordic climate : opportunities and challenges" (Trondheim, Norway, 28th-29th May).

10.1.2. Scientific Events: Selection

10.1.2.1. Member of the Conference Program Committees

O. Bernard is in the technical committee of the Computer Applied to Biotechnology (CAB) conferences, of the conference Foundations of Systems Biology in Engineering (FOSBE) and of the Algae Europe conference.

O. Bernard is area chair (Biosystems and Bioprocesses) for the IFAC World Conference (Berlin, Germany, 12nd-17th July).

M. Chaves was on the PC of the following conferences: JOBIM (Nantes, France), FOSBE (Valencia, Spain) , and CSBio (Nice, France).

J.-L. Gouzé is a member of the program committee for the International Conference on Positive Systems, and CSBio (Nice, France).

10.1.2.2. Reviewer

All BIOCORE members have been reviewers for the major 2019 conferences in our field: CDC, ECC, IFAC Congress, FOSBE,...

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

M. Chaves is an Associated Editor of SIAM Journal on Applied Dynamical Systems (SIADS), since January 2015.

S. Touzeau is an Academic Editor of PLOS ONE since August 2018.

10.1.3.2. Reviewer - Reviewing Activities

All BIOCORE members have been reviewers for the major journals in our field: Automatica, IEEE Transactions on Automatic Control, Journal of Mathematical Biology, Mathematical Biosciences, Algal Research, New Phytologist,...

10.1.4. Invited Talks

O. Bernard was invited to give a conference on microalgae at Ecole Centrale de Paris (“Biotechnological challenge”) “Use of microorganisms for biofuel production” (January, 16th, 2018).

O. Bernard was invited to give a conference at the workshop MADEV19, ("Mathématiques Appliquées à des questions de DEVeloppement ") (Dakar, November, 25th-27th).

O. Bernard was invited at the workshop "Control engineering concepts in systems- and synthetic biology" (Stavanger, Norway 20th-21st May).

P. Bernhard gave invited presentations at the “Rencontre interdisciplinaire: Théorie des jeux: concept mathématique et applications en économie”, University of Nice (November 2019).

M. Chaves gave a seminar on dynamics and feedback architectures in gene-metabolic pathways at the center for Modeling, Simulation and Interactions (MSI), Université Côte d’Azur (June 2019).

M. Chaves was invited to give a presentation at the Minisymposium on Modeling signal transduction/gene regulatory networks organized by T. Gedeon at the 9^{th} International Congress on Industrial and Applied Mathematics (Valencia, Spain, July 2019).

M. Chaves was invited to give a presentation at the Symposium on Modeling approaches for cancer therapy, at Université de Lille (PHLAM) (September 2019).

Jean-Luc Gouzé was invited to give presentations at Autrans (IBIS seminar), Ifremer Nantes, Inria Paris (Kaist seminar with South-Korea).

S. Touzeau was invited to present works of the EPITAG associate team at the AgriNumA’2019 Symposium on “Digital agriculture in Africa”, Dakar, Senegal (April 30th, 2019) [43].

10.1.5. Scientific Expertise

O. Bernard is a member of the scientific committee of the companies Inalve and BioEnTech.

M. Chaves was a member of the Selection Committee for a Maitre de Conference position at the Univ. Rennes.

J.-L. Gouzé was in several evaluation committees or juries: FWO, NWO, FNRS...

10.1.6. Research Administration

O. Bernard represents Inria at the ANCRE (Alliance Nationale de Coordination de la Recherche pour l’Energie).

O. Bernard is a member of the ADT (Technological Development Actions) commission at Inria.

M. Chaves is a member of the COST-GTRI (working group on International Relations at Inria’s council for scientific and technological orientation). The group is charged with evaluating Inria’s Associated Teams.

M. Chaves and W. Djema are members of the CLDD of Inria Sophia Antipolis (local committee for sustainable development).

M. Chaves is a member of the Education Board of the Master “Quantitative and Computational Sciences for Biomedical data”, Université Côte d’Azur.

J.-L. Gouzé is in the Inria committee supervising the doctoral theses, and a member of the scientific committee of Labex SIGNALIFE of the University of Nice-Sophia-Antipolis, and of COREBIO PACA. He is in the scientific committee of Académie 4 of UCA-Jedi. He is a member of the board of the SFBT (French Speaking Society for Theoretical Biology).

F. Grognard is a member of the NICE committee, which allocates post-doctoral grants and fundings for visiting scientists at Inria Sophia Antipolis.

Since 2015, F. Grognard is a member of the MBIA CSS (Specialised Scientific Commission), in charge of the research scientists evaluation at INRA. He is a member of the steering committee of Academy 3, Space, Environment, Risk & Resilience of UCA-JEDI. He is co-responsible of the development of the MSc Risk of UCA-JEDI.

L. Mailleret is the head of the M2P2 team (Models and Methods for Plant Protection) of ISA. He's in the Unit and scientific council of Institut Sophia Agrobiotech.

S. Touzeau is a member of the steering committee of the INRA metaprogramme on “Plant Health”, a follow-up of the SMaCH metaprogramme (since 2016).

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence: F. Grognard (45.5h ETD) and L. Mailleret (26h ETD), “Equations différentielles ordinaires et systèmes dynamiques”, L3, 1st year Engineering in Modeling and Applied Mathematics, Polytech Nice Sophia, Université Nice Sophia Antipolis, France.

Master: O. Bernard (4.5h ETD), “Bioenergy from microalgae”, M2, Master International Energy Management : alternatives pour l'énergie du futur, Ecole Nationale Supérieure des Mines de Paris, France.

Master: O. Bernard (18h ETD), “Modeling biotechnological processes”, M2, Ecole CentraleSupelec, Saclay, France.

Master: O. Bernard (18h ETD), “Automatic Control applied to biotechnological processes”, M2, Ecole CentraleSupelec, Saclay, France.

Master : J.-L. Gouzé (18h ETD), M. Chaves (12h ETD), “Modeling biological networks by ordinary differential equations”, M1, 2nd year Engineering in Génie biologique, Polytech Nice Sophia, Université Nice Sophia Antipolis, France.

Master: F. Grognard (21h ETD) and L. Mailleret (21h ETD), “Bio-Mathématiques”, M1, 2nd year Engineering in Modeling and Applied Mathematics, Polytech Nice Sophia, Université Nice Sophia Antipolis, France.

Master: F. Grognard (45h ETD), "Elements of mathematical modelling", M1, MSc in Environmental Hazards and Risks Management, Université Côte d'Azur, France.

Master: S. Touzeau (27h ETD), “Analyse de données”, M1, 2nd year Engineering in Génie biologique, Polytech Nice Sophia, Université Nice Sophia Antipolis, France.

10.2.2. Supervision

PhD: M. Haond. “Impact de la capacité de charge de l'environnement sur les dynamiques d'expansions de métapopulations. Théories et applications à un système expérimental hôte-parasitoïde”, 2015-2019, Université Côte d'Azur. Supervisors: E. Vercken (UMR ISA), L. Mailleret and L. Roques (UR BioSP). Defended on 03/26/2019.

PhD: C. Martinez von Dossow. “Modélisation, analyse et contrôle de la croissance microalgale en cultures à haute densité”, 13 May 2019, Sorbonne Université. Supervisors: O. Bernard, F. Mairet and A. Sciandra.

PhD: L. Gomes Pereira “Modeling cell response heterogeneity to pro-apoptotic ligands”, 26 November 2019, Univ. Côte d'Azur. Supervisors: M. Chaves and J. Roux (IRCAN, Nice).

PhD in progress: I. Tankam Chedjou. “Modeling, analysis and control of plantain plant-parasitic nematodes”, University of Yaoundé I, Cameroon, since December 2015. Supervisors: J.-J. Tewa (Univ. Yaoundé I), F. Grognard, L. Mailleret, S. Touzeau.

PhD in progress: L. Chambon. “Control of models of genetic regulatory networks”, since October 2016, Université Côte d'Azur. Supervisor J.-L. Gouzé.

PhD in progress: S. Nilusmas. “Gestion durable des nématodes à galles en cultures maraîchères : modélisation et optimisation du déploiement des résistances et des pratiques agronomiques”, Université Côte d'Azur, since December 2016. Supervisors: S. Touzeau, C. Caporalino (ISA), V. Calcagno (ISA) and L. Mailleret.

PhD in progress: Y. Fotso Fotso. "Modeling, analysis and control of coffee berry borers", University of Dschang, Cameroon, since January 2017. Supervisors: B. Tsanou (Univ. Dschang), S. Bowong (Univ. Douala), F. Grognard, S. Touzeau.

PhD in progress: M. Gachelin. "Selection pressure to improve lipid productivity of microalgae", since March 2017, UPMC. Supervisors: O. Bernard and A. Sciandra.

PhD in progress: E. Firippi. "Mathematical analysis, control design and coupling for models of biological oscillators", since October 2017, Univ. Côte d'Azur. Supervisors: M. Chaves.

PhD in progress: A. Yabo. "Control and optimal control of bacterial growth", since October 2018, Université Côte d'Azur. Supervisors J.-L. Gouzé and J.-B. Caillau (team McTao).

PhD in progress: A. Dos Reis de Souza. "Estimation and Control Methods for Microbial Communities", since October 2018, Université de Lille. Supervisors: J.-L. Gouzé and D. Efimov (team Valse, Inria Lille).

PhD in progress: B. Assis Pessi. "Modelling and Control of outdoor microalgal processes", since November 2019, Université Côte d'Azur. Supervisors: O. Bernard and L. Giraldi (team McTao).

PhD in progress: C. Djuikem. "Modelling and control of perennial plant phytopathogens", Université Côte d'Azur, since October 2019. Supervisors: F. Grognard, S. Touzeau, S. Bowong (Univ. Douala).

PhD in progress: M. Péré. "'Modeling cancer drug response heterogeneity using experimental tumor single-cell dynamics and transcriptomics', since October 2019, Univ. Côte d'Azur. Supervisors: M. Chaves and J. Roux (IRCAN, Nice).

10.2.3. Master thesis and internships

PFE: L. Guitou, EPU MAM, supervisors J.-L. Gouzé et V. Baldazzi.

M1: L. Guitou, EPU MAM, supervisors J.-L. Gouzé et V. Baldazzi.

M1: V. Tapissier, EPU MAM, supervisors J.-L. Gouzé et J. A. Sepulchre (UCA).

M2: L. Etienne. "Combinaison de microhabitats artificiels et de ressources alimentaires pour des acariens agents de lutte biologique", Université de Montpellier & Montpellier SupAgro, supervisors: C. Bresch (ISA), L. van Oudenhove (ISA) and L. Mailleret.

M2: B. Louis. "Modélisation individu-centrée pour optimiser l'introduction de populations et Applications en biologie de la conservation et lutte biologique". Université Côte d'Azur, supervisor: L. Mailleret.

M2: L. Plaza Alvarez, "Microalgae growth limited by light, nitrogen, and phosphorus". Universidad Técnica Federico Santa María, Valparaiso. Supervisors: C. Martinez von Dossow and O. Bernard.

Other: O. Bernard supervised a project involving 4 students from CentraleSupelec (first year of engineering school), 4 months, to design a system for microalgae growing under biofilm forms.

10.2.4. Juries

O. Bernard was referee for the jury of the PhD thesis of Angela La, "Process development for symbiotic culture of *Saccharomyces cerevisiae* and *Chlorella vulgaris* for in situ CO_2 mitigation". University Paris-Saclay (May, 22nd 2019).

M. Chaves was in the HDR jury of Eugenio Cinquemani as reviewer (November, Univ. Grenoble Alpes).

M. Chaves was in the PhD jurys of: Mohamed Ladjimi (as reviewer; September, Univ. Lille), Hugues Mandon (as examiner; November, Univ. Paris-Saclay), Luis Pereira (as advisor; November, Univ. Côte d'Azur).

J.-L. Gouzé was reviewer of the PhD thesis of Fatima-Zahra Tani, November, University of Montpellier.

10.3. Popularization

10.3.1. Articles and contents

- A popularization article has been published in the book " "Chimie verte et IAA - Vers une bioéconomie durable" [69].

10.3.2. Interventions

- O. Bernard gave two general public conferences on the topic “Will we drive cars powered by microalgae in 2030” (Saint Etienne de Tinée, 21st September and MAMAC, Nice, November, 13th).
- P. Bernhard did several interventions for a general audience in the Alpes-Maritimes (at Biot, Saint-Vallier and Sospel).
- L. Chambon participated in MASTIC activities in the school Emile Roux (5 June 2019).
- Several members of Biocore hosted schoolchildren to show them the team’s research topics.

10.3.3. Internal action

- M. Chaves gave a presentation at the local PhD Seminars organized by the students, on modeling the interactions between mammalian cell cycle and circadian clock.

11. Bibliography

Major publications by the team in recent years

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[4] V. Calcagno, F. Grognard, F. M. Hamelin, E. Wajnberg, L. Mailleret.*The functional response predicts the effect of resource distribution on the optimal movement rate of consumers*, in "Ecology Letters", December 2014, vol. 17, n° 12, p. 1570-1579 [*DOI :* 10.1111/ele.12379], https://hal.inria.fr/hal-01084299

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[9] C. POIGNARD, M. CHAVES, J.-L. GOUZÉ.*Periodic Oscillations for Non Monotonic Smooth Negative Feedback Circuits*, in "SIAM Journal on Applied Dynamical Systems", 2016, vol. 15, n^O^ 1, p. 257–286 [*DOI :* 10.1137/15M1033368], https://hal.archives-ouvertes.fr/hal-01242157

[10] L. TOURNIER, M. CHAVES.*Interconnection of asynchronous Boolean networks, asymptotic and transient dynamics*, in "Automatica", 2013, vol. 49, n^O^ 4, p. 884-893 [*DOI :* 10.1016/J.AUTOMATICA.2013.01.015,], http://hal.inria.fr/hal-00848450

Publications of the year

Doctoral Dissertations and Habilitation Theses

[11] L. G. PEREIRA.*Modeling cell response heterogeneity to pro-apoptotic ligands*, Université Côte d'Azur, November 2019

[12] C. M. VON DOSSOW.*Modélisation, analyse et contrôle de la croissance microalgale en cultures à haute densité*, Sorbonne Université, May 2019

Articles in International Peer-Reviewed Journal

[13] S. ALMEIDA, M. CHAVES, F. DELAUNAY.*Transcription-based circadian mechanism controls the duration of molecular clock states in response to signaling inputs*, in "Journal of Theoretical Biology", January 2020, vol. 484, 110015 [*DOI :* 10.1016/J.JTBI.2019.110015], https://hal.archives-ouvertes.fr/hal-02299359

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Project-Team BIOVISION

Biologically plausible Integrative mOdels of the Visual system : towards synergIstic Solutions for visually-Impaired people and artificial visiON

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Computational Neuroscience and Medicine

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1. Team, Visitors, External Collaborators

Research Scientists

Bruno Cessac [Team leader, Inria, Senior Researcher, HDR]
Aurelie Calabrèse [Inria, Starting Research Position, from Nov 2019]
Pierre Kornprobst [Inria, Senior Researcher, HDR]

External Collaborator

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Technical Staff

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2. Overall Objectives

2.1. Overall Objectives

Vision is a key function to sense the world and perform complex tasks. It has a high sensitivity and a strong reliability, given that most of its input is noisy, changing and ambiguous. Better understanding biological vision will have a strong scientific, medical, societal and technological impact in the near future. In this context, Biovision aims at developing fundamental research as well as technological transfer along two axes: (i) developing of high tech vision aid-systems for low-vision patients and (ii) modeling of the visual system for normal and distrophic conditions, targeting applications for low-vision and blind patients. These axes are developed in strong synergy, involving a large network of national and international collaborators with neuroscientists, physicians, and modellers.

3. Research Program

3.1. Introduction

The Biovision team has started on January 1st, 2016 and became an Equipe Projet Inria on August 1st, 2018 . It aims at developing fundamental research as well as technological developments along two axes.

3.1.1. Axis 1: High tech vision aid-systems for low-vision patients

Visual impairment, also known as vision loss, is a decreased ability to see to a degree that causes problems not fixable by usual means, such as glasses or lenses. Low-vision is a condition caused by eye disease, in which visual acuity is 20/70, meaning that the person is able to see, at 20 meters from a chart, what a normal person would see at 70 meters. Visual impairment affects some 285 million humans in the world, mostly in developed countries where this number is going to increase rapidly due to aging. 85% have low-vision or poorer. [0] There is a strong need to conceive new aid-systems to help these people in their daily living activities. Such systems already exist and can be divided into two categories according to their function. The first category concerns aids that translate visual information into alternative sensory information, such as touch or sound, called Sensory Substitution Devices (SSDs) [45], [40]. The second category concerns aids that adapt visual information to render it more visible to the patients, using scene processing methods and suitable devices. These are based on technological and algorithmic solutions that enhance salient scene characteristics [60], [56]. In Biovision team, we focus on this second category by targeting new vision aid-systems helping patients in their daily life, adapting to their own pathology.

We have strong contacts and collaborations with low-vision centers and associations in order to better understand low-vision patients needs, and have feedback on our prototypes aimed to be distributed to patients via transfer or company creation (startup). With the fast-growing number of incurable eye diseases, crucial steps must be taken to increase visual accessibility by:

- Designing solutions for earlier and more decisive detection of visual pathologies,
- Developing efficient rehabilitation protocols, and,
- Designing innovative vision-aid systems to empower patients with improved perceptual capacities.

To do this, we need to work in synergy with patients to assess their needs, understand their pathologies at a perceptual level and design personalized solutions to create change and adoption. This will require developing state-of-the-art methods in computer science, necessitating skills from many areas such as artificial intelligence, virtual and augmented reality, human-machine interface, multimedia systems, etc. By doing so, we will leverage new technologies to offer life-changing solutions for people with visual impairment [12], [15].

[0] Source: VisionAware

3.1.2. Axis 2: Human vision understanding through joint experimental and modeling studies, for normal and distrophic retinas

A holistic point of view is emerging in neuroscience where one can observe simultaneously how vision works at different levels of the hierarchy in the visual system. Multiple scales functional analysis and connectomics are also exploding in brain science, and studies of visual systems are upfront on this fast move. These integrated studies call for new classes of theoretical and integrated models where the goal is the modeling of visual functions such as motion integration.

In Biovision we contribute to a better understanding of the visual system with those main goals:

1. Proposing simplified mathematical models characterizing how the retina converts a visual scene into **spike population coding**, in normal and under specific pathological conditions.
2. Designing biophysical models allowing to better understand the **multiscale dynamics** of the retina, from dynamics of individual cells to their collective activity, and how changes in biophysical parameters (development, pharmacology, pathology) impacts this dynamics.
3. Elaborating an **integrated mathematical and numerical model** of the visual stream, with a focus on motion integration, from retina to early visual cortex (V1).
4. Developing a **simulation platform** emulating the retinal response to visual and prosthetic simulations, enabling us to test hypotheses about the functioning of the early visual system, in normal, pharmacological or pathological conditions.

Finally, although this is not the main goal of our team, two other natural avenues of our research are (i) to develop novel synergistic solutions to solve computer vision tasks based on bio-inspired mechanisms [7]; (ii) collaborate with neuroscientists and neuronal modellers to address mathematical problems outside the scope of the retina or the early visual system.

3.2. Scientific methodology

In this section we briefly describe the scientific methods we use to achieve our research goals.

3.2.1. Adaptive image enhancement

Image enhancement is a natural type of image processing method to help low-vision people better understand visual scenes. An impressive number of techniques have been developed in the fields of computer vision and computer graphics to manipulate image content for a variety of applications. Some of these methods have a direct interest in the design of vision aid-systems. Only a few of them have been carefully evaluated with patients [36], [49], [50], [41], [37]. Our objective is to further exploit and evaluate them with patients, considering dedicated use-cases, using virtual and augmented reality technology (Sec. 3.2.2). We consider not only classical brightness manipulations (e.g., equalization, gamma correction, tone mapping, edge enhancement, image decomposition and cartoonization) but also more sophisticated approaches which can change the geometric information of the scene to highlight the most relevant information (e.g., scene retargeting and seam carving). In addition, we investigate how image enhancements could be adapted to patients needs by relating tuning parameters to the patient pathology.

3.2.2. Virtual, mixed and augmented reality

Virtual, mixed and augmented reality technology (VR/MR/AR) is based on the idea of combining digital worlds with physical realities in different ways. It encompasses a wide spectrum of hardware. It is our conviction that this technology will play a major role in the domain of low-vision. Not only can this technology be useful to design novel vision aid-systems and rehabilitation programs, but also it has the potential to revolutionize how we study the behaviour of low-vision people (controlled condition, free head, eye tracking, possibilities for large scale studies). These projects require a constant interaction with psychophysicists and ophtalmologists so as to design our solutions based on patients needs and capabilities.

3.2.3. Biophysical modeling

Modeling in neuroscience has to cope with several competing objectives. On one hand, describing the biological realm as close as possible, and, on the other hand, providing tractable equations at least at the descriptive level (simulation, qualitative description) and, when possible, at the mathematical level (i.e., affording a rigorous description). These objectives are rarely achieved simultaneously and most of the time one has to make compromises. In the Biovision team we adopt the point of view of a physicist: try to capture the phenomenological description of a biophysical mechanism, removing irrelevant details in the description, and try to have a qualitative description of equations behaviour at least at the numerical simulation level, and, when possible, obtain analytical results. We insist on the quality of the model in predicting and proposing new experiments. This requires a constant interaction with neuroscientists so as to keep the model on the tracks, warning of too crude approximation, still trying to construct equations from canonical principles [1], [2], [6].

3.2.4. Methods from theoretical physics

Biophysical models mainly consist of differential equations (ODEs or PDEs) or integro-differential equations (neural fields). We study them using dynamical systems and bifurcation theory as well as techniques coming from nonlinear physics (amplitude equations, stability analysis, Lyapunov spectrum, correlation analysis, multi-scales methods) [23].

For the study of large scale populations (e.g., when studying population coding) we use methods coming from statistical physics. This branch of physics gave birth to mean-field methods as well statistical methods for large population analysis. We use both of them. Mean-field methods are applied for large scale activity in the retina and in the cortex [4], [8], [39].

For the study of retina population coding we use the so-called Gibbs distribution, initially introduced by Boltzmann and Gibbs. This concept includes, but *is not limited to*, maximum entropy models [55] used by numerous authors in the context of the retina (see, e.g., [57], [59], [52], [51], [61]). These papers were restricted to a statistical description without memory neither causality: the time correlations between successive times is not considered. However, maximum entropy extends to spatio-temporal correlations as we have shown in, e.g., [2] [62], [43]. In this context, we study how the retina respond to transient stimuli (moving objects), i.e. how spatio-temporal correlations are modified when a moving object crosses the receptive fields of ganglion cells, taking into account the lateral connectivity due to amacrine cells [42], [20], [11], [21].

4. Application Domains

4.1. Applications of virtual/augmented reality for low-vision

- **Rehabilitation**: Serious games are games designed for a primary purpose which is not pure entertainment. In our context, we think about serious games as a way to help low-vision patients in performing rehabilitation exercises. Virtual/augmented reality technology is a promising platform to develop such rehabilitation exercises targeted to specific pathologies. For example, with Age Macular Degeneration (AMD), our objective is to propose solutions allowing rehabilitation of visuo-perceptual-motor functions to optimally use residual portions of the peripheral retina and obtain efficient eccentric viewing.
- **Vision aid-systems**: A variety of aids for low-vision people are already on the market using different kinds of virtual/augmented reality platforms (dedicated or large public ones). They offer different functionalities (magnification, image enhancement, text to speech, face and object recognition). Our goal is to design new solutions allowing autonomous interaction in mixed reality environments, and take advantage of the improvement of functions obtained via rehabilitation protocols.
- **Cognitive research**: Virtual/augmented reality technology represents a new opportunity to conduct cognitive and behavioural research using virtual environments where all parameters can be psychophysically controlled. Our objective is to re-assess common theories by allowing patients to freely explore their environment in more ecological conditions.

4.2. Applications of vision modeling studies

- **Neuroscience research.** Making in-silico experiments is a way to reduce the experimental costs, to test hypotheses and design models, and to test algorithms. Our goal is to develop a large-scale simulations platform of impaired retinas, called Macular, allowing to mimic specific degeneracies or pharmacologically induced impairments, as well as to emulate electric stimulation by prostheses. In addition, the platform provides a realistic entry to models or simulators of the thalamus or the visual cortex, in contrast to the entries usually considered in modelling studies.
- **Education.** Macular is also targeted as a useful tool for educational purposes, illustrating for students how the retina works and responds to visual stimuli.

5. Highlights of the Year

5.1. Highlights of the Year

In November 2019, the Biovision project team recruited Dr. Aurelie Calabrèse as a “Starting Research Position” for a 3-year period. A. Calabrèse is a psychophysicist specialized in visual neuroscience with a strong clinical expertise. She has done extensive work on enhancing further the methods to detect and measure reading deficit in low-vision populations. She has extensive practice in experimenting with visually impaired individuals and will be a great asset to bridge the gap between development and validation of assistive technology solutions.

6. New Software and Platforms

6.1. Virtual Retina

A biological retina model with contrast gain control for large scale simulations

KEYWORDS: Neurosciences - Simulation - Biology - Health

SCIENTIFIC DESCRIPTION: Virtual Retina has a variety of biological features implemented such as (i) spatio-temporal linear filter implementing the basic center/surround organization of retinal filtering, (ii) non-linear contrast gain control mechanism providing instantaneous adaptation to the local level of contrast, (iii) spike generation by one or several layers of ganglion cells paving the visual field.

FUNCTIONAL DESCRIPTION: Virtual Retina is a simulation software that allows large-scale simulations of biologically-plausible retinas.

- Participants: Adrien Wohrer, Pierre Kornprobst, Bruno Cessac, Maria-Jose Escobar and Thierry Viéville
- Contact: Pierre Kornprobst
- Publication: Virtual Retina: A biological retina model and simulator, with contrast gain control
- URL: https://team.inria.fr/biovision/virtualretina/

6.2. PRANAS

Platform for Retinal ANalysis And Simulation

KEYWORDS: Retina - Neural Code - Data management - Statistics - Modeling - Vision

SCIENTIFIC DESCRIPTION: PRANAS was designed as a user-friendly tool dedicated to the neuroscientist community in a large sense, i.e., not only experienced computational neuroscientists. It has two main goals : (i) to analyze retina data, especially spatio-temporal correlations, at single cell but also population levels, (ii) to simulate the spike response of the retina to a visual flow with a customizable retina simulator which evolves in synergy with experimental data analysis. In general, PRANAS allows us to explore several aspects of retinal image processing such as understanding how to reproduce accurately the statistics of the spiking activity at the population level, or reconciling connectomics and simple computational rules for visual motion detection. This makes this tool a unique platform to better understand how the retina works.

FUNCTIONAL DESCRIPTION: The retina encodes a visual scene by trains of action potentials sent to the brain via the optic nerve. PRANAS brings to neuroscientists and modelers tools to better understand this coding. It integrates a retina simulator allowing large scale simulations while keeping a strong biological plausibility and a toolbox for the analysis of spike trains population statistics. The statistical method (entropy maximization under constraints) takes into account both spatial and temporal correlations as constraints, allowing to analyze the effects of memory on statistics. PRANAS also integrates a tool computing and representing in 3D (time-space) receptive fields. All these tools are accessible through a friendly graphical user interface. The most CPU-costly of them has been implemented to run in parallel. The actual version simulates healty retinas but the long term goal is to study retinas with a pathology (DMLA, Retinitis Pigmentosa, Glaucoma).

- Authors: Bruno Cessac, Pierre Kornprobst, Sélim Kraria, Hassan Nasser, Daniela Pamplona, Geoffrey Portelli and Adrien Wohrer
- Contact: Bruno Cessac
- Publication: PRANAS: A New Platform for Retinal Analysis and Simulation
- URL: https://team.inria.fr/biovision/pranas-software/

6.3. Platforms

6.3.1. Macular

Macular https://team.inria.fr/biovision/macular-software/ is a platform for the numerical simulation of the retina and primary visual cortex. It aims to reproduce the response of the retina to visual or electrical stimulation – produced by retinal prostheses – under normal or pathological conditions. The objective is to develop a tool that can be used by neuroscience researchers to reproduce experimental results, but also to guide their experiments through hypotheses that can be tested in the simulator. This can save a considerable amount of experimental resources. Macular is based on the central idea that its use and its graphic interface can evolve according to the objective of the user. It can be used in several cases, such as the simulation of retinal waves, the simulation of retinal and cortical responses to electrosurgical stimulation, the study of the contribution of specific classes of retinal cells in the encoding of visual scenes. Macular's modular architecture makes it flexible and makes it easy to implement new features. It also includes a scripting option, which offers the user the ability to decode his own model, with a given set of equations, variables and parameters, without having to program a code. Finally, thanks to a highly parallelizable architecture, Macular makes it possible to simulate a large number of cells of different classes (see Fig. 1).

7. New Results

7.1. High tech vision aid-systems for low-vision patients

7.1.1. Multilayered Analysis of Newspaper Structure and Design

Participants: Hui-Yin Wu, Pierre Kornprobst.

The understanding of newspaper document structure can help in the adaptation of text and visual content for different devices and media [53], as well as, in the context of low vision, to enhance accessibility by combining magnification and text-to-speech aids. However, automated segmentation of complex document structures like newspapers remains an ongoing challenge due its dense layout with numerous visual and textual design elements [38], [44].

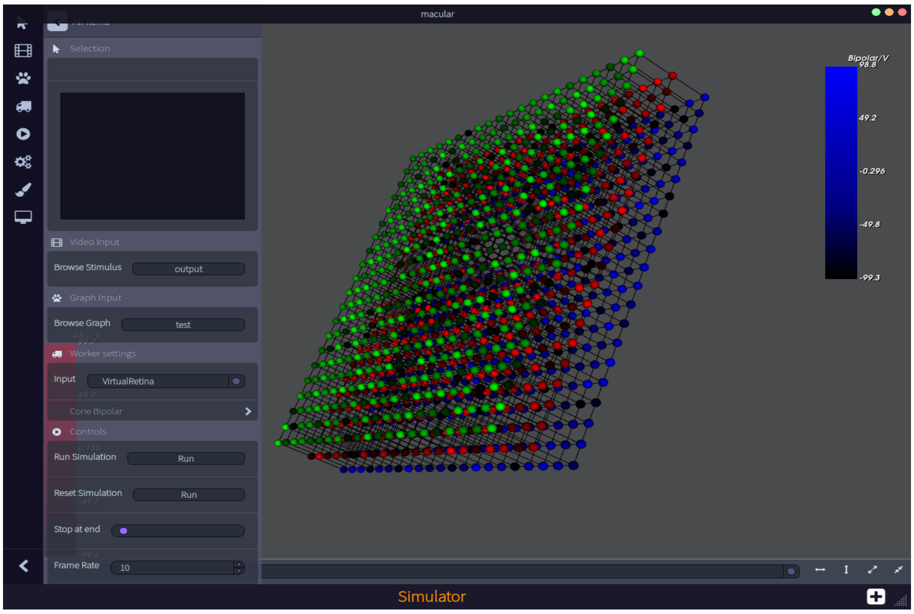

Figure 1. The Macular software. Here we see a three dimensional view of three retinal cells layers.

To address this challenge, we propose a multi-layered analysis of structure and design, presented in [27]. Taking images of newspaper front pages as input, our approach uses a combination of computer vision techniques to segment newspapers with complex layouts into meaningful blocks of varying degrees of granularity, and convolutional neural network (CNN) to classify each block. The final output presents a visualization of the various design elements present in the newspaper such as in Figure 2. Compared to previous approaches, our method introduces a much larger set of design-related labels (23 labels against less than 10 before) resulting in a very fine description of the pages, with high accuracy (83%), as shown in Figure 3.

This work is presented in [27].

7.1.2. Towards accessible news reading design in virtual reality for low vision

Participants: Hui-Yin Wu, Aurélie Calabrèse, Pierre Kornprobst.

Low-vision conditions resulting in partial loss of the visual field strongly affect patients' daily tasks and routines, and none more prominently than the ability to access text. Though vision aids such as magnifiers, digital screens, and text-to-speech devices can improve overall accessibility to text, news media, which is non-linear and has complex and volatile formatting, bars low-vision patients from easy access to essential news content [54].

Our aim is to position virtual reality as the next step towards accessible and enjoyable news reading for the low vision. Our ongoing work, which we present in [26], consists of an extensive review into existing research on low-vision reading technologies and accessibility for modern news media. From previous research and studies, we then conduct an analysis into the advantages of virtual reality for low-vision reading and propose comprehensive guidelines for visual accessibility design in virtual reality, with a focus on reading. This is coupled with a hands-on study of eight reading applications in virtual reality to evaluate how accessibility design is currently implemented in existing products. Finally, we present a framework that integrates the design principles resulting from our analysis and study, and implement a proof-of-concept for this framework

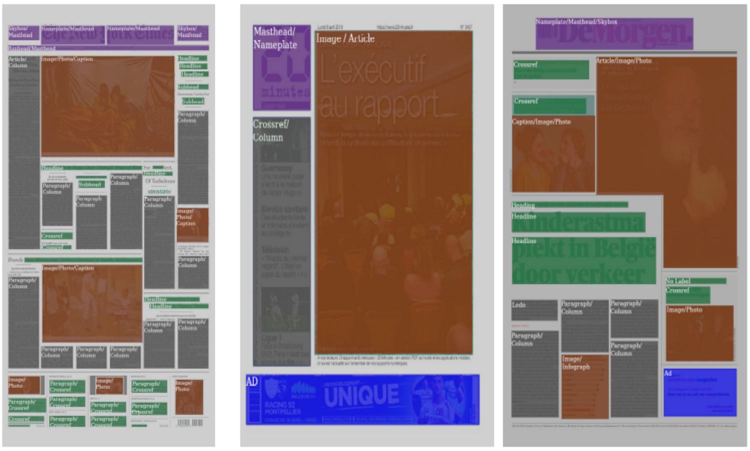

Figure 2. Visualization of the classification results on three different newspapers in our test set. Colors indicate primary categories as masthead elements (purple), text column (gray), ads (blue), images (brown) and minor text elements (green). Original images copyright of (from left to right) New York Times, 20 Minutes, and DeMorgan, courtesy of Newseum.

Group			Correct	F-neg	F-pos
Structural regions of the document	1A	ad	19	7	5
	1B	article	40	1	1
	1C	masthead	40	2	2
	1D	nameplate	14	0	9
	1E	textbox	22	2	7
Structural elements of each region	2A	column	60	6	0
	2B	image	35	1	3
	2C	paragraph	153	6	1
	2D	skybox	3	3	11
Various specific text	3A	authors	6	0	0
	3B	caption	11	3	1
	3C	crossref	83	3	0
	3D	headline	48	3	1
	3E	heading	86	4	3
	3F	invtext	8	3	3
	3G	lede	3	0	0
	3H	runhead	16	2	0
	3I	subhead	20	0	0
	3J	topline	0	0	1
Image categories	4A	barcode	4	1	0
	4B	graphic	1	3	0
	4C	infograph	1	0	0
	4D	photo	30	2	4

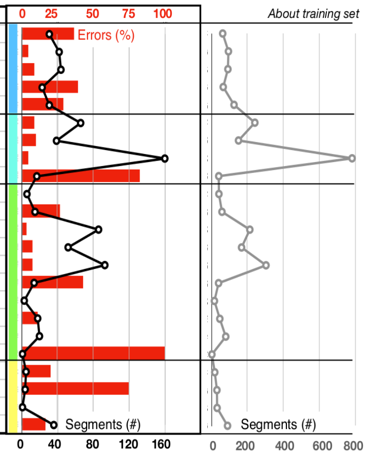

Figure 3. Classification result per categories. Results are presented in the table, showing the number of design elements that are correctly classified, false-negative (i.e. missing label), and false-positive (i.e. wrongly assigned label). Then a red chart shows the errors together with the number of segments (black line) used for the test dataset. To the right, the grey curve indicates the number of segments which were available in the training set.

using browser-based graphics (Figure 4 and 5) to demonstrate the feasibility of our proposal with modern virtual reality technology.

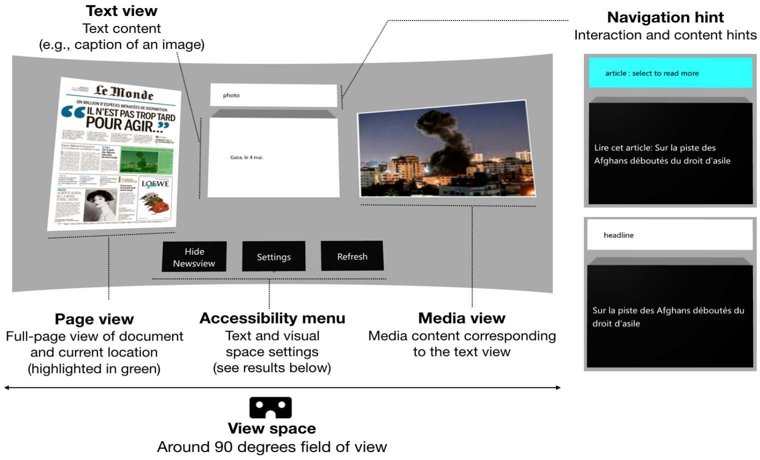

Figure 4. Application prototype: The global overview of the newspaper page is shown side-by-side with the enlarged text and images of the highlighted region. Navigation hints above the card show what type of content is displayed (e.g. photo, heading, paragraph) and whether the card can be selected (i.e. highlighted in light blue) to reveal further content. Text and images of the newspaper are purely for demonstrating a proof-of-concept. Excerpted from 7 May 2019 issue of ©Le Monde.

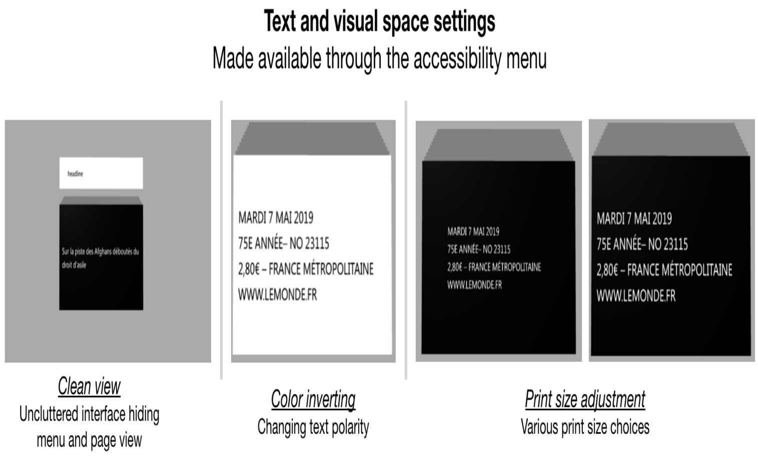

Figure 5. The accessibility menu provides a number of functions including (1) showing/hiding the page and menu view to personalize the view space, (2) invert foreground and background color only for text content, and (3) change the print size. Text on the cards excerpted from 7 May 2019 issue of ©Le Monde

This work is presented in [26].

7.2. Human vision understanding through joint experimental and modeling studies, for normal and distrophic vision

7.2.1. From micro- to macroscopic description of the retina

7.2.1.1. Retinal Waves

Participants: Dora Matzakos-Karvouniari [Laboratoire Jean-Alexandre Dieudonné, (LJAD), Nice, France], Bruno Cessac, Lionel Gil [Institut de Physique de Nice (InPhyNi), France].

Retinal waves are bursts of activity occurring spontaneously in the developing retina of vertebrate species, contributing to the shaping of the visual system organization: retina circuitry shaping, retinotopy, eye segregation [63], [47], [58], [48]. They stop a few weeks after birth. Wave activity begins in the early development, long before the retina is responsive to light. It was recently found that they can be reinitiated pharmacologically in the adult mammalian retina [46]. This could have deep consequences on therapy for several degenerative retinal diseases. The mechanism of their generation, in developing, or adult retinas, remains however incompletely understood [64].

We have proposed a model for stage II retinal waves - induced by bursting Starburst Amacrine Cells (SACs) coupled by acetylcholine - with two objectives: (i) being sufficiently close to biophysics to explain and propose experiments and (ii) affording a mathematical analysis [14], [34]. From a bifurcations analysis we have highlighted several relevant biophysical parameters controlling waves generation, mainly regulating potassium and calcium dynamics. We thus explain how SACs in different species exhibit a large variability in their bursting periods with a common mechanism.

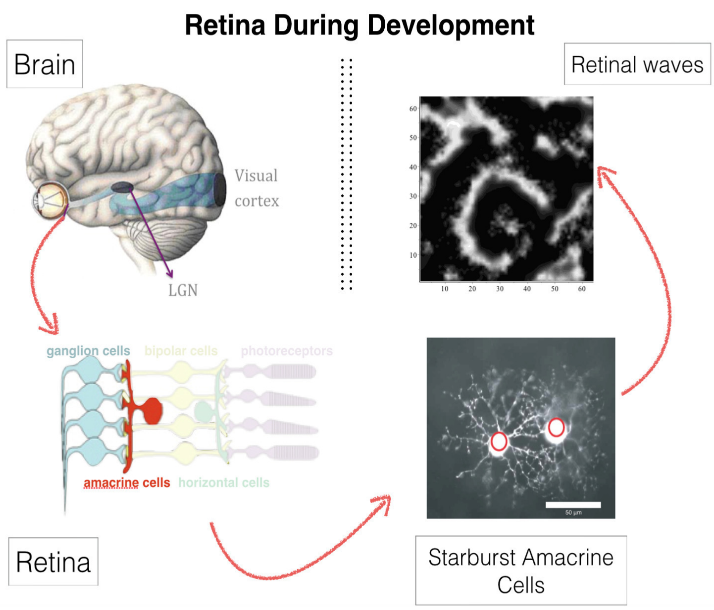

Figure 6. Top left. View of the human visual system. Bottom left. Right after birth the retina is not fully developed (shadowed parts). The retinal waves (top right) contributes to this development. They are mediated by specific cells (Starburst Amacrine Cells in stage II, bottom right).

Based on this biophysical model we have analysed here the dynamics of retinal waves and their statistics. We show that, despite the acetylcholine coupling intensity has been experimentally observed to change during development, SACs retinal waves can nevertheless stay in a regime with power law distributions, reminiscent of a critical regime. Thus, this regime occurs on a range of coupling parameters instead of a single point as in usual phase transitions. We explain this phenomenon thanks to a coherence-resonance mechanism, where noise is responsible for the broadening of the critical coupling strength range. This work has been presented in [14], [16], [25]

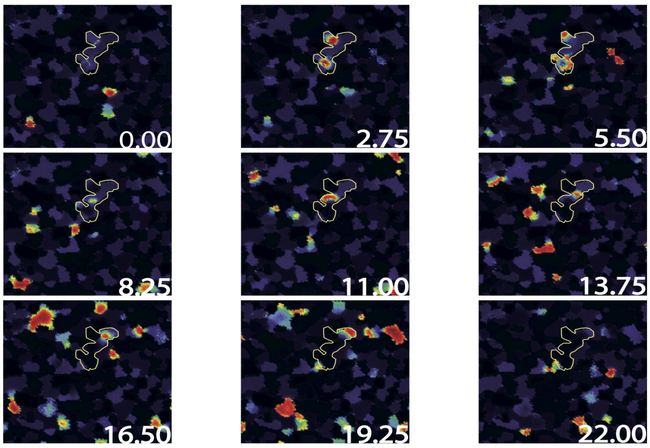

Figure 7. Example of the two dimensional time evolution of the calcium concentration C. Dark regions correspond to low calcium concentration while red corresponds to high concentration (wave). The time (in s) is displayed in the bottom right corner. The same thin white line in the center of each image, delimits a closed domain where wave propagates almost periodically. Hence, after the sequence shown above which correspond to a single period, a new one takes place a time later with a new wave following almost the same trajectory. The domain delimited by the white line is circled with high sAHP regions and therefore slowly evolves with time. A numerical movie is available on the website : https://www.youtube.com/watch?v=shMR3NMCBDE

7.2.1.2. Anticipation in the retina and the visual cortex V1

Participants: Bruno Cessac, Frédéric Chavane [Institut de Neurosciences de la Timone (CNRS and Aix-Marseille Université, France)], Alain Destexhe [Institute de Neuroscience Paris-Saclay (UNIC)], Sandrine Chemla [Institut de Neurosciences de la Timone (CNRS and Aix-Marseille Université, France)], Selma Souihel, Matteo Di Volo [Institute de Neuroscience Paris-Saclay (UNIC)].

This work has been done in the context of the ANR Trajectory and Selma Souihel Thesis [11].

Vision is initiated in the retina, where light is converted into electrical signals by photoreceptors, sent to bipolar cells then ganglion cells, generating spike trains. Visual information is then transmitted to the thalamus via the optic nerve which in turn transmits it to the visual cortex. The retinal processing alone takes time, up to 150 ms, not to mention the time lags introduced by synaptic transmissions between the three processing units. This shows that the existence of compensatory mechanisms to reduce processing delays is absolutely essential. These compensatory mechanisms are known as anticipation. Anticipation first occurs at the level of the retina and is further carried out by the primary visual cortex. In its first occurrence, anticipation is either characterized by a shift in the the peak response, or a short range wave of activation. In the second case, it is characterized by a wider range wave of activation.

The first contribution of this work is the development of a generalized 2D model of the retina, mimicking three types of ganglion cells : Fast OFF cells with gain control, direction selective cells with gap junction connectivity, and differential motion cells connected through an upstream amacrine circuit, able of anticipating different kinds of moving stimuli. The second contribution is to use our retina model as an input to a mean field cortical model to reproduce motion anticipation as observed in voltage sensitive dye imaging recordings. Throughout our work, we will study the effect of non linear phenomena involved in anticipation, as well as connectivity, both at the level of the retina and the primary visual cortex. The integrated retino-cortical model allowed us to study the effects of anticipation on two-dimensional stimuli, and to highlight the collaborative aspect of anticipation mechanisms in the retina and the cortex.

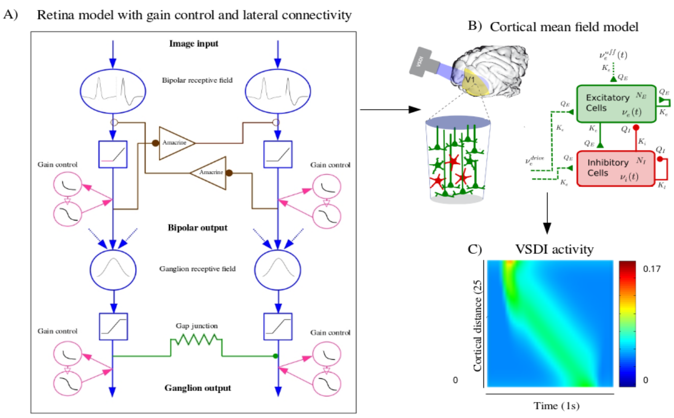

Figure 8. Schematic of our retino cortical model for anticipation. Left. Structure of the retinal model with 3 pathways: Blue: Gain control. Green: Gap junctions laterally connecting Ganglion Cells. Brown. Amacrine cells lateral connectivity. Right top. Cortical model (from Destexhe-Boustani 2009). Bottom. Simulation of VSDI activity in response to a moving bar.

This work has been presented in [17], [22], [20], [34], [21], [11]

7.2.1.3. Dynamical synapse in the retina

Participants: Bruno Cessac, Simone Ebert, Olivier Marre [Institut de la Vision (IdV), Paris, France], Romain Veltz [MathNeuro].

A very sophisticated example of the computations within the retina is observed when the visual system is exposed to a periodic stimulus, such as a regular series of flashes. If the retina would simply respond proportionally to the stimulus input, one might expect that ganglion cells would become entrained into aperiodic activity, responding to each flash. When the stimulus sequence ends,the activity would end as well. However, ganglion cells can exhibit various different kinds of response patterns to this form of stimulation shown in Figure 3. At the beginning of the stimulus, cells typically respond to the first flash of this new stimulus with a peak of activity, but then very rapidly decay in the amplitude of their response to the following flashes. Most remarkably, when the flash sequence ends ganglion cells do not just stop to respond, but in fact may generate a pulse of activity signalling the missing stimulus. This property of indicating a deviation from an expected pattern has been termed the Omitted Stimulus Response (OSR) (Schwartz, Harris, Shrom, Berry, 2007). The aim of this study was to implement and compare the two existing models of Omitted Stimulus Response in the retina, as well as exploring potential mechanisms that may be involved in generating it. Especially synaptic mechanisms may provide an explanation here, but the integration of such a mechanism into an OSR model has not been explored yet. A potential synaptic property that provides an interesting candidate to test here would be short-term plasticity (STP), which modulates synaptic efficacy depending on the previous activity in a short time interval (Blitz, Foster, Regehr, 2004). STP thus modulates signal transmission and a consecutive spike pattern and has been found to take place within the retina (Dunn, Rieke, 2008). Examining the models' underlying mechanisms, advantages and disadvantages as well as similarities and differences will provide a good foundation to modify existing models by adding potential mechanisms and exploring their effect on a ganglion cell response to a periodic stimulus. Ultimately, this may help shedding light on cellular properties in a neuronal circuit as of as few as 3 cells can contribute to already interpreting information from the environment.

This work has been presented in [32]. It has lead to experiments done in the Institut de la Vision by S. Ebert (internship Biovision) and O. Marre (Institut de la Vision (IdV), Paris, France) in November 2019.

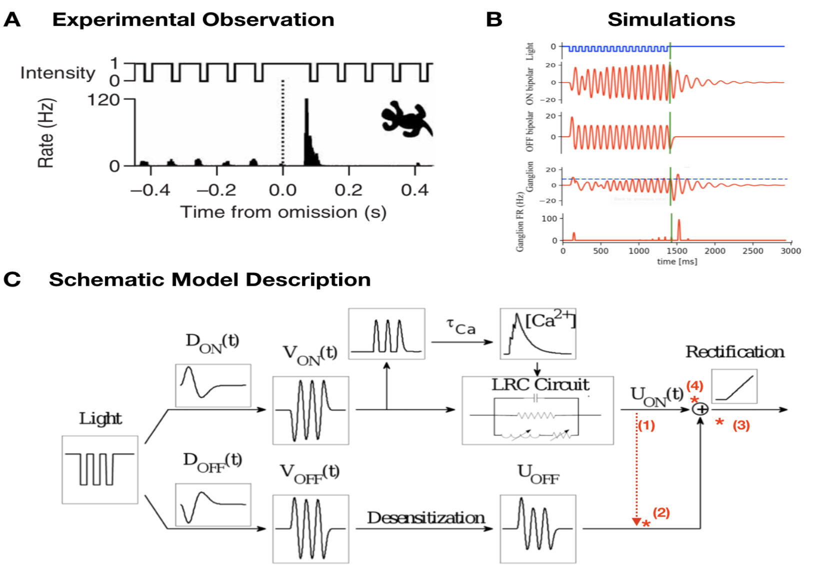

Figure 9. A. Experimentally observed Omitted Stimulus Response (OSR) to a periodic flash sequence. B. Simulations performed with an existing Model from Gao et al., 2009. C. Schematic description of the used 'Calcium-tuned Oscillator' Model from Gao et al., 2009. It is based on a feedforward circuit consisting of two different pathways with different intrinsic processing steps. Both pathways are combined to represent the synaptic input ganglion cells, who's activity with generate an Omitted Stimulus Response. Planned modifications planned are marked in red. (1) a presynaptic connection before summation of both pathways. (2),(3),(4) are synapses where short term synaptic plasticity could occur.

7.2.2. Numerical modelling of the retina in normal and pathological conditions

7.2.2.1. Probing retinal function with a multi-layered simulator

Participants: Bruno Cessac, Gerrit Hilgen [Institute of Neuroscience (ION), Newcastle, UK], Evgenia Kartsaki, Evelyne Sernagor [Institute of Neuroscience (ION), Newcastle, UK].

Our brain can recreate images from interpreting a stream of information emitted by one million parallel channels in the retina. This ability is partly due to the astonishing functional and anatomical diversity of the retinal ganglion cells (RGCs), each interpreting a different feature of the visual scene. How precisely this complexity is encoded in the spike trains produced by the population of RGCs is, however, largely unknown. Adding to the complexity, RGCs "speak" to each other during complex tasks (especially motion handling), via amacrine cells (ACs - lateral connectivity). To decipher their role, we study an experimental setting where neurons co-express the genes Grik4 or Scnn1a and excitatory or inhibitory DREADDs (Designer Receptors Exclusively Activated by Designer Drugs), activated by the designer drug CNO. Switching on or off RGCs and/or ACs cells may not only impact the RGCs individual response but also their concerted activity to different stimuli, thus allowing us to understand how they contribute to the encoding of complex visual scenes. However, it is difficult to distinguish on pure experimental grounds the effect of CNO when both cell types express DREADDs, as these cells "antagonise" each other. Contrarily, numerical simulation can afford it. Here, we propose a novel simulation platform that can reflect normal and impaired retinal function (from single-cell to large-scale level). It is able to handle different visual processing circuits and allows us to visualise responses to visual scenes (movies). In addition, the platform allows simulation of retinal responses when DREADD-expressing cell subclasses are either silenced or excited with CNO. To demonstrate how our simulator works, we deploy a circuit that handles motion on a large-scale level and study how the retina responds to visual scenes by visualising retinal processing at each level. The simulator also provides a tunable parameter to control the CNO effect (excitation or inhibition). Consequently, it facilitates the disentanglement of the effect of CNO on ACs and RGCs. Nevertheless, simulations and experiments are widely complementary. Experiments are necessary to constrain the numerical model and check its validity (especially, its predictions), while the computational approach affords to explore aspects that cannot be easily achieved experimentally.

This work has been presented in [24], [19], [33]

7.2.2.2. Simulating the cortical activity evoked by artificial retinal implants

Participants: Teva Andréoletti, Bruno Cessac, Frédéric Chavane [Institut de Neurosciences de la Timone (CNRS and Aix-Marseille Université, France)], Sébastien Roux [Institut de Neurosciences de la Timone (CNRS and Aix-Marseille Université, France)].

Recent advances in neuroscience and microelectronics opens up the possibility of partially restoring vision to blind patients using retinal prostheses. These are devices capturing the light of a visual scene and converting it to electric impulses sent by a matrix of electrodes chirurgically fixed on the retina. The simulation of an electrode elicits an activation in the visual cortex that evokes a percept similar to a light spot called phosphene. The joint stimulation of electrodes allows to reproduce simple shapes (letters, objects, stairs) and to restore a low resolution vision to blind people (see Fig 1). This domain of research is however at an early stage compared to cochlear implants. Especially, the way an electric stimulation activates the visual cortex is still poorly understood. The group of F. Chavane (NeOpTo team at INT Marseille) has used mesoscopic recordings of cortical activity (optical imaging) to better understand the activity evoked by stimulation of the retina with implanted multi electrodes arrays (Roux et al 2016 eLife). Their results show that local stimulation of the retina evoked a cortical activity that is up to 10 times larger than what is expected based on the activity evoked by visual stimuli. This result is in line with known poor resolutions of percepts evoked by stimulation of artificial retinas implanted in blind patients. This observed spread of evoked cortical activity is now better understood. An important effect, evidenced by Roux et al (2017) https://elifesciences.org/articles/12687 is the asymmetrical spread of electric activity induced by the direct activation of retinal cells axons away from their somata.

This effect can be modelled at the level of a single electrode with a significant match to experimental measurement. Retinal prostheses integrate hundreds of electrodes and this model can be used to anticipate the simultaneous activation of several electrodes reproducing the shape of an object (Fig 1). This figure has been produced by a retina simulator, called Macular, developed by the Biovision team at Inria, and aiming at reproducing the retina response to stimulation in normal (stimulation by light) and pathological conditions (electric stimulation by prostheses) https://team.inria.fr/biovision/macular-software/ . In a previous work https://hal.inria.fr/hal-02292831 [28], [29] we have been able to numerically model the effect of the static joint stimulation of electrodes in retina prostheses on the primary visual cortex (V1) and to compare it to normal vision.

This work has been presented in [28], [29]

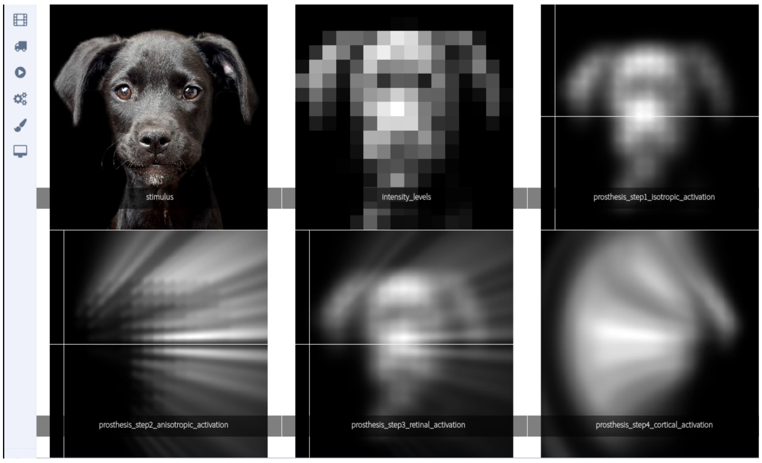

Figure 10. Simulation of the retinal and cortical response to a prosthesis simulation. An image (up-left) is digitalized into small squares (up-left). Each square corresponds to the degree of activation of a corresponding electrode in retinal implant (up-right). The electric stimulation activates neurones en passant of retinal cells leading to non linear diffusion (left bottom) and an effective stimulation pattern (down-middle) which is blurred in comparison to the expected stimulation pattern (up-right). The induced cortical representation is shown in the bottom-right figure.

7.3. Neuronal modelling

7.3.1. Linear response in neuronal networks: from neurons dynamics to collective responses

Participant: Bruno Cessac.

We have reviewed two examples where the linear response of a neuronal network submitted to an external stimulus can be derived explicitly, including network parameters dependence. This is done in a statistical physics-like approach where one associates to the spontaneous dynamics of the model a natural notion of Gibbs distribution inherited from ergodic theory or stochastic processes. These two examples are the Amari-Wilson-Cowan mode and a conductance based Integrate and Fire model

This work has been published in [13], [31], [18].

7.3.2. On the role of Nav1.7 sodium channels in chronic pain: an experimental and computational study

Participants: Lyle Armstrong [Institute of Neuroscience (ION), Newcastle, UK], Alberto Capurro [Institute of Neuroscience (ION), Newcastle, UK], Bruno Cessac, Jack Thornton [Institute of Neuroscience (ION), Newcastle, UK], Evelyne Sernagor [Institute of Neuroscience (ION), Newcastle, UK].

Chronic pain is a global healthcare problem with a huge societal impact. Its management remains generally unsatisfactory, with no single treatment clinically approved in most cases. In this study we use an in vitro model of erythromelalgia consisting of dorsal root ganglion neurons derived from human induced pluripotent stem cells obtained from a patient (carrying the mutation F1449V) and a control subject. We combine neurophysiology and computational modelling to focus on the Nav1.7 voltage gated sodium channel, which acts as an amplifier of the receptor potential in nociceptive neurons and plays a critical role in erythromelalgia due to gain of function mutations causing the channel to open with smaller depolarisations. Using extracellular recordings, we found that the scorpion toxin OD1 (a Nav1.7 channel opener) increases dorsal root ganglion cell excitability in cultures obtained from the control donor, evidenced by an increase in spontaneous discharges, firing rate and spike amplitude. In addition, we confirmed previous reports of voltage clamp experiments concerning an increase in spontaneous discharge in the patient cell cultures and the analgesic effects of the Nav1.7 blocker PF-05089771. Our findings are explained with a conductance-based model of the dorsal root ganglion neuron, exploring its behaviour for different values of half activation voltage and inactivation removal rate of the Nav1.7 current. Erythromelalgia was simulated through a decrease of the Nav1.7 half activation voltage, turning previously subthreshold stimuli to pain-inducing, and successfully counteracted with the channel blocker. The painful effects of OD1 were simulated through a quicker removal of Nav1.7 inactivation that reproduced the effects of the toxin not only on the spike frequency but also on its amplitude. This work has been submitted to J. Neuroscience. [30].

7.3.3. Ghost attractors in spontaneous brain activity: wandering in a repertoire of functionally relevant BOLD phaselocking solutions

Participants: Joana Cabral [Department of Psychiatry, Medical Sciences Division, University of Oxford,UK], Bruno Cessac, Gustavo Deco [Catalan Institute for Research and Advance Studies (ICREA), Spain], Morten L. Kringelbach [University of Oxford, UK], Jakube Vohryzek [Center for Music in the Brain, Department of Clinical Medicine, Aarhus University, Denmark].

Functionally relevant network patterns form transiently in brain activity during rest, where a given subset of brain areas exhibits temporally synchronized BOLD signals. To adequately assess the biophysical mechanisms governing intrinsic brain activity, a detailed characterization of the dynamical features of functional networks is needed from the experimental side to inform theoretical models. In this work, we use an open-source fMRI dataset from 100 unrelated participants from the Human Connectome Project and analyse whole-brain activity using Leading Eigenvector Dynamics Analysis, which focuses on the detection of recurrent phase-locking patterns in the BOLD signal. Borrowing tools from dynamical systems theory, we characterise spontaneous brain activity in the form of trajectories within a low-dimensional phase space. Decomposing the phase space into Voronoi-like cells using k-means clustering algorithm, we demonstrate that the cluster centroids (representing recurrent BOLD phase-locking patterns) closely overlap with previously identified resting-state networks. We further demonstrate that the metric associated with the phase-locking patterns shows moderate reliability across recordings indicating potential existence of subject specific dynamical landscapes. Our results point to the hypothesis that functional brain networks behave as ghost attractor states in a low-dimensional phase space, providing insights into the evolutionary rules governing brain activity in the spontaneous state and reinforcing the importance of addressing brain function within the framework of dynamical systems theory. This work has been submitted to Frontiers in Systems Neuroscience.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Helping visually impaired employees to follow presentations in the company: Towards a mixed reality solution

Participants: Riham Nehmeh [InriaTech], Carlos Zubiaga [InriaTech], Julia-Elizabeth Luna [InriaTech], Arnaud Mas [EDF], Alain Schmid [EDF], Aurélie Calabrèse, Pierre Kornprobst

Duration: 2 months

The objective of the work is to develop a first proof-of-concept (PoC) targeting a precise use-case scenario defined by EDF (contract with InriaTech, supervised by Pierre Kornprobst). The use-case is one of an employee with visual impairment willing to follow a presentation. The idea of the PoC is a vision-aid system based on a mixed-reality solution. This work aims at (1) estimating the feasibility and interest of such kind of solution and (2) identifying research questions that could be jointly addressed in a future partnership.

APP Deposit (on-going)

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

9.1.1.1. Trajectory

Title: Encoding and predicting motion trajectories in early visual networks

Programme: ANR

Duration: October 2015 - September 2020

Coordinator: Invibe Team, Institut des Neurosciences de la Timone, Frédéric Chavane,

Partners:

Institut de Neurosciences de la Timone (CNRS and Aix-Marseille Université, France)

Institut de la Vision (IdV), Paris, France

Universidad Tecnico Federico Santa María (Electronics Engineering Department, Valparaíso, Chile)

Inria contact: Bruno Cessac

Global motion processing is a major computational task of biological visual systems. When an object moves across the visual field, the sequence of visited positions is strongly correlated in space and time, forming a trajectory. These correlated images generate a sequence of local activation of the feed-forward stream. Local properties such as position, direction and orientation can be extracted at each time step by a feed-forward cascade of linear filters and static non-linearities. However such local, piecewise, analysis ignores the recent history of motion and faces several difficulties, such as systematic delays, ambiguous information processing (e.g., aperture and correspondence problems) high sensitivity to noise and segmentation problems when several objects are present. Indeed, two main aspects of visual processing have been largely ignored by the dominant, classical feed-forward scheme. First, natural inputs are often ambiguous, dynamic and non-stationary as, e.g., objects moving along complex trajectories. To process them, the visual system must segment them from the scene, estimate their position and direction over time and predict their future location and velocity. Second, each of these processing steps, from the retina to the highest cortical areas, is implemented by an intricate interplay of feed-forward, feedback and horizontal interactions. Thus, at each stage, a moving object will not only be processed locally, but also generate a lateral propagation of information. Despite decades of motion processing research, it is still unclear how the early visual system processes motion trajectories. We, among others, have proposed that anisotropic diffusion of motion information in retinotopic maps can contribute resolving many of these difficulties. Under this perspective, motion integration, anticipation and prediction would be jointly achieved through the interactions between feed-forward, lateral and feedback propagations within a common spatial reference frame, the retinotopic maps. Addressing this question is particularly challenging, as it requires to probe these sequences of events at multi-scale (from individual cells to large networks) and multiple stages (retina, primary visual cortex (V1)). “TRAJECTORY” proposes such an integrated approach. Using state-of-the-art micro- and mesoscopic recording techniques combined with modeling approaches, we aim at dissecting, for the first time, the population responses at two key stages of visual motion encoding: the retina and V1. Preliminary experiments and previous computational studies demonstrate the feasibility of our work. We plan three coordinated physiology and modeling work-packages aimed to explore two crucial early visual stages in order to answer the following questions: How is a translating bar represented and encoded within a hierarchy of visual networks and for which condition does it elicit anticipatory responses? How is visual processing shaped by the recent history of motion along a more or less predictable trajectory? How much processing happens in V1 as opposed to simply reflecting transformations occurring already in the retina? The project is timely because partners master new tools such as multi-electrode arrays and voltage-sensitive dye imaging for investigating the dynamics of neuronal populations covering a large segment of the motion trajectory, both in retina and V1. Second, it is strategic: motion trajectories are a fundamental aspect of visual processing that is also a technological obstacle in computer vision and neuroprostheses design. Third, this project is unique by proposing to jointly investigate retinal and V1 levels within a single experimental and theoretical framework. Lastly, it is mature being grounded on (i) preliminary data paving the way of the three different aims and (ii) a history of strong interactions between the different groups that have decided to join their efforts.

9.2. European Initiatives

9.2.1. Collaborations in European Programs, Except FP7 & H2020

- Program: Leverhulme Trust
- Project acronym:
- Project title: A novel approach to functional classification of retinal ganglion cells
- Duration: 2017-2020
- Coordinator: Evelyne Sernagor, Institute of Neuroscience (ION), Newcastle, UK
- Inria contact: Bruno Cessac
- Other partners:

  Melissa Bateson Institute of Neuroscience (ION), Newcastle, UK

  Matthias Hennig Institute for Adaptive and Neural Computation (ANC, School of Informatics University of Edinburgh, UK)

  Gerrit HilgenInstitute of Neuroscience (ION), Newcastle, UK
- Abstract: Vision begins with photoreceptors converting light from different parts of the visual scene into electrical signals, compressing our visual world into a parsimonious code of impulses at the retinal output level, the retinal ganglion cells (RGCs). This information is sent to the brain via only $\approx$1m RGCs (45,000 in mouse). Amazingly, the brain can recreate images from interpreting these "barcodes" or trains of impulses. This ability is partly due to the astonishing functional diversity of RGCs, each interpreting a different feature of the visual scene. It is all these parallel streams of information that impart the complexity of visual scenes to our brain visual areas. At present, at least 30 RGC subtypes have been identified. Classification is typically based on common anatomical features, or on basic functions (e.g. whether cells respond to the onset or offset of the light, or whether they are sensitive to motion direction) and it has recently progressed to include molecular markers. Recent studies have successfully characterised common physiological properties between RGCs sharing gene expression, suggesting that their molecular signature may indeed be a good indicator of function. However, according to mouse genetics repositories (e.g., the Allen Brain Project) many genes are expressed in subpopulations of RGCs for which we have no phenotype yet. Genes that are expressed in most RGCs probably do not reflect specific functional populations, but some other genes are expressed only in sparse RGC groups. Each gene-specific class exhibits a distinct spatial mosaic pattern across the retina, suggesting that the cells belong to a common group. Many classes, even sparse, exhibit asymmetric distributions across the retina, e.g., with larger numbers on the ventral or dorsal side, suggesting specific roles in ecological vision, e.g., specialised in detecting moving objects in the sky (ventral) or on the ground (dorsal).

  We propose to develop a multidisciplinary approach to functionally phenotype new RGC subclasses sharing gene expression. Rather than inferring knowledge about the entire population from studying individual cells, we will take a global approach based on large-scale, high-density pan-retinal recordings, pharmacogenetics (allowing us to selectively silence defined cell populations at will) and high-resolution imaging combined with computational approaches and behaviour. This novel approach necessitates collaboration between retinal neurophysiologists, animal behaviour specialists (Newcastle) and modellers (Inria) who specialise in visual processing and have sophisticated mathematical tools and software to handle and interpret the encoding of visual information at the pan-retinal level.

9.3. International Initiatives

9.3.1. Inria International Labs

Inria Chile

Associate Team involved in the International Lab:

9.3.1.1. MAGMA

Title: Modelling And understandinG Motion Anticipation in the retina

International Partner (Institution - Laboratory - Researcher):

Universidad Técnica Federico Santa Marı´a, Valparaiso (Chile) - Department of Electric Engineering - Maria-José Escobar

Start year: 2019

See also: https://team.inria.fr/biovision/associated-team-magma/.

Motion processing represents a fundamental visual computation ruling many visuomotor features such as motion anticipation which compensates the transmission delays between retina and cortex, and is fundamental for survival. We want to strengthen an existing collaborative network between the Universidad de Valparaiso in Chile and the Biovision team, gathering together skills related with physiological recording in the retina, data analysis numerical platforms and theoretical tools to implement functional and biophysical models aiming at understanding the mechanisms underlying anticipatory response and the predictive coding observed in the mammalian retina, with a special emphasis on the role of lateral connectivity (amacrine cells and gap junctions).

9.4. International Research Visitors

9.4.1. Visits of International Scientists

Helene Schreyer (University of Göttingen, Germany)

Dr Cyril Eleftheriou (IIT, Genova)

R. Cofré (Universidad Valparaíso, Chile).

9.4.1.1. Internships

- **September-November 2019 (M1).** Ignacio Ampuero, Université de Valparaiso.
- **March-August 2019 (M1).** Min-Toan Nguyen, Cycle Ingénieur Polytechnicien 3A. (co-direction with A. Muzy (I3S) et P. Reynaud-Bourret (LJAD)).
- **March-May 2019 (M1)** Safia Mensor, Master Mod4NeuCog (co-direction with A. Guyon (IPMC)) [35].
- **March-May 2019 (M1) et September 2019 - February 2020 (M2)** Simone Ebert, Master Mod4NeuCog (Co-direction with O. Marre Institut de la Vision (IdV), Paris, France et R. Veltz (Mathneuro)).
- **March-August 2019 (M2)** Téva Andreoletti, ENSEA Cergy.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events

- Bruno Cessac was a member of the Local Committee of the Conference NeuroFrance 2019 https://www.neurosciences.asso.fr/V2/colloques/SN19/ (22-24 May 2019) one of the most important congress organised by the Société des Neurosciences with 1260 registrations: researchers, medical doctors, students, industrials, from France and from 26 foreign countries.
- Bruno Cessac has co-organized the parallel topical meetings and plenary sessions "Nonlinear waves in biology" in the international conference "Waves Cote d'Azur" http://wavescotedazur.org/ Nice, France, 4-7 June 2019.
- Hui-Yin Wu was in the Program Chair of the 8th Eurographics Workshop on Intelligent Cinematography and Editing, Genoa, Italy
- Hui-Yin Wu was member of the conference program committees IEEE Conference on Games, London, UK
- Hui-Yin Wu was member of the 3rd Conference on Computing Systems and Applications, Algiers, Algeria
- Bruno Cessac has co-organized the 1st meeting of the NeuroMod Institute, Frejus, 1-2 july 2019

10.1.2. Scientific Events: Organisation

- MOMI 2019 (Le MOnde des Mathématiques Industrielles) was a two-day workshop on applied and industrial mathematics. The workshop took place on the 25th and 26th of February, 2019 at the Inria Sophia Antipolis-Mediteranée research center with a focus on Big Data and Machine Learning. It was supported and financed by Inria, by the Maison de la Modélisation, de la Simulation et des Interactions – MSI of Université Côte d'Azur, by the Graduate School "Digital Systems for Humans" (EUR project ANR-17-EURE-004 from the "Programme Investissements d'Avenir"), by the Agence pour les Mathématiques en Interaction avec l'Entreprise et la Société (AMIES) and by the companies OLEA Medical, Thales Alenia Space and Wildmoka. In total, 3 keynote speakers, 7 industrial speakers and 90 participants (researchers, PhDs , postdocs and engineers) attended MOMI 2019. Finally, a company fair was organized to promote networking and identify future opportunities and collaborations. Selma Souihel and Evgenia Kartsaki have actively participated to the organizing committee. Their duties involved writing funding proposals, budget handling, communication and traveling arrangements for the keynote speakers, company fair and social event organization.
- E. Kartsaki and S. Souihel are participating to the organization of the PhD Seminars of Inria Sophia Antipolis - Méditerranée, organized and held by PhD candidates every two weeks and aim to share knowledge, and to promote collaborations, all in a friendly and interactive way. Selma Souihel and Evgenia Kartsaki have been members of the organizing committee during the academic year 2018/2019 (Evgenia Kartsaki is still an ongoing member). Both have been involved in the scheduling, communication and diffusion of the seminars. These tasks include calls for presentations, calendar planning and promotion of each seminar. Finally, they were also involved in the organization of the MOMI 2019 conference.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

Pierre Kornprobst has been associate editor for the Computer Vision and Image Understanding Journal (CVIU) since Jul 2016.

10.1.3.2. Reviewer - Reviewing Activities

- A. Calabrèse has served as a peer-reviewer for the following international journals (IF):
  - Scientific Reports (4.644)
  - Investigative Ophthalmology and Vision Science (3.683)
  - PLoS ONE (3.344)
  - Acta Ophthalmologica (3.206)

  - Translational Vision Science and Technology (2.399)
  - Journal of Vision (2.141)
- Bruno Cessac has been reviewer for J. Math. Neuro (IF 2.091)
- Hui-Yin Wu has been reviewer for Multimedia Tools and Applications. (IF: 2.101)

10.1.4. Invited Talks

- E. Karstaki, The Rank Prize Funds - Symposium on The retinal processing of natural signals, Jun 2019, Grasmere, United Kingdom. Probing retinal function with a multi-layered simulator.
- E. Karstaki, First meeting of the NeuroMod Institute, Jul 2019, Fréjus, France. Probing retinal function with a multi-layered simulator.
- B. Cessac, D. Karvouniari, L. Gil, O. Marre,, Multiscale dynamics in retinal waves,LACONEU 2019 Conference, Valparaiso, Chile, January 18th, 2019.
- B. Cessac, S. Souihel, "Anticipation in the retina and the primary visual cortex : towards an integrated retino-cortical model for motion processing", Workshop on Visuo-motor Integration, EITN, Paris, 6-7 Jun 2019. https://visuomotor.sciencesconf.org/.
- B. Cessac, M. Mantegazza (IPMC) "Modelling of physiological and pathological states in neuroscience: exchanges among theoreticians and experimentalists", First meeting of the NeuroMod Institute 1-2 July 2019, Fréjus.
- B. Cessac, S. Souihel,"Motion anticipation in the retina", Neurostic Conférence, Sophia Antipolis, 14-15 October 2019, http://www.gdr-isis.fr/neurostic/?p=452.
- Hui-Yin Wu, "Thinking Like a Director: Film Editing Patterns for Virtual Cinematographic Storytelling", 8th Eurographics Workshop on Intelligent Cinematography and Editing, Genoa, Italy. May 2019.
- Hui-Yin Wu, "Interactive and Multimedia Storytelling", PhD Seminars, UCA Inria. November 2019.

10.1.5. Research Administration

Bruno Cessac is a member of the scientific council of the Institut NeuroMod de "Modélisation en Neurosciences et Cognition".

Bruno Cessac is a member of the "Bureau" of the Institut NeuroMod de "Modélisation en Neurosciences et Cognition".

Bruno Cessac was a member of the Groupe de Travail for the creation of the Inria project team FACTAS.

Bruno Cessac was a member of the Groupe de Travail for the creation of the Inria project team ATLANTIS.

Pierre Kornprobst has been an elected member of the Academic Board of UCA (*Conseil Académique*, from Nov. 2015 to Aug. 2019).

Pierre Kornprobst has been a member of the Comité de Suivi Doctoral (CSD) since March 2017.

Pierre Kornprobst has been an elected member of the Academic Council of UCA (*Conseil d'Administration*, since Dec. 2019).

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence :

- Selma Souihel "Advanced network administration and security: architecture of a company network, services installation and configuration, users management, system and network security, cryptography, virtual private networks and secured protocols, and supervision tools, Numeric transmission : data acquisition, satellite and cable transmission, numeric modulation", 1ere année de l'IUT, Département Réseaux et Télécommunications, 64h/year, 50 students.

Master 1: Bruno Cessac (with F. Lavigne), *Introduction to Modelling in Neuroscience*, 40 hours, Master Mod4NeuCog, Université Nice Sophia Antipolis, France.

10.2.2. Supervision

- PhD defended on December 18th, 2019. Selma Souihel, "Generic and specific computational principles for the visual anticipation of motion trajectories". Started in November 2016. Supervisor B. Cessac
- PhD in progress: Evgenia Kartsaki. "How Specific Classes of Retinal Cells Contribute to Vision: a Computational Model", Started in October 2017. Supervisor B. Cessac codirection with E. Sernagor, ION.

10.2.3. Juries

Pierre Kornprobst was member of the Comité de suivi de thèse of Alexandre Montlibert, from CERCO, Toulouse, France.

Pierre Kornprobst was reviewer of the PhD of Erwan David, entitled “L’impact des troubles du champ visuel sur les dynamiques spatio-temporelles de l’observation de sce`nes naturelles”, from Université de Nantes, France.

Bruno Cessac was member of the Comité de suivi de thèse of Matthieu Sarazin from Paris VI and Halgurd Taher from EDSFA Nice.

11. Bibliography

Major publications by the team in recent years

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Publications of the year

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Project-Team CAMIN

Control of Artificial Movement & Intuitive Neuroprosthesis

IN COLLABORATION WITH: Laboratoire d'informatique, de robotique et de microélectronique de Montpellier (LIRMM)

IN PARTNERSHIP WITH:
Université de Montpellier

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Computational Neuroscience and Medicine

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Project-Team CAMIN

Creation of the Team: 2016 January 01, updated into Project-Team: 2019 March 01

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A1.3. - Distributed Systems
A2.3. - Embedded and cyber-physical systems
A2.5.2. - Component-based Design
A4.4. - Security of equipment and software
A4.5. - Formal methods for security
A5.1.4. - Brain-computer interfaces, physiological computing
A6.1.1. - Continuous Modeling (PDE, ODE)
A6.3.2. - Data assimilation
A6.4.1. - Deterministic control

Other Research Topics and Application Domains:

B1.2.1. - Understanding and simulation of the brain and the nervous system
B2.2.1. - Cardiovascular and respiratory diseases
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B2.2.6. - Neurodegenerative diseases
B2.5.1. - Sensorimotor disabilities
B2.5.3. - Assistance for elderly

1. Team, Visitors, External Collaborators

Research Scientists

Christine Azevedo Coste [Team leader, Inria, Senior Researcher, HDR]
François Bonnetblanc [Inria, Researcher, HDR]
Charles Fattal [CRRF La Châtaigneraie, Researcher, Médecin-chef, HDR]
David Guiraud [Inria, Senior Researcher, HDR]
Daniel Simon [Inria, Researcher, HDR]

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Sofiane Ramdani [Univ de Montpellier]

Technical Staff

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Ronan Le Guillou [Inria, Engineer]
Guillaume Souquet [Univ de Montpellier, Engineer]

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Anthony Boyer [Univ de Montpellier, PhD Student, until Aug 2019]
Vincent Iampietro [Univ de Montpellier, PhD Student]
Xinyue Lu [ATROTECH, PhD Student]
Victor Vagné [CIFRE ARNGDC, PhD Student, until Sep 2019]
Lucie William [Inria, PhD Student, from Oct 2019]

Post-Doctoral Fellows
Lucas Oliveira Da Fonseca [Inria, Post-Doctoral Fellow, from Sep 2019]
Martin Schmoll [Univ de Montpellier, Post-Doctoral Fellow, from Jun 2019]

Visiting Scientists
Emerson Fachin Martins [Universty of Brasilia, until Feb 2019]
Henrique Resende Martins [University of Mina Gerais, until Feb 2019]

Administrative Assistant
Annie Aliaga [Inria, Administrative Assistant]

2. Overall Objectives

2.1. Overall Objectives

CAMIN research team is dedicated to the **design and development of realistic neuroprosthetic solutions for sensorimotor deficiencies** in collaboration with clinical partners. Our efforts are focused on clinical impact: improving the functional evaluation and/or quality of life of patients. Movement is at the center of our investigative activity, and the **exploration and understanding of the origins and control of movement** are one of our two main research priorities. Indeed, optimizing the neuroprosthetic solutions depends on a deeper understanding of the roles of the central and peripheral nervous systems in motion control. The second research priority is **movement assistance and/or restoration**. Based on the results from our first research focus, neuroprosthetic approaches are deployed (Figure 1).

Electrical stimulation (ES) is used to activate muscle contractions by recruiting muscle fibers, just as the action potentials initiated in motoneurons would normally do. When a nerve is stimulated, both afferent (sensitive) and efferent (motor) pathways are excited. ES can be applied externally using surface electrodes positioned on the skin over the nerves/muscles intended to be activated or by implantation with electrodes positioned at the contact with the nerves/muscles or neural structures (brain and spinal cord). ES is the only way to restore movement in many situations.

Yet although this technique has been known for decades, substantial challenges remain, including: (i) detecting and reducing the increased early fatigue induced by artificial recruitment, (ii) finding solutions to nonselective stimulation, which may elicit undesired effects, and (iii) allowing for complex amplitude and time modulations of ES in order to produce complex system responses (synergies, coordinated movements, meaningful sensory feedback, high-level autonomic function control).

We investigate functional restoration, as either a **neurological rehabilitation solution** (incomplete SCI, hemiplegia) or for **permanent assistance** (complete SCI). Each of these contexts imposed its own set of constraints on the development of solutions.

Functional ES (FES) rehabilitation mainly involves external FES, with the objective to increase neurological recuperation by activating muscle contractions and stimulating both efferent and afferent pathways. Our work in this area naturally led us to take an increasing interest in brain organization and plasticity, as well as central nervous system (brain, spinal cord) responses to ES. When the objective of FES is a permanent assistive aid, invasive solutions can be deployed. We pilot several animal studies to investigate neurophysiological responses to ES and validate models. We also apply some of our technological developments in the context of human per-operative surgery, including motor and sensory ES.

CAMIN research is focused on **exploring and understanding human movement** in order to propose neuroprosthetic solutions in sensorimotor deficiency situations to **assist or restore movement**. Exploration and understanding of human movement will allow us to propose assessment approaches and tools for diagnosis and evaluation purposes, as well as to improve FES-based solutions for functional assistance.

We have chosen not to restrict our investigation spectrum to specific applications but rather to deploy our general approach to a variety of clinical applications in collaboration with our medical partners. **Our motivation and ambition is to have an effective clinical impact**.

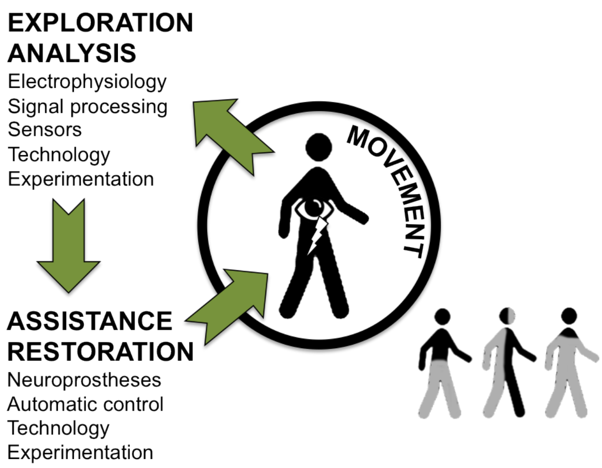

Figure 1. Overview of CAMIN *general scientific approach.*

3. Research Program

3.1. Exploration and understanding of the origins and control of movement

One of CAMIN's areas of expertise is **motion measurement, observation and modeling** in the context of **sensorimotor deficiencies**. The team has the capacity to design advanced protocols to explore motor control mechanisms in more or less invasive conditions in both animal and human.

Human movement can be assessed by several noninvasive means, from motion observation (MOCAP, IMU) to electrophysiological measurements (afferent ENG, EMG, see below). Our general approach is to develop solutions that are realistic in terms of clinical or home use by clinical staff and/or patients for diagnosis and assessment purposes. In doing so, we try to gain a better understanding of motor control mechanisms, including deficient ones, which in turn will give us greater insight into the basics of human motor control. Our ultimate goal is to optimally match a neuroprosthesis to the targeted sensorimotor deficiency.

The team is involved in research projects including:

- Peripheral nervous system (PNS) exploration, modeling and electrophysiology techniques
  Electroneurography (ENG) and electromyography (EMG) signals inform about neural and muscular activities. The team investigates both natural and evoked ENG/EMG through advanced and dedicated signal processing methods. Evoked responses to ES are very precious information for understanding neurophysiological mechanisms, as both the input (ES) and the output (evoked EMG/ENG) are controlled. CAMIN has the expertise to perform animal experiments (rabbits, rats, earthworms and big animals with partners), design hardware and software setups to stimulate and record in harsh conditions, process signals, analyze results and develop models of the observed mechanisms. Experimental surgery is mandatory in our research prior to invasive interventions in humans. It allows us to validate our protocols from theoretical, practical and technical aspects.
- Central nervous system (CNS) exploration

Stimulating the CNS directly instead of nerves allows activation of the neural networks responsible for generating functions. Once again, if selectivity is achieved the number of implanted electrodes and cables would be reduced, as would the energy demand. We have investigated **spinal electrical stimulation** in animals (pigs) for urinary track and lower limb function management. This work is very important in terms of both future applications and the increase in knowledge about spinal circuitry. The challenges are technical, experimental and theoretical, and the preliminary results have enabled us to test some selectivity modalities through matrix electrode stimulation. This research area will be further intensified in the future as one of ways to improve neuroprosthetic solutions.
We intend to gain a better understanding of the electrophysiological effects of DES through electroencephalographic (EEG) and electrocorticographic (ECoG) recordings in order to optimize anatomo-functional brain mapping, better understand brain dynamics and plasticity, and improve surgical planning, rehabilitation, and the quality of life of patients.

- Muscle models and fatigue exploration
  Muscle fatigue is one of the major limitations in all FES studies. Simply, the muscle torque varies over time even when the same stimulation pattern is applied. As there is also muscle recovery when there is a rest between stimulations, modeling the fatigue is almost an impossible task. Therefore, it is essential to monitor the muscle state and assess the expected muscle response by FES to improve the current FES system in the direction of greater adaptive force/torque control in the presence of muscle fatigue.
- Movement interpretation
  We intend to develop ambulatory solutions to allow ecological observation. We have extensively investigated the possibility of using inertial measurement units (IMUs) within body area networks to observe movement and assess posture and gait variables. We have also proposed extracting gait parameters like stride length and foot-ground clearance for evaluation and diagnosis purposes.

3.2. Movement assistance and/or restoration

The challenges in movement restoration are: (i) improving nerve/muscle stimulation modalities and efficiency and (ii) global management of the function that is being restored in interaction with the rest of the body under voluntary control. For this, both local (muscle) and global (function) controls have to be considered.
Online modulation of ES parameters in the context of lower limb functional assistance requires the availability of information about the ongoing movement. Different levels of complexity can be considered, going from simple open-loop to complex control laws (Figure 2).

Real-time adaptation of the stimulation patterns is an important challenge in most of the clinical applications we consider. The modulation of ES parameters to adapt to the occurrence of muscular fatigue or to environement changes needs for advanced adaptive controllers based on sensory information. A special care in minimizing the number of sensors and their impact on patient motion should be taken.

3.3. On-going clinical protocols

One specificity of CAMIN team is to be involved in Clinical protocols. At the moment we are involved in the following protocols:

- CYCLOSEF: Training spinal cord injured people pedaling a tricycle assisted by electric stimulation of sublesional muscles: case study - Protocol RCB 2019-A00808-49. CRF La Châtaigneraie.
- AGILIS - Functional evaluation of the recovery of prehension in quadriplegics by implanted neural stimulation - Protocol RCB 2019-A02037-50. APHP (Paris)
- E-PREHENSTROKE - Evaluation of optimal piloting modalities and their impact on the grasping capacity in Functional Electrical Stimulation of Finger Extensor Muscles in the Hemiplegic Patient in Chronic Phase - Protocol RCB 2018-A02144-51. CHU Nîmes.
- PBREATHLOOP - Recording tracheal sounds for the purpose of developing a breath control algorithm - Protocol RCB 2019-A01813-54. ADOREPS

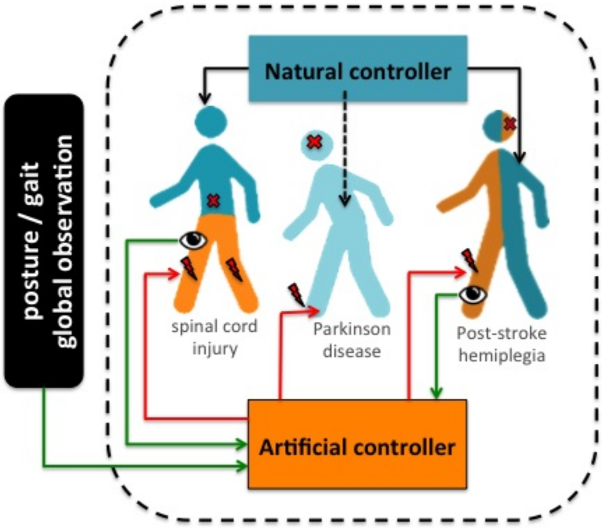

Figure 2. FES assistance should take into account the coexistence of artificial and natural controllers. Artificial controllers should integrate both global (posture/gait) and local (limb/joint) observations.

- Variability and evolution of the single fiber potentials of a spastic muscle treated with botulinum toxin - Protocol RCB 2019-A01863-52A. CHU Nîmes
- Pilot study: measurement of evoked potentials in electroencephalography and electrocorticography by electrical stimulation of the brain during awake neuro-surgery of low-grade infiltrating gliomas - Protocol RCB 2014-A00056-43. CHU Montpellier

4. Highlights of the Year

4.1. Highlights of the Year

4.1.1. Awards

Student Paper price: X. Lu, D. Guiraud, S. Renaux, T. Similowski, C. Azevedo-Coste, "Monitoring phrenic nerve stimulation-induced breathing via tracheal sounds", the 58th International Spinal Cord Society Annual Scientific Meeting (ISCoS), Nice, France, 2019
Student Paper competition Finalist: L. Fonseca, A. Bo, D. Guiraud, B. Navarro, A. Gelis and C. Azevedo-Coste, "Investigating Upper Limb Movement Classification on Users with Tetraplegia as a Possible Neuro-prosthesis Interface," 2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Honolulu, USA, 2018, pp. 5053-5056.

5. New Software and Platforms

5.1. RT_Stim

Real-Time simulation for functional electrical Stimulation

KEYWORDS: Real time - Biomechanics - Control - Co-simulation

FUNCTIONAL DESCRIPTION: Hybrid simulation architecture gathering in a single framework and consistent time scales both the numerical integration of the continuous model of a bio-mechanical system (bones, joints and muscles) and a model of the hardware and software control architecture, including control tasks, communication protocols and real-time schedulers. Simulation run in real-time when possible, and otherwise consistent time scales are generated. The framework is intended to seamlessly evolve from purely software models to hardware-in-the-loop simulation.

- Authors: Daniel Simon and Samy Lafnoune
- Contact: Daniel Simon
- URL: https://gforge.inria.fr/projects/rtstim/trunk

5.2. Platforms

5.2.1. Platform : IMUSEF Modular embedded architecture for real time control of a FES system

Participants: Christine Azevedo Coste, Benoît Sijobert, Ronan Le Guillou, Martin Schmoll.

We have been working on the development of a new hardware and software architecture embedding a network of sensors and an electrical stimulator interfaced to a controller. The controller intends to be worn by the experiment participants.
A mini low-cost single board computer (Raspberry Pi3) was embedded in a 3D-printed case strapped around the waist of the subject. Using wireless inertial sensors connected as a WBAN, the sink node gets data from all the IMUs, therefore highly decreasing data flow when multiple IMUs are transmitting inside the network. To get rid of this limitation and guarantee an overall 100 Hz sampling rate no matter the number of IMUs, the wireless inertial sensors can be replaced by wired ones, low-cost with a high speed ARM Cortex-M0 based processor and a Kalman Filter directly providing quaternion estimation at 100 Hz for each IMU. The use of a multiplexer connected through an I2C interface (Inter Integrated Circuit) enabled to keep a 100 Hz rate using 4 IMUs.
The autonomous FES controller is able to acquire and process data, execute control algorithms and send the appropriate command to the stimulator. For safety reasons, in order to access to the FES controller and to enable a remote access to the stimulation from a computer, an ad-hoc Wi-Fi network is automatically provided by the Raspberry on start-up. The ad-hoc network enables to be independent from a network infrastructure where the connection is not always possible (e.g. Wi-Fi network from the hospital).

This scalable architecture (fig. 3), developed as a modular system, allowed us to implement new commands laws for Real Time closed loop control as well as giving us the possibility to use various types of sensors and stimulators to meet the needs of specific applications. To achieve this and in order for the FES architecture to directly control different electrical stimulators, Application Programming Interfaces (APIs) were developed for 3 main commercial stimulators in the team. They each corresponds to a specific need and use case. The Vivaltis Phoenix Stimulator allows for low-weight embedding, wireless network control, but only 2 stimulation channels are available at the moment, while being scalable, it is mainly used for experiments on gait. The BerkelBike Stimulator v2.0 presents a cumbersome but extended control compromise with 8 independent stimulation channels, which is an ideal solution for FES-assisted cycling. And finally the Hasomed Rehastim v1.0 allowing fine control but isn't battery powered in its commercial version, used mainly for upper limb experiments.

This new architecture is currently used in clinical experiments and will continue to evolve with a goal of being easy to use, even by untrained clinicians (i.e. FES assisted cycling §6.8).

The software APP of this platform can be found at https://bil.inria.fr/fr/software/view/3520/tab as the *IMUSEF Project* with the Bil Id: Software_3520.

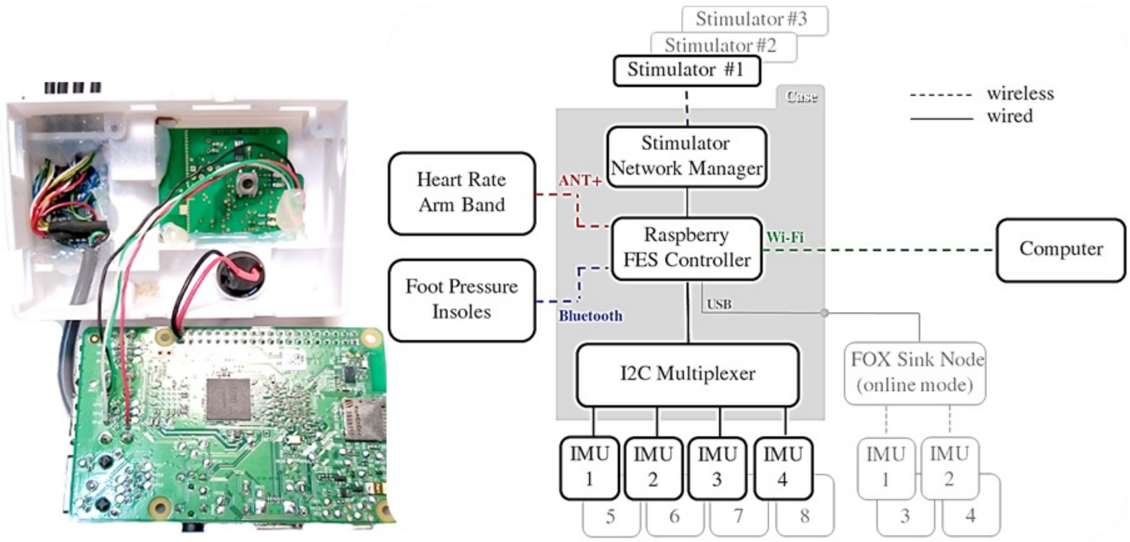

Figure 3. Experimental protocols have led to the development of a scalable hardware architecture decentralized on the subject.

5.2.2. Platform : FESCYCLING FES-cycling platforms

Participants: Christine Azevedo Coste, Ronan Le Guillou, Martin Schmoll.

The embedded FES controller (IMUSEF) was reshaped for cycling application to improve modularity, performances and stability, using fully the capabilities of the Raspberry Pi 3B platform. These modifications now allow easier implementation, integration and usage of new control algorithms that could, in the future, be used for various end applications and contexts. Furthermore a Graphical User Interface (GUI) communicating with the embedded platform was developed, allowing on-the-fly modification of various parameters as well as safe control and monitoring of the running algorithms. An add-on relay box module allowing mechanical switching of the stimulating channels for more precise On/Off stimulation synchronization as well as more control and safety measures was also created. The two commercially available recumbent tricycles that we adapted for Spinal Cord Injured FES Cycling can be seen in Figure 4.

5.2.3. Platform : MEDITAPARK Wearable Tremor monitoring system based on acceleration monitoring

Participants: Christine Azevedo Coste, Ronan Le Guillou, Marion Holvoet.

As part of a preliminary study on the effects of Mindfulness meditation on participants with Parkinson's Disease (PD) (§3), an application was developed to monitor at home tremor occurrence using a smartwatch Samsung Gear S3 and its newer model, the Samsung Galaxy Watch (Fig:5a). A Python program has been developed to process and format data and present characteristics of the tremor under a user friendly and comprehensible format for clinicians. The goal of this system being to identify Parkinson's tremors characteristics qualitatively and quantitatively to highlight global tendencies and help objectively determine effectiveness of diverse treatments against PD tremors. This system was tested on long duration acquisitions (2 and 4 days) with 2 volunteers subject to PD tremors of moderate and high severity and proved to be able to highlight tremor tendencies and characteristics in real conditions. These acquisitions were done in order to experimentally validate the inner-workings of the developed system in real conditions and its capacity to

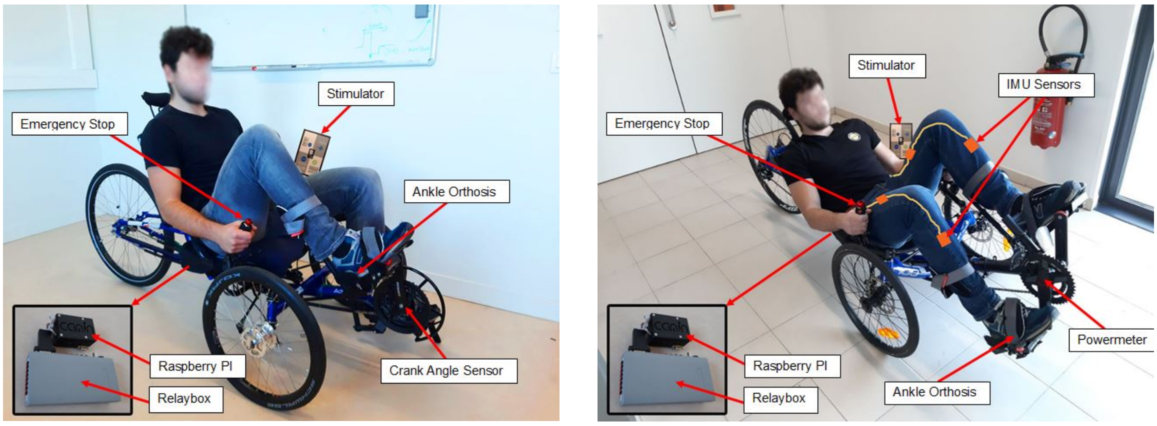

Figure 4. FES Cycling platforms developed in the CAMIN team. a) ICE Trike Adventure 26 setup adapted for Spinal Cord Injured FES Cycling b) CAT Trike 700 setup adapted for Spinal Cord Injured FES Cycling

detect PD tremors of moderate and high severity as well as to refine the classification and processing of the data. An example of 4 days acquisition is presented in Figure 5b.

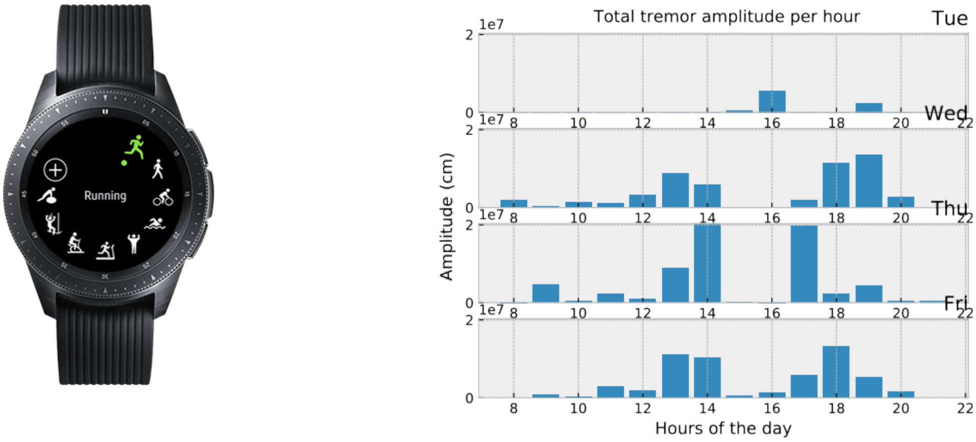

Figure 5. Meditapark figures. a) Smart watch used as the embedded platform for this monitoring application : Samsung Galaxy Watch b) Showcase of experimental data acquired in ecological conditions over 3.5 days presenting a quantitative and objective evaluation of the Parkinson's tremors under a daily format condensed hourly.

The created system allows qualification of tremors in punctual clinical check-ups in the Hospital as well as quantitative formatting of daily tendencies. This system should then allow to highlight the evolution of Parkinson's tremors characteristics throughout the MBSR (Mind-fullness Based Stress Reduction) meditation program which is yet to be undertaken. A protocol is still waiting for validation from the CPP to begin inclusions and conduct the MBSR meditation program, monitored with the developed system.

The software APP of this platform can be found at https://bil.inria.fr/fr/software/view/3565/tab as the *PARa-Keet Project* with the Bil Id: Software_3565.

5.2.4. Platform : AGILIS-EX software

Participants: Arthur Hiairrassary, Christine Azevedo Coste, David Guiraud.

The AGILIS-EX software was specially developed as part of the AGILIS project for exploratory clinical trials governed by the ID RCB research protocol: 2019-A02037-50. It allows the configuration and triggering of the stimulation generated by the STIMEP (neural stimulator) or the VIVALTIS (external stimulator) (Fig.6). The stimulation parameters are automatically selected according to predefined configurations (frequency, current and pulse-width) in order to obtain the functional movements of the hand desired by the subject (Fig.7). To detect and interpret patient voluntary movement or contraction to infer the activation or deactivation of the pre-programmed stimulation, it uses measurements from the DELSYS acquisition system (EMG, FSR, trigger).

This medical grade software is compliant with the IEC 62304 (class B).

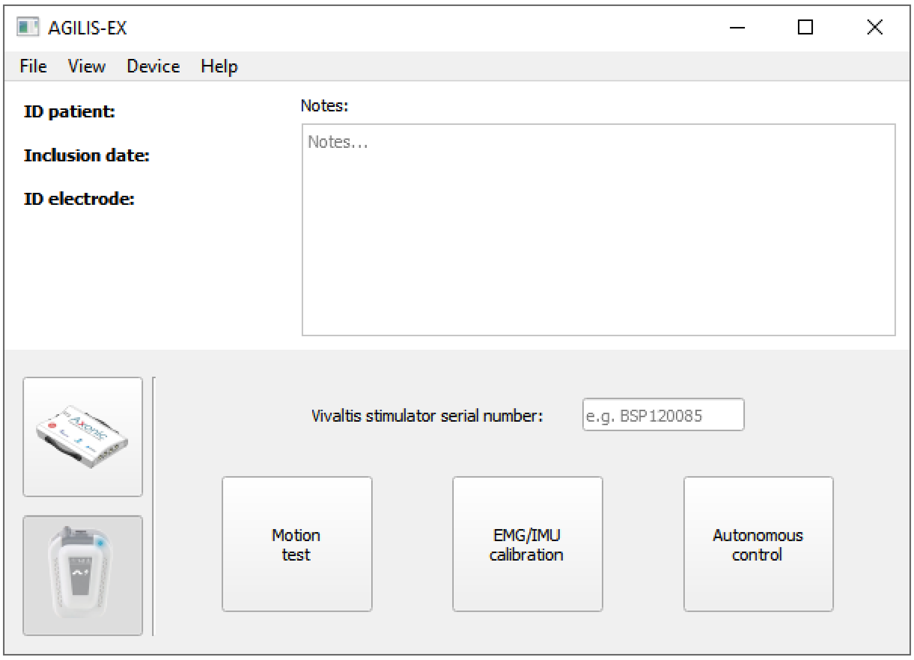

Figure 6. Main window of the AGILIS-EX software.

6. New Results

6.1. Selectivity of implanted neural electrical stimulation

Participants: Lucie William, David Guiraud, Charles Fattal, Christine Azevedo, Arthur Hiairrassary.

In the context of using a multi-contact cuff electrode positioned around a trunk nerve to activate selectively the fascicles leading to selective movements, a pre-clinical study was performed on the sciatic nerve of four rabbits

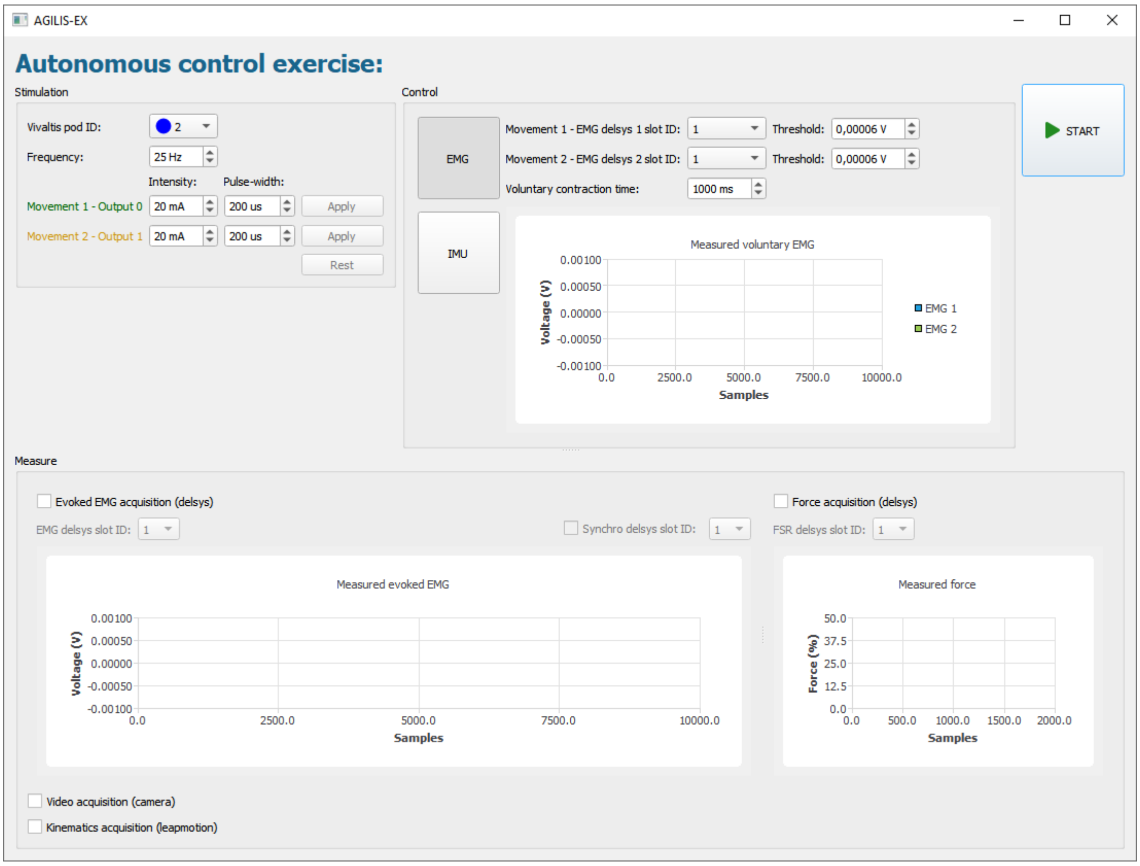

Figure 7. Autonomous control exercise window used for external stimulation

(Lab. Chirurgie Experimentale, Institut de Biologie, University of Montpellier). The purpose was to compare and classify six different currents configuration (current ratios) (Fig.8) with a 12- contact cuff electrode using selectivity, robustness (i.e. ability to maintain selectivity within a range of current amplitudes) and efficiency (i.e. electrical consumption of the considered multipolar configuration *versus* the electrical consumption of the reference whole-ring configuration) indexes.

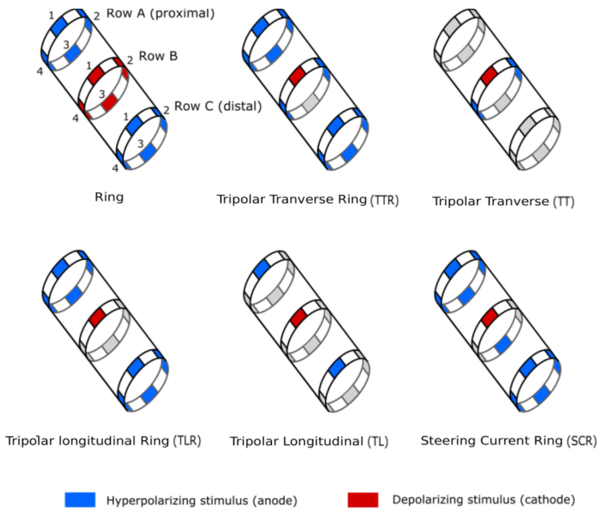

Figure 8. Six different configurations of the 12-contact electrode were tested: Ring, Tripolar Transverse Ring (TTR), Tripolar Transverse (TT), Tripolar Longitudinal Ring (TLR), Tripolar Longitudinal (TL), Steering Current Ring (SCR)

Results indicated that the optimal configuration depends on the weights applied to selectivity robustness and efficiency criteria. Tripolar transverse is the most robust configuration and the less efficient, whereas tripolar longitudinal ring is efficient but not robust. New configurations issued from a previous theoretical study we carried out such as steering current ring appears as good compromise between the 3 criteria [18].
The PhD of Lucie William (started in October 2019) will be the continuation of this work in the context of neural electrical stimulation of complete quadriplegic human participants (AGILIS project).

6.2. Selective Neural Electrical Stimulation to restores Hand and Forearm Movements in Individuals with Complete Tetraplegia

Participants: David Guiraud, Charles Fattal, Christine Azevedo, Mélissa Dali, Jacques Teissier [Beau Soleil clinic, Montpellier], Anthony Gélys [Propara Rehab. Center, Montpellier].

Selective neural electrical stimulation of radial and median nerves enables the activation of functional movements in the paralyzed hand of individuals with tetraplegia. In eight participants (Clinique Beau Soleil and Propara Rehabilitation Center, Montpellier) with complete tetraplegia, during a programmed surgery and under complete anesthesia, we demonstrated that selective stimulation based on multicontact cuff electrodes and optimized current spreading over the active contacts provided isolated, compound, functional and strong movements. Several configurations were needed to target different areas within the nerve to obtain all the envisioned movements. We further confirmed that the upper limb nerves have muscle specific fascicles, which makes possible to activate isolated movements. The future goal is to provide patients with functional restoration of object grasping and releasing with a minimally invasive solution: only two cuff electrodes above the elbow. This will be the objective of AGILIS project supported by EIT Health.

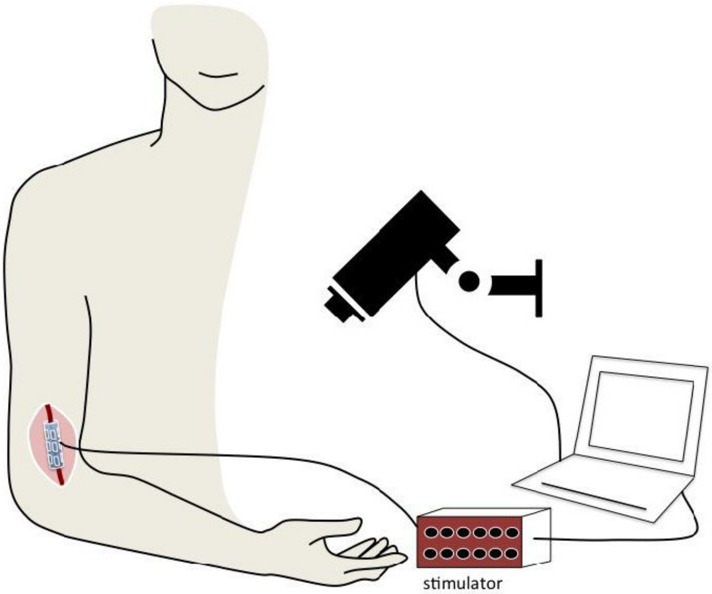

Figure 9. Neural electrical stimulation of radial or median nerve using a multi-contact cuff electrode allows to elicit different individual or grouped muscle contractions inducing different fingers and wrist movements.

6.3. Assisted Grasping in Individuals with Tetraplegia: Improving Control through Residual Muscle Contraction and Movement

Participants: Lucas Fonseca [UnB, Brazil], David Guiraud, Charles Fattal, Christine Azevedo, Arthur Hiairrassary, Camilo Silva, Anthony Gélys [Propara Rehab. Center, Montpellier].

Individuals who sustained a spinal cord injury often lose important motor skills, and cannot perform basic daily living activities. Several assistive technologies, including robotic assistance and functional electrical stimulation, have been developed to restore lost functions. However, designing reliable interfaces to control assistive devices for individuals with C4–C8 complete tetraplegia remains challenging. Although with limited grasping ability, they can often control upper arm movements via residual muscle contraction. We have explored the feasibility of drawing upon these residual functions to pilot two devices, a robotic hand and an electrical stimulator. We studied two modalities, supra-lesional electromyography (EMG), and upper arm inertial sensors (IMU). We interpreted the muscle activity or arm movements of subjects with tetraplegia attempting to control the opening/closing of a robotic hand, and the extension/flexion of their own contralateral hand muscles activated by electrical stimulation. Two groups of participants with quadriplegia were recruited (Clinique Propara, Montpellier): eight subjects issued EMG-based commands; nine other subjects issued IMU-based commands. For each participant, we selected at least two muscles or gestures detectable by our algorithms. Despite little training, all participants could control the robot's gestures or electrical stimulation of their own arm via muscle contraction or limb motion [20].

In the AGILIS project supported by EIT Health, we intend to extend this approach to participants with 2 implanted electrodes on median and radial nerves participating in a 30-days clinical study (APHP, Paris and Clinique La Châtaigneraie, Menucourt).

We are currently working on the software that is responsible for acquiring sensor data and controlling the stimulator (§5.2.4). The previous algorithms are being implemented in a single platform focusing on the 30-

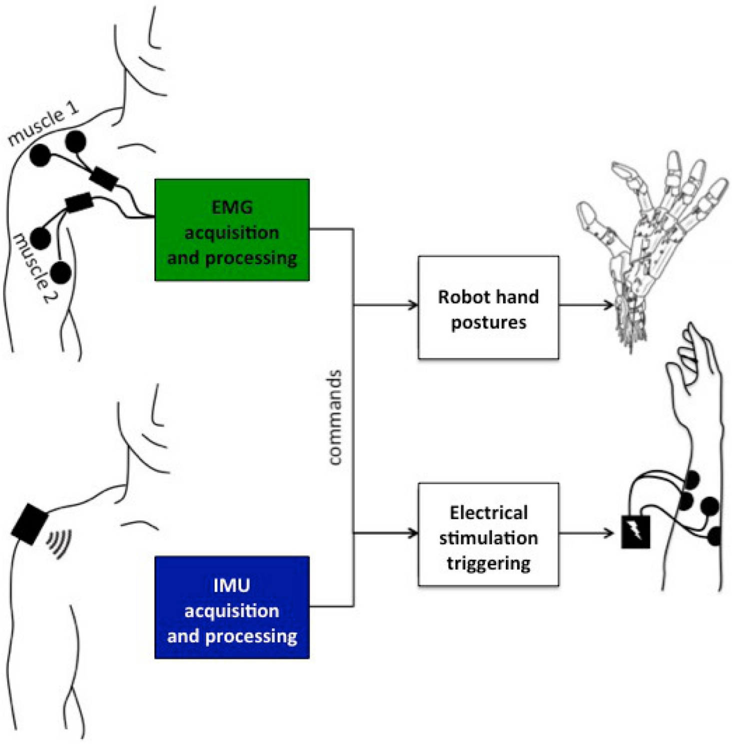

Figure 10. Protocol principle. EMG or IMU signals are converted into commands for the robotic hand or the electrical stimulator. The robotic hand has three possible gestures: at-rest, open and close. The electrical stimulator can receive three commands: no stimulation, stimulate channel 1 (wrist flexion) or stimulate channel 2 (wrist extension). Users are able to observe the outcome of their input and use it as biofeedback.

days clinical study. The residual motion based system was improved based on the results published in [20]. It is also faster and more efficient. The inertial sensors now have higher frequency, which leads to higher accuracy of movement classification, particularly with faster movements.

6.4. Modeling and simulation of a human hand

Participants: Daniel Simon, Ahmed Farek.

The AGILIS stimulation system is intended to generate grasping action on some objects such as balls and cans. A high-fidelity hand model and associated simulation software was developed to anticipate real experiments and help for the system identification and tuning [30]. The hand model uses 23 degrees of freedom for the wrist and fingers. 28 muscles are considered, including the 12 muscles which are expected to be activated using electrical stimulation of the median and radial nerves. Others are also considered in the model as, even if not stimulated, they contribute to the hand and fingers movements through passive forces when extended. Several actuation models are investigated to allow for the identification of muscles-to-movements relations.

The active forces provided by the stimulated muscles are computed thanks to the original model developed over the past years by the team, where the inputs are currents injected to muscles or nerves. The fingers are assumed to interact with the grasped object through elastic contacts and limited friction.

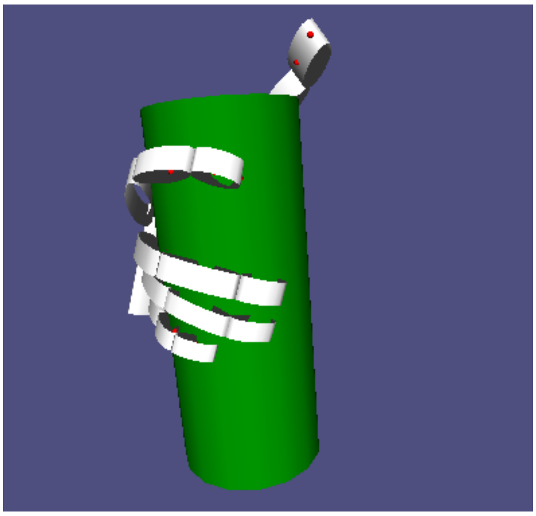

Figure 11. Simulation of a stimulated hand grasping a can

6.5. Functional impact of a self-triggered grasping neuroprosthesis in post-stroke subjects

Participants: David Gasq, Christine Azevedo, Ronan Le Guillou, Jérôme Froger [CHU Nîmes, France].

The improvement of the grasp abilities remains a challenge in the 50% of post-stroke subjects who have not recovered functional grasping due to paralysis of the finger's extensor muscles. The ePrehension-Stroke is a prospective, bicentric (promoted by the CHU de Nîmes), multi-crossover, blinded evaluation study which assesses the functional impact of a self-triggered grasping neuroprosthesis. We have developed a specific software, NeuroPrehens, which controls external electrical stimulations applied over finger's extensor muscles and was triggered by voluntary head movements or electromyography activity of leg muscles. The main objective is to assess the impact of the self-triggered grasping neuroprosthesis on the ability to perform a standardized task of grasping, moving and releasing either a glass (palmar grasp) or a spoon (key pinch), compared to the absence of neuroprosthesis use. Secondary objectives are to assess (1) the preferential modes of neuroprosthesis control, (2) the impact of the neuroprosthesis on a standardized unimanual grip scale (Action Arm Research Test), (3) the psycho-social impacts (Psychosocial Impact of Assistive Devices Scale questionnaire) and the subject's satisfaction and tolerance (Quebec User Assessment of Satisfaction with Assistive Technology questionnaire) related to neuroprosthesis use. Over 20 subjects planned to include until June 2020, we have included 8 subjects since July 2019. The prospects of this pilot study are to develop a fully wearable and self-piloted neuroprosthesis that can be used in daily life by the largest number of post-stroke subjects who have not recovered active grasping abilities.

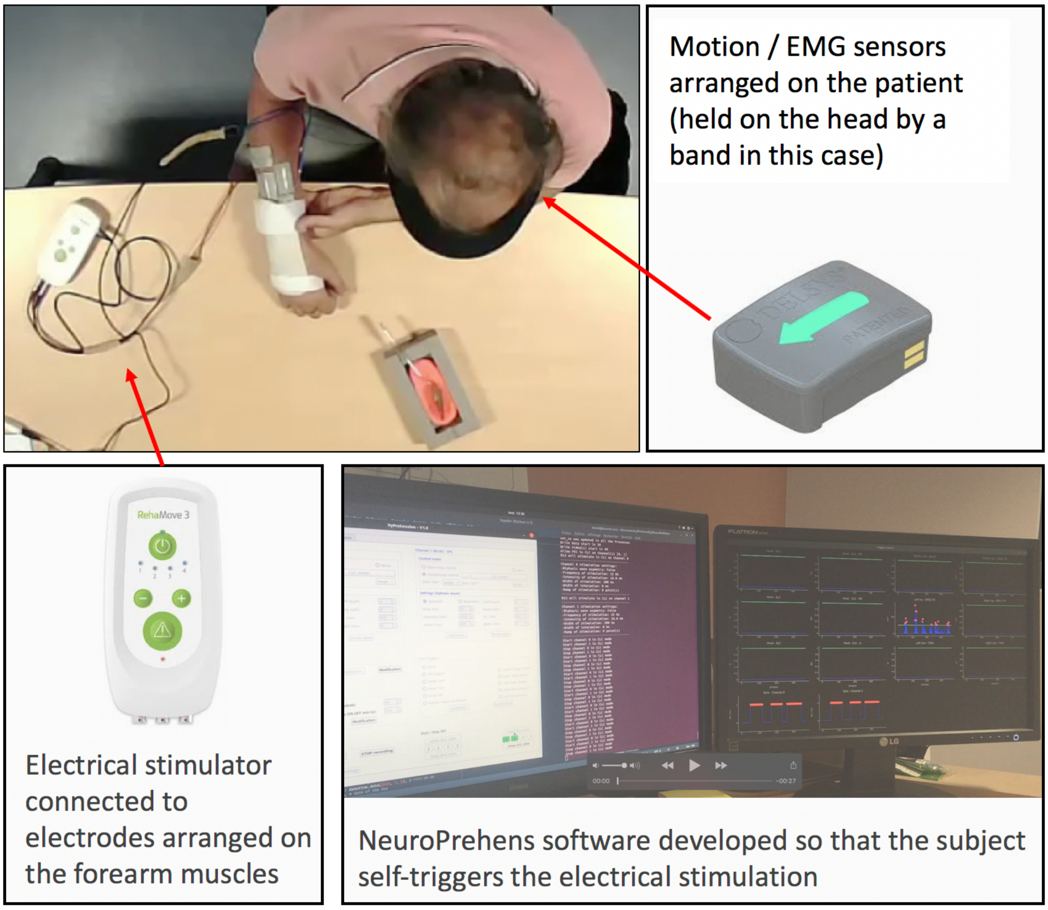

Figure 12. Experimental device constituting the self-triggered grasping neuroprosthesis.

6.6. Near-infrared spectroscopy time course under hypercapnia

Participants: Victor Vagné, David Guiraud, Vincent Costalat [CHU Montpellier], Emmanuelle Le-Bars, Stephane Perrey.

Partial arterial pressure of carbon dioxide (CO2) modulates cerebral blood flow through vasoreactivity mechanism. Near infrared spectroscopy (NIRS) can be used to record these changes in cerebral hemodynamics.

However, no laterality comparison of the NIRS signal has been performed despite being a prerequisite for the use of such method in a vasoreactivity monitoring context. We propose to investigate laterality of NIRS signal in response to a CO2-inhalation-based hypercapnia paradigm in healthy volunteers.

Methods: Eleven healthy volunteers (6 women, 5 men, mean age: 31 $\pm$ 11) underwent a 3-block-design inhalation paradigm: normoxia (5min, “baseline”) – hypercapnia (2min, “stimulation”) – normoxia (5min, “post-stimulation”). NIRS signal was measured using a two-channel oximeter (INVOS 5100C, Medtronic, USA) with sensors placed symmetrically on both the left and right sides on each subject’s forehead. Additional heart rate (HR) monitoring was performed simultaneously. Based on the NIRS mean signal pattern, an a priori model of parametric identification was applied for each channel to quantify parameters of interest (amplitude, time delay, excitation and relaxation time) for each inhalation block.

Results: HR increased significantly during the stimulation block. The quality of the model was satisfactory: mean absolute error between modeled and experimental signals were lower than the resolution of the device. No significant lateralization were found between left and right values of most of the parameters.

Conclusion: Due to the lack of lateralization, this parametric identification of NIRS responses to hypercapnia could bring light to a potential asymmetry and be used as a biomarker in patients with cerebrovascular diseases.

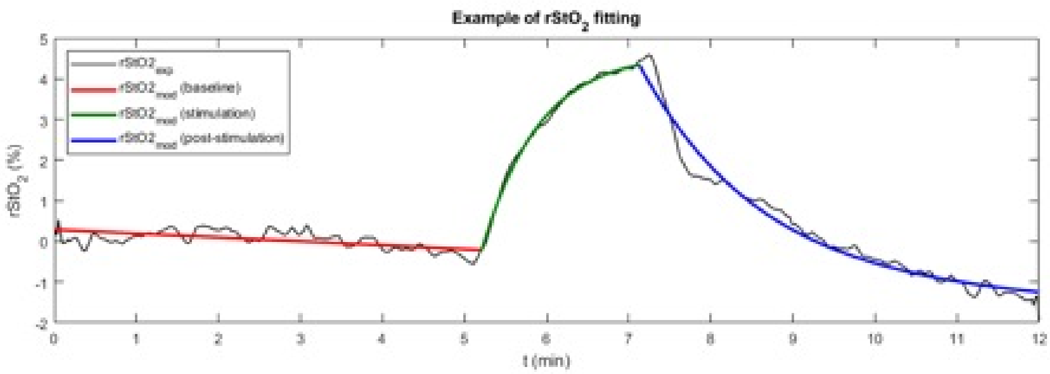

Figure 13. Example of curve fitting on NIRS signal with a compartmental first order model in response to a 2-min hypercapnic stimulus.

6.7. EPIONE

Participants: David Andreu, David Guiraud, Arthur Hiairrassary.

The project was completed in 2017 but major publications were issued in 2018 and 2019 reporting the most important results of both stimulation of the upper and lower limbs in amputees to restore sensations using 4 TIME electrodes. We developed original algorithms that convert signals acquired from sensors of the artificial lower limb, namely the prosthetic limb, into stimulus to the afferent branches of the sciatic nerve. This pioneering work shows that not only the gait performances were greatly enhanced but also the phantom pain relief was effective with a long lasting after stopping the therapy [22] [21]. These results follows the previous ones pbtained on the upper limb with similar results [23].

6.8. FES-assisted cycling

Participants: Benoît Sijobert, Ronan Le Guillou, Charles Fattal, Christine Azevedo, Martin Schmoll, Emerson Fachin-Martins [UnB, Brazil], Henrique Resende [UFMG, Brazil], David Lobato [UnB, Brazil].

Our team is working for several years on FES-assisted cycling for individuals with spinal cord injury. We intend to improve cycling accessibility to a larger population in order to propose exercising and leisure activity to improve quality of life and self esteem. On this context we have been working on three aspects this year: 1) improving training to be able to propose patients in rehabilitation centers a simplified and acceptable protocol to prepare muscles to cycling, 2) improving usability in a rehabilitation context to ease and simplify the access to FES-cycling, 3) better understanding fatigue phenomena to improve cycling performances.
A funding (EDF Foundation) has been obtained by our clinical partner "CRF La Châtaigneraie" to perform a clinical protocol to follow up the physical preparation of individuals with spinal cord injury to manage overground active pedaling after 4 months of 3 sessions per week training at home. The protocol has been approved by an ethical committee (§3.3). One of the participants will be involved in Cybathlon 2020 event. The inclusions began in September 2019. A longitudinal follow-up will allow to precisely assess the performances progress along the training period. After the 4-months at home training the participants will be using the overground cycling platform that has been developed by our team (§5.2.2).

Figure 14. Muscular preparation for overground cycling training. Left: Participant executing strengthening program with conventional multichannel stimulator (CEFAR); Right: Participant performing endurance training on FES-ergocycle.

It has been shown that FES-cycling of subjects with Spinal Cord Injuries (SCI) results in physiological and psychological positive effects such as cardiovascular training, decrease in pressure sores occurrence and self-esteem improvements. However, the use of this technology has often remained restricted to indoor and stationary ergometers in clinical contexts, partly due to the small amount (10–25 W) of power produced and the requirement of experimented users to finely tuned the stimulation patterns needed to stimulate lower limb muscles with an adequate modality. Our latest study on this subject introduces a novel approach of a Functional Electrical Stimulation (FES) controller intended for FES-induced cycling based on inertial measurement units (IMUs). This study aimed at simplifying the design of electrical stimulation timing patterns while providing a method adapted to different users and devices. In most of the different studies and commercial devices, the crank angle is used as an input to trigger stimulation onset. We propose to use instead thigh inclination as the reference information to build stimulation timing patterns. The tilting angles of both thighs are estimated from one inertial sensor located above each of the knees. An IF-THEN rules algorithm detects online and automatically the thigh peak angles in order to start and stop the stimulation of quadriceps muscles depending on these events. One participant with complete paraplegia was included and was able to propel a recumbent trike using the proposed approach after a very short setting time. This new modality opens the way to a simpler and user-friendly method to automatically design FES-induced cycling stimulation patterns, adapted to a clinical use, to multiple bike geometries and user morphologies. Using the online peak knee flexion algorithm developed in the study presented in last years section 6.2 to continuously detect this event, we validated a novel approach in order to trigger the quadriceps stimulation at the beginning of the pushing phase. These results can be seen in Figure 15. Enabling this method to take into account a possible sliding in seat position without requiring an accurate placement of the IMUs or a geometrical model of the individual [24].

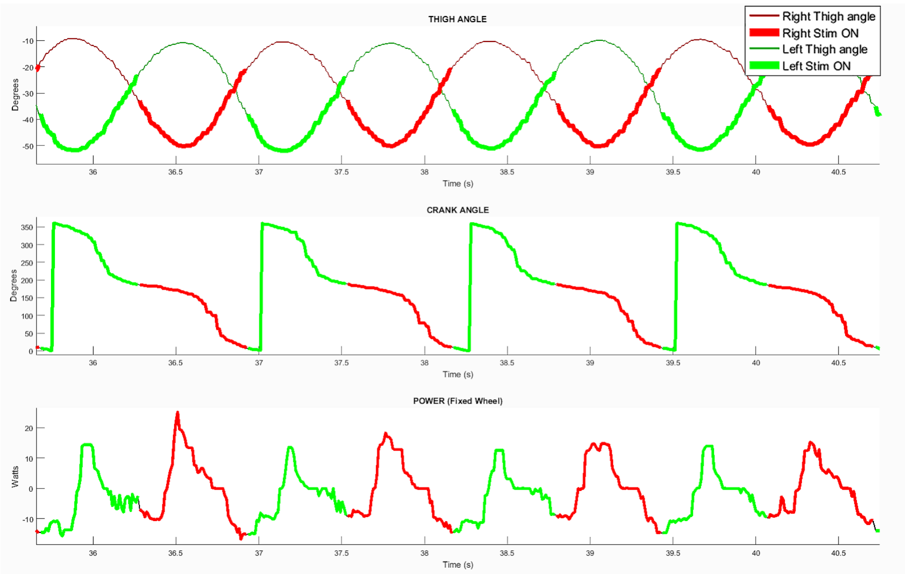

Figure 15. Data sample illustrating the results over four pedalling cycles in home trainer condition. TOP: Left (green) and right (red) thigh tilting angles - MIDDLE: crank angle - BOTTOM: developed power. The two stimulation channels activation are highlighted.

Another important aspect concerning FES-cycling is the pilots ability to resist fatigue for a prolonged time. Muscular activation as a result of electrical nerve stimulation is known to introduce a rather quick onset of fatigue. Therefore different approaches have been tested in literature to reduce the effective stimulation frequency received by individual motor-units. Several studies were able to show improvements using distributed multichannel stimulation against conventional single channel stimulation. A direct comparison between the different techniques is difficult as all studies use different methods of quantifying muscular fatigue. Further most studies fail to mention measured absolute values during a contraction at maximum strength. Therefore our team was designing a new testing protocol in collaboration with the University of Brasilia (CACAO Associate team) with the aim to assess muscular fatigue of currently published and new electrode positions against conventional single channel stimulation (baseline) in a more practical setting. The fatigue testing protocol was tailored to mimic 10 min FES-cycling at 50 RPM using an isokinetic dynamometer (Biodex System 4). Assuming a torque-production of 40 percent of the maximal torque-production-capacity of a well-trained quadriceps

Figure 16. Overground cycling. The participant was able to propel the recumbent trike over a 40 meter corridor.

muscle to be sufficient for FES-cycling. The active torque produced at this starting level was measured in a series of contractions, tracking the decline of torque. The study was conducted in Brasilia on 3 individuals expressing a complete spinal cord injury. All participants were enrolled in a FES-training program for about 14months. All participants were highly motivated and fulfilled the demanded inclusion criteria ensuring a safe execution of the protocol. For every subject both legs were measured individually leading to an overall sample size of n=6. Currently the data-analysis is still in progress. The results of this study should lead to optimized stimulation techniques to prolong the onset of fatigue during FES-cycling.

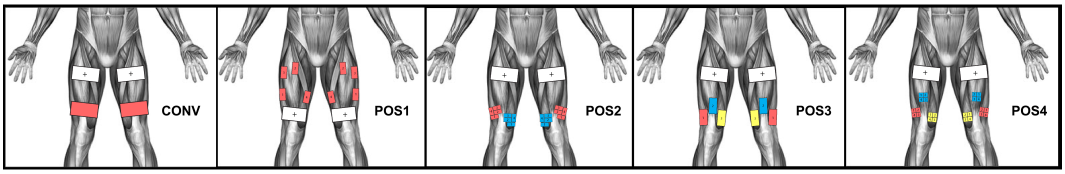

Figure 17. Electrode configurations examined. Electrodes marked with "+" were the Anodes (reference electrodes). CONV: Standard electrode configuration 40 Hz delivered to one pair of electrodes; POS1: One channel with 40 Hz distributed over 4 electrodes – common anode; POS2: Two channels with each 40 Hz distributed via 4 electrodes – common anode; POS3: Three channels of 40 Hz each delivered to one electrode – common anode: POS4: Three channels with each 40 Hz distributed via 4 electrodes – common anode

6.9. Breathing detection via tracheal sounds

Participants: Xinyue Lu, David Guiraud, Christine Azevedo, Serge Renaux [Neuroresp], Thomas Similowski [Hosp. LA Salpêtrière, Paris].

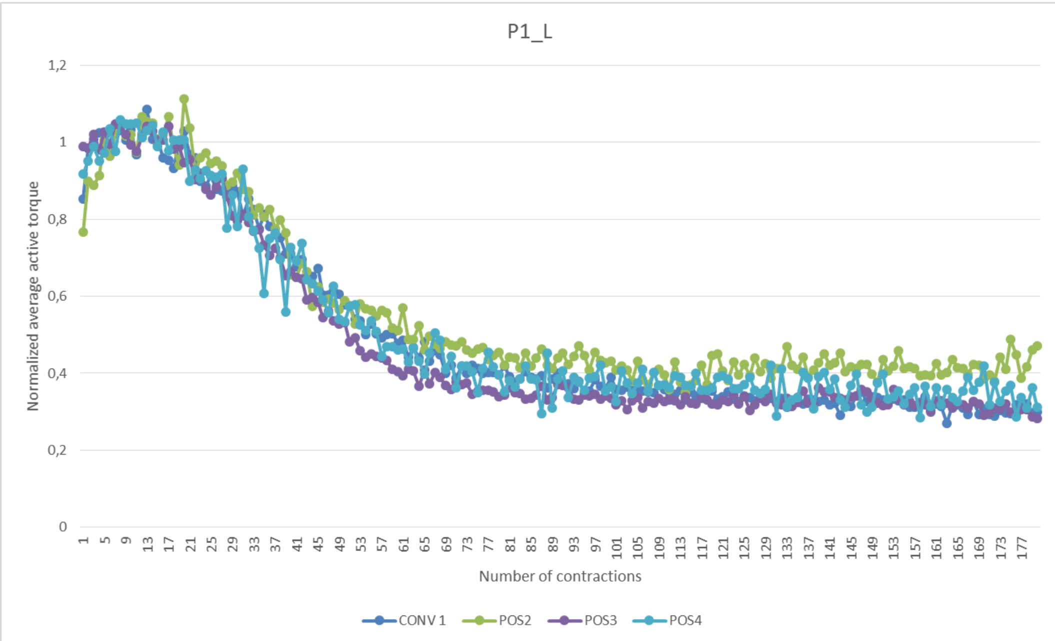

Figure 18. Preliminary data retrieved of the left leg of patient 1. The average active torque of the first 20 contractions was used to normalize fatigue curves. POS1 was excluded from the figure due to exaggerated fluctuations in torque.

Individuals with a respiratory paralysis are essentially supplied by mechanical ventilation. However, severe drawbacks of mechanical ventilation were reported: low autonomy, high health costs, infection risk, etc. If patients' phrenic nerves and diaphragms are still functional, implanted diaphragm pacing can provide them a more natural respiration. Compared to classic mechanical ventilation, implanted diaphragm pacing can cancel some of the disadvantages mentioned above, and can also help to significantly improve speech and recover some olfactory sensation.

But existing implanted diaphragm pacing systems can not monitor patient's induced respiration and they stimulate at constant intensity and frequency - they work in open-loop. It means that stimulation intensity, pulse width and frequency are fixed at the installation of the implant, updated at each control visit, but do not adapt to patient's continuous situation evolution because of the absence of respiratory monitoring. To close the loop, an ambulatory respiratory monitoring solution needs to be developed. Adding adaptive abilities to existing systems would improve the efficiency of the delivered stimulation.

The gold standard for apnea/hypoventilation evaluation is the polygraph, which includes an pulse oximeter and at least one respiratory flow sensor. In a clinical use, flow sensors could be nasal cannula, pneumotachograph, thermistor or plethysmograph. But these sensors need to be placed over the face or are sensitive to patient's movements. They are therefore not compatible with an implanted diaphragm pacing system which is portable and for a daily living use. With this in mind, this study investigated an acoustic method. The proposed tracheal sounds recording requires only one tiny microphone fixed on the neck with a support, which is the only physical contact with the patient.

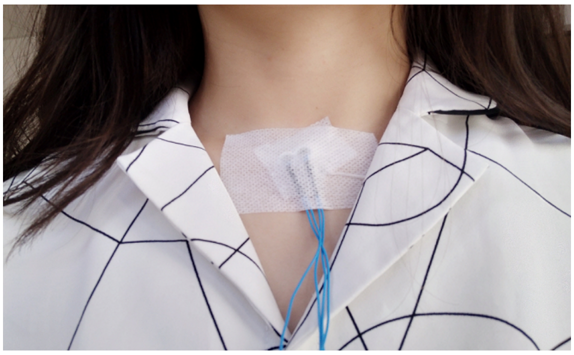

Figure 19. The position of microphone to record tracheal sounds.

Many previous studies have shown some positive results on respiration analysis from tracheal sounds in sleep apnea, especially for obstructive sleep apnea. But only few methods are developed for real-time applications (processing delay within seconds) with robustness requirements, indeed, all these studies have been carried out in quiet and controlled acoustic environments with stable sources of noises, and with limited movements of the subjects (during sleep).

In collaboration with NEURORESP company and La Salpêtrière Gospital (Paris) we are investigating the possibility to perform a real-time and continuous breathing detection (day and night), even during wakefulness in noisy environments. We proposed thea method with tracheal sounds recorded on the neck at suprasternal notch (Fig.19). This method is noninvasive and easy to apply. And the recorded tracheal sounds contain not only respiratory sounds, but also heart beats sounds (as phonocardiogram: PCG) so that some basic cardiac information, as cardiac rhythm, could be calculated. Furthermore, inspired by ECG-derived respiration, the similar method could also be applied on obtained PCG to get respiratory information.

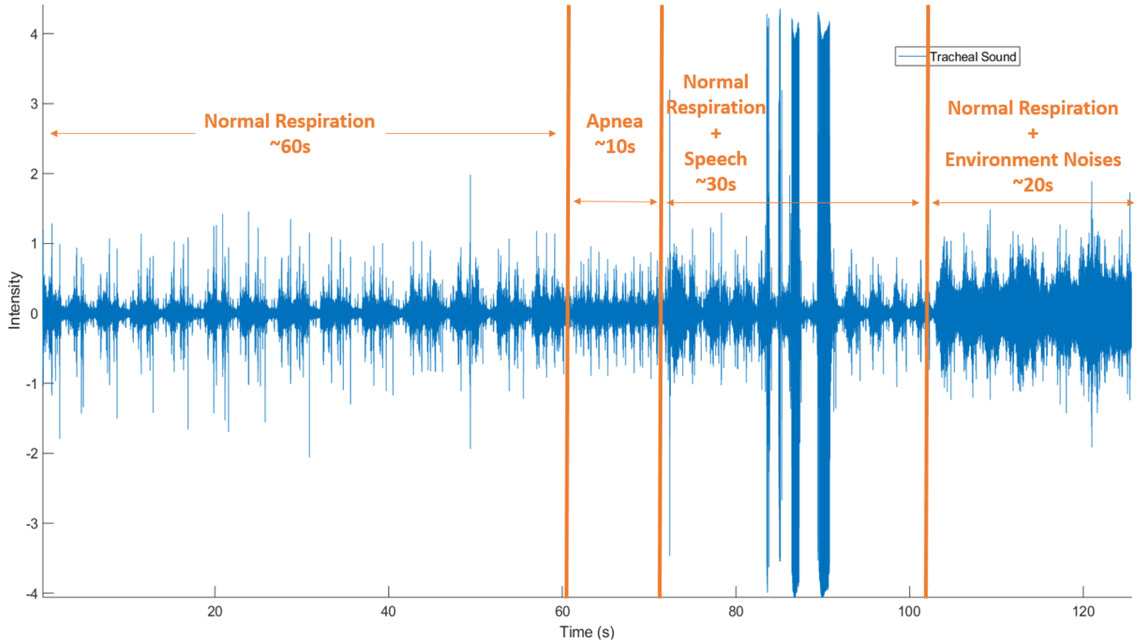

Figure 20. One example of a 2-min recording of tracheal sounds.

The proposed method has been tested on 30 recordings from 15 healthy subjects with different respiratory condition, one example is shown in Fig.20. We proposed a new algorithm to detect respiration phases, by combining the signal processing both in the temporal (envelope and PCG-derived respiration) and the frequency domains. We assessed the performances of the algorithm in emulated noisy environments. The accuracy, sensibility and specificity of system are all superior to 90%. The result is good enough to show a proof of such a conception. Furthermore, a tracheal sounds recording from a patient under implanted phrenic nerve stimulation has shown that the recording system has the possibility to capt an image of stimulation impulse from the wireless transmission. Getting the synchronization with respiratory sounds and stimulation signals can help to verify and even to adjust patient's stimulation parameters.

6.10. Attenuation and Delay of Remote Potentials Evoked by Direct Electrical Stimulation During Brain Surgery

Participants: Anthony Boyer, Hugues Duffau [CHU Montpellier], Emmanuel Mandonnet [CHU Lariboisière], Marion Vincent, Sofiane Ramdani [LIRMM], David Guiraud, François Bonnetblanc.

Direct electrical stimulation (DES) is used to perform functional brain mapping during awake surgery but its electrophysiological effects remain by far unknown. DES may be coupled with the measurement of evoked potentials (EPs) to study the conductive and integrative properties of activated neural ensembles and probe the spatiotemporal dynamics of short- and long-range networks. We recorded ECoG signals on two patients undergoing awake brain surgery and measured EPs on functional sites after cortical stimulations, using combinations of stimulation parameters. EPs were similar in shape but delayed in time and attenuated in amplitude when elicited from a different gyrus or remotely from the recording site. We were able to trigger remote EPs using low stimulation intensities. We propose different activation and electrophysiological propagation mechanisms following DES based on activated neural elements [15].

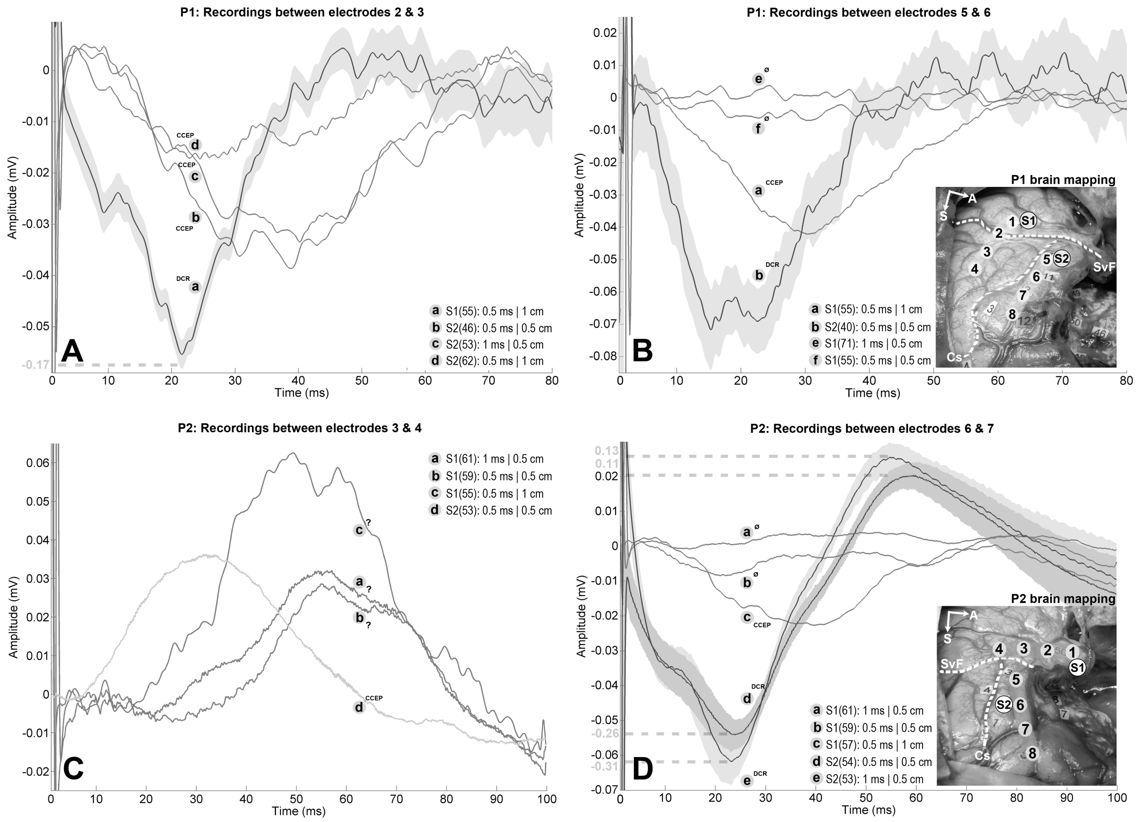

Figure 21. P1 and P2 brain mappings: Pictures illustrating the stimulation sites (S1, S2) and ECoG positioning with respect to the initial 60 Hz cortical brain mapping (numbered paper tags).

Electrodes of both ECoG strips are numbered from 1 to 4 and from 5 to 8. The Sylvian fissure and central sulcus are highlighted by a white dashed lines and annoted "SyF" and "Cs" respectively. For P1, experimental DES was applied on: (1) the Wernicke's area (S1), associated with complete anomia; (2) the ventral premotor cortex (S2), which led to movement and counting interruptions. Strip 1 spans over both temporal and parietal lobe with: electrode 1 over the most posterior part of the superior temporal gyrus; electrode 2 over the Sylvian fissure; electrodes 3 and 4 over the adjacent supramarginal gyrus. Strip 2 spans over the precentral gyrus with: electrodes 5 to 7 over the ventral premotor cortex; electrode 8 is bordering with the most posterior part of the partially resected dorsolateral prefrontal cortex. For P2, experimental DES was applied on: (1) the middle part of the superior temporal gyrus (S1) which led to complete anomia; (2) the precentral gyrus (S2), which induced articulatory disorders. Strip 1 spans over the superior temporal gyrus with: electrodes 1 and 2 over its middle third; electrodes 3 and 4 over its most posterior part. Strip 2 spans over the precentral and dorsolateral prefrontal gyri with: electrodes 5 and 6 over the ventral premotor cortex; electrodes 7 and 8 are respectively bordering and within the adjacent dorsolateral prefrontal cortex. Tumor was about 164 cm3 for P1 and 150 cm3 for P2. The number of averaged stimuli is reported within parentheses for each trace. 99% confidence interval estimated for DCRs are represented by grey surfaces to demonstrate that CCEPs do not belong to them. Additional traces corresponding to variations of stimulation parameters were added if available, regardless of the presence of EPs. A: Differential recordings between electrodes 2 and 3 for P1 while stimulating S1 (-170 μV, 21 ms delay) and S2 (amplitudes ranging from -40 μV to -17 μV, delays ranging from 25 ms to 38 ms). EPs following S2 stimulation are CCEPs because of the presence of the central fissure between the stimulation and recording sites. The EP measured after stimulating S1 is ambiguous because electrode 2 lies on the Sylvian fissure, but the short latency and enhanced amplitude with regard to the CCEPs suggest a DCR. Note the dashed line indicating a different amplitude scale for the DCR, which was reduced by a factor 3 for visualization purposes. B: Differential recordings between electrodes 5 and 6 for P1 while stimulating S2 (-75 μV, 20 ms delay) and S1 (-44 μV, 30 ms delay). EP following S1 stimulation is a CCEP because of the presence of the Sylvian fissure between the stimulation and recording sites. EP following S2 stimulation should be viewed as DCR as it was recorded on the same gyrus and it showed shorter latency and enhanced amplitude in comparison with the CCEP. C: Differential recordings between electrodes 3 and 4 for P2 while stimulating S1 (amplitudes ranging from +29 μV to +62 μV, delays ranging from 52 ms to 62 ms) and S2 (+36 μV, 32 ms delay). EP following S2 stimulation is a CCEP because of the presence of the Sylvian fissure between the stimulation and recording sites. EPs following S1 stimulations should be viewed as DCRs as they are recorded on the same gyrus but the latencies and amplitudes appeared unusual. EPs are positive because of differential measure. D: Differential recordings between electrodes 6 and 7 for P2 while stimulating S2 (amplitudes ranging from -260 μV to -310 μV, 20 ms delay) and S1 (-24 μV, 38 ms delay). EP following S1 stimulation is a CCEP because of the presence of the Sylvian fissure and the operative cavity between the stimulation and recording sites. EPs following S2 are likely DCRs as they are recorded on the same gyrus, which is corroborated by their short latencies and maximized amplitudes with regard to the CCEP. Note the dashed lines indicating different amplitude scales for the DCRs, which were reduced by a factor 5 for visualization purposes.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

NEURINNOV startup finances half of the PhD thesis salary of Lucie William.

8. Partnerships and Cooperations

8.1. Regional Initiatives

- Occitanie Region finances half of the PhD thesis salary of Lucie William.

- Occitanie Region gave a grant to CAMIN for the PhD thesis of XinYue Lu (PILE-CIFRE) - 10.000 euros.

8.2. National Initiatives

- Inria ADT STIMBIO

  Participants : Christine Azevedo, Daniel Simon, Ronan Le Guillou, Benoît Sijobert.

  A 1-year engineer (R. LeGuillou) was funded by Inria ADT on the development of an architecture dedicated to FES-cycling platform.
- I-SITE MUSE COMPANIES AND CAMPUS grant - SPINSTIM project

  Collaboration with academic local partners (CHU, IES) and NEURINNOV company on the spinal stimulation for bladder and bowel functions restoration. This is linked to an ongoing collaboration with Oslo University (Norway).
- LABEX NUMEV - MEDITAPARK project Collaboration with Montpellier Hospital (Neurology service) and the Montpellier Mindfulness Center to analyze the impact of meditation on upper limb tremor.
- EDF Foundation - CYCLOSEF project

  Collaboration with La Châtaigneraie Hospital on FES-assisted cycling. Financial support for a study on FES-cycling training method and performance otimization on individuals with complete spinal cord injury.
- I-SITE MUSE - EXPLORE

  Support for the visit of Henrique Resende (UFMG, Brazil) and Emersion Fachin (UNB, Brazil) as guest researchers from December to February 2019. Completed with a LIRMM laboratory financial aid.
- I-SITE MUSE - EXPLORE

  Support for the visit of François Bonnetblanc at the Karolinska institute Hospital, Neurosurgery and Neurology Department
- ANR Grasp-It (2019-2023) - Leader LORIA, Nancy.

8.3. European Initiatives

8.3.1. Collaborations with Major European Organizations

CAMIN team is leader of a EIT Health project "AGILIS" on Grasping rehabilitation in individuals with quadriplegia (http://www.lirmm.fr/camin/agilis-project/).

8.4. International Initiatives

8.4.1. Inria Associate Teams Not Involved in an Inria International Labs

8.4.1.1. CACAO

Title: Lower limb electrical stimulation for function restoration

International Partner (Institution - Laboratory - Researcher):

UNB (Brazil) Physiology Faculty - FACHIN-MARTINS Emerson

Start year: 2019

See also: https://team.inria.fr/cacao/

The CACAO team has developed an expertise in the application of electrical stimulation for assisting seat-to-seat transfers and pedaling for people with paraplegia. The team shared a unique experience in 2016 by participating in the first Cybathlon techno-sports games with a Brazilian driver and a French driver in the assisted bicycle race. The team wishes to continue the work by optimizing the quality of pedaling to participate in the Cybathlon 2020 and extending the technique for the rehabilitation of patients with hemiplegia in a rehabilitation context.

8.4.1.2. Informal International Partners

We have an ongoing informal collaboration with Andrew Murray (DIMLAB, Dayton University) on the design of complex mechanisms in the context of cycling (trike design) and grasping (orthosis design).

8.5. International Research Visitors

Henrique Resende (UFMG, Brazil) and Emerson Fachin (UNB, Brazil) spent 3 months in CAMIN team from December 2018 to February 2019 to work on FES-cycling project (I-SITE MUSE Explore program and LIRMM support).

8.5.1. Internships

Camilo Silva is achieving a 6-months ERASMUS internship in the team on motion recognition using Deep Learning techniques.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events: Organisation

Christine Azevedo, Jessica Rose (Univ. Stanford, USA), Kelly Greves (Cincinnati Children's Hospital Medical Center, USA) organized an Instructional course during the EACD Conference (May, 23rd, 2019) in Paris : "Multichannel Neuromuscular Stimulation: NMES-assisted gait for children with cerebral palsy".

9.1.1.1. Member of the Conference Program Committees

- Daniel Simon is member of the ICINCO conference program committee

9.1.1.2. Reviewer

- Daniel Simon was reviewer for the RTNS, IEEE SYSTOL and IFAC ICINCO conferences
- Christine Azevedo was reviewer for IEEE EMBC, IROS, IFESS conferences

9.1.2. Journal

9.1.2.1. Member of the Editorial Boards

- David Guiraud is member of the Editorial Board of Journal of Neural Engineering (JNE) and Medical and Biological Engineering and Computing (MBEC).
- David Guiraud is Associate Editor of Theme 6 (Neurorahabilitation) at IEEE EMBC conference.
- Christine Azevedo is member of the Editorial Board of Neuroprosthetics as Review Editor for Frontiers in Neurology and Frontiers in Neuroscience
- Christine Azevedo is member if ERCIM News' Editorial Board as Inria representant.

9.1.2.2. Reviewer - Reviewing Activities

- Daniel Simon was reviewer for Simulation: Transactions of the Society for Modeling and Simulation International.

9.1.3. Invited Talks

- Daniel Simon gave a talk on "Feedback schedulers in practice A video decoder example" at the 40th International Summer School of Automatic Control Grenoble, France, September 9th, 2019.
- Daniel Simon gave a talk on "Dynamic simulation of a hand under electrical stimulation" at the "Modeling human through robotics, neuroscience, and ergonomics" AIST workshop, Montpellier, France, October 24th, 2019.
- François Bonnetblanc gave a talk on "Awake neurosurgery and electrophysiological spreading in the human brain: towards clinical applications through brain mapping? A new insight in brain connetivity" at the "Modeling human through robotics, neuroscience, and ergonomics" AIST workshop, Montpellier, France, October 24th, 2019.
- David Guiraud gave a talk on "Bidirectional control of hand prosthesis for amputees. A new breakthrough with sensory feedback to the brain" at the "Modeling human through robotics, neuroscience, and ergonomics" AIST workshop, Montpellier, France, October 24th, 2019.
- Christine Azevedo gave a talk on "FES-assisted grasping" at the "Modeling human through robotics, neuroscience, and ergonomics" AIST workshop, Montpellier, France, October 24th, 2019.
- Christine Azevedo gave a talk on " Interest of IMU sensors in various FES usages" at Lyon CyberBike event (https://lcb2019.sciencesconf.org/), September 9th, 2019.
- Christine Azevedo gave a talk on "Restoring a sport activity by stimulating paralyzed muscles" during Inria Scientific Days (June 2019).

9.1.4. Leadership within the Scientific Community

Christine Azevedo is member of the board of directors of International Functional Electrical Stimulation Society (IFESS).

9.1.5. Scientific Expertise

- Christine Azevedo is member of LIRMM CNU 61 commission
- Christine Azevedo was member of the selection committee for a Lecturer position at ISIR laboratory (Université Pierre et Marie Curie), (April 15th, 2019)
- Christine Azevedo was member of the selection committee of Researcher Competition at Inria Bordeaux (May 2019)

9.1.6. Research Administration

Christine Azevedo was member of Inria Evaluation Committee (CE). She participated in the competitive examinations for junior researcher recruitment in Inria Bordeaux Center (April 2019) and Inria Grenoble Center (May 2018).

Christine Azevedo is member of Inria Ethical Committee (COERLE).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master Neuroprothèses : Daniel Simon, "Control basics", 6.5h, M2, Université de Montpellier, France

Master Neuroprothèses : François Bonnetblanc, "Neurophysiologie", 8h, M2, Université de Montpellier, France

9.2.2. Supervision

PhD : Maxence Blond, "Optimisation de la propulsion d'un véhicule sous-marin à propulseurs azimutaux", University of Montpellier, April 17th 2019, Daniel Simon

PhD : Anthony Boyer, "Électrophysiologie cérébrale associée à la chirurgie éveillée des tumeurs lentes : Couplage de l'ECoG et de la SED pour les investigations peropératoires et analyse de l'EEG postopératoire", University of Montpellier, September 24th 2019, François Bonnetblanc.

PhD in progress : XinYue Lu, "Cardiorespiratory Monitoring by Microphone via Tracheal Sounds in the Context of Implanted Phrenic Nerve Stimulation", University of Montpellier - Inria - NeuroResp, April 2017-March 2020, Christine Azevedo, Thomas Similowski, Serge Renaux

PhD in progress : Lucie William, "Selective implanted neural stimulation to recover the prehension for quadriplegic", University of Montpellier-Inria-NEURINNOV, october 2019-september 2022, supervised by David Guiraud and Christine Azevedo

PhD in progress : Hélène Moron, MD, "Jitter of MUAP measured through needle EMG used as a biomearker of the Botulin toxin effect", University of Montpellier-Inria, october 2019-september 2022, supervised by David Guiraud and Arnaud Dupeyron.

9.2.3. Juries

Christine Azevedo was external examiner for the PhD thesis of Sean Doherty (UCL, London, France) "Investigation of transcutaneous neuromodulation techniques and development of a wearable device for control of the bladder following spinal cord injury." (April 30th 2019).

Christine Azevedo was examiner for the PhD thesis of Osama Mazhar (University of Montpellier, LIRMM, France) "Recognition of human gestures based on vision for the human-robot interaction." (October 24th 2019).

Christine Azevedo was examiner for the PhD thesis of Andrii Shachykov (University of Lorraine, LORIA, France) "Neural modeling of human motor coordination inspired by biological signals aiming for parkinsonian gaits." (December 17th 2019).

9.3. Popularization

- Christine Azevedo presented FREEWHEELS project at Sport Unlimitech event in Lyon https://sportunlimitech.com/ (September 2019)
- CAMIN team was present (demonstration and masterclass lecture) at FUTURES festival in Paris https://futures.paris/ (June 13th 2019)
- CAMIN team was present (demonstration and lecture) during the visit of the Secretary of State for Persons with Disabilities at Inria Paris Center (November 19th 2019)

9.3.1. Education

- Christine Azevedo was mentor (2018-2019) for one Savanturiers project with Saussan school (CM1/CM2 level) https://savanturiersdelahightech.wordpress.com/category/projets-2018-2019/ecole-elementaire-joseph-delteil/
- Christine Azevedo is mentor (2019-2020) for one Savanturiers project with Montbazin school (CE1/CE2 level) https://savanturiers-projects.cri-paris.org/projects/NhbsL7Uz/blogentries
- Christine Azevedo organized initiation sessions to informatics using Thymio robot at École Valfalis (Montbazin, France) in CP, CE1, CE2, CM1 and CM2 levels, 5 sessions of 1 hours per level (March-June 2019).
- Christine Azevedo participated to a 1-day of training future trainers in robotics at school (DANE) (March 2019).

9.3.2. Interventions

- CAMIN team welcomed 1 week internships of 3 schoolchildren this year (4e, 3e)

10. Bibliography

Major publications by the team in recent years

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Software

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Other Publications

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Project-Team CASTOR

Control, Analysis and Simulations for TOkamak Research

IN COLLABORATION WITH: Laboratoire Jean-Alexandre Dieudonné (JAD)

IN PARTNERSHIP WITH:
CNRS

Université Nice - Sophia Antipolis

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Earth, Environmental and Energy Sciences

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Project-Team CASTOR

Creation of the Team: 2012 July 01, updated into Project-Team: 2014 July 01

Keywords:

Computer Science and Digital Science:

A6. - Modeling, simulation and control
A6.1. - Methods in mathematical modeling
A6.1.1. - Continuous Modeling (PDE, ODE)
A6.1.4. - Multiscale modeling
A6.1.5. - Multiphysics modeling
A6.2. - Scientific computing, Numerical Analysis & Optimization
A6.2.1. - Numerical analysis of PDE and ODE
A6.2.6. - Optimization
A6.2.7. - High performance computing
A6.2.8. - Computational geometry and meshes
A6.3. - Computation-data interaction
A6.3.1. - Inverse problems
A6.3.2. - Data assimilation
A6.3.4. - Model reduction
A6.4. - Automatic control
A6.4.1. - Deterministic control
A6.4.4. - Stability and Stabilization

Other Research Topics and Application Domains:

B4. - Energy
B4.2.2. - Fusion

1. Team, Visitors, External Collaborators

Research Scientists

Hervé Guillard [Team leader since July 2019, Inria, Senior Researcher, HDR]
Florence Marcotte [Inria, Researcher, from Nov 2019]
Sebastian Minjeaud [CNRS, Researcher]
Richard Pasquetti [CNRS, Emeritus Researcher, HDR]

Faculty Members

Jacques Blum [Team leader until Jun 2019, Univ de Nice - Sophia Antipolis, Professor, HDR]
Cédric Boulbe [Univ Côte d'Azur, Associate Professor]
Boniface Nkonga [Univ Côte d'Azur, Professor]
Francesca Rapetti [Univ de Nice - Sophia Antipolis, Associate Professor]
Afeintou Sangam [Univ Côte d'Azur, Associate Professor]

External Collaborator

Didier Auroux [Univ Côte d'Azur]

Technical Staff

Blaise Faugeras [CNRS, Engineer]

PhD Students

Ashish Bhole [Univ Côte d'Azur, PhD Student]
Ali Aboudou Elarif [Inria, PhD Student]
Xiao Song [CEA, PhD Student, until Nov 2019]

Visiting Scientists

Praveen Chandrashekarappa [Tata Institute of Fundamental Research, from Mar 2019 until May 2019]
Guillaume Leroy [Univ de Nice - Sophia Antipolis, until Feb 2019]

Administrative Assistant

Montserrat Argente [Inria, Administrative Assistant]

2. Overall Objectives

2.1. Presentation

In order to fulfill the increasing demand, alternative energy sources have to be developed. Indeed, the current rate of fossil fuel usage and its serious adverse environmental impacts (pollution, greenhouse gas emissions, ...) lead to an energy crisis accompanied by potentially disastrous global climate changes.

Controlled fusion power is one of the most promising alternatives to the use of fossil resources, potentially with a unlimited source of fuel. France with the ITER (http://www.iter.org/default.aspx) and Laser Megajoule (http://www-lmj.cea.fr/) facilities is strongly involved in the development of these two parallel approaches to master fusion that are magnetic and inertial confinement. Although the principles of fusion reaction are well understood from nearly sixty years, (the design of tokamak dates back from studies done in the '50 by Igor Tamm and Andreï Sakharov in the former Soviet Union), the route to an industrial reactor is still long and the application of controlled fusion for energy production is beyond our present knowledge of related physical processes. In magnetic confinement, beside technological constraints involving for instance the design of plasma-facing component, one of the main difficulties in the building of a controlled fusion reactor is the poor confinement time reached so far. This confinement time is actually governed by turbulent transport that therefore determines the performance of fusion plasmas. The prediction of the level of turbulent transport in large machines such as ITER is therefore of paramount importance for the success of the researches on controlled magnetic fusion.

The other route for fusion plasma is inertial confinement. In this latter case, large scale hydrodynamical instabilities prevent a sufficiently large energy deposit and lower the return of the target. Therefore, for both magnetic and inertial confinement technologies, the success of the projects is deeply linked to the theoretical understanding of plasma turbulence and flow instabilities as well as to mathematical and numerical improvements enabling the development of predictive simulation tools.

CASTOR gathers the activities in numerical simulation of fusion plasmas with the activities in control and optimisation done in the laboratory Jean-Alexandre Dieudonné of the University of Nice. The main objective of the CASTOR team is to contribute to the development of innovative numerical tools to improve the computer simulations of complex turbulent or unstable flows in plasma physics and to develop methods allowing the real-time control of these flows or the optimisation of scenarios of plasma discharges in tokamaks. CASTOR is a common project between Inria (http://www.inria.fr/centre/sophia) and the University of Nice Sophia-Antipolis and CNRS through the laboratory Jean-Alexandre Dieudonné, UMR UNS-CNRS 7351, (http://math.unice.fr).

3. Research Program

3.1. Plasma Physics

Participants: Jacques Blum, Cédric Boulbe, Blaise Faugeras, Hervé Guillard, Holger Heumann, Sebastian Minjeaud, Boniface Nkonga, Richard Pasquetti, Afeintou Sangam.

The main reseach topics are:

1. Modelling and analysis
   - Fluid closure in plasma
   - Turbulence
   - Plasma anisotropy type instabilities
   - Free boundary equilibrium (FBE)
   - Coupling FBE – Transport
2. Numerical methods and simulations
   - High order methods
   - Curvilinear coordinate systems
   - Equilibrium simulation
   - Pressure correction scheme
   - Anisotropy
   - Solving methods and parallelism
3. Identification and control
   - Inverse problem: Equilibrium reconstruction
   - Open loop control
4. Applications
   - MHD instabilities : Edge-Localized Modes (ELMs)
   - Edge plasma turbulence
   - Optimization of scenarii

4. New Results

4.1. On the identification of the electron temperature profile from polarimetry Stokes vector measurements in Tokamak free-boundary equilibrium reconstruction

Participants: Blaise Faugeras, Francesco Orsitto.

This paper reports numerical investigations on the identification of the electron temperature profile Te from interferometry and polarimetry Stokes vector measurements with the equilibrium code NICE (Newton direct and Inverse Computation for Equilibrium). This latter enables the consistent resolution of the inverse equilibrium reconstruction problem in the framework of nonlinear free-boundary equilibrium coupled to the Stokes model equation for polarimetry. We find that for ITER plasma with high Ip, Ne and Te the identification from noisy measurements is possible (Project EUROfusion / WP01Jet Campaigns (WPJET1) .

4.2. Equilibrium reconstruction for the JT-60SA tokamak

Participant: Blaise Faugeras.

Twin experiments were performed with this tokamak geometry in the framework of the EUROfusion / WP10 JT-60SA (WPSA) project.

4.3. Plasma boundary reconstruction for the ISTTOK tokamak

Participants: Blaise Faugeras, Rui Coelho, R. Santos.

Plasma boundary reconstruction is one of the main tools to provide a reliable control and tokamak performance. We explore the feasibility for the ISTTOK tokamak (Portugal) of a reconstruction method based on calculated vacuum magnetic flux map and plasma intersection with the wall. We show that via square wave input response curves and pre-processing of the poloidal field coil currents, it is possible to build for ISTTOK a simple scaling model for the effective equilibrium magnetic fields, and perform plasma boundary reconstruction using the algorithm VacTH. This algorithm, included in the NICE numerical code suite, relies on the decomposition of the poloidal flux in toroidal harmonics. The reconstructed plasma boundary is shown for a given discharge and its shape and position are shown to evolve consistently with the typical timescale evolution of ISTTOK discharges. This provides an opportunity of using this plasma boundary reconstruction method as a diagnostic tool for ISTTOK.

4.4. Implementation of a method enabling error bar computations for all reconstructed equilibrium quantitites

Participant: Blaise Faugeras.

Error bars on control variables are directly given by the inverse of the Hessian of the minimized cost function. This is not the case for other quantities such as the safety factor profile for example, and the computation of error bars for these important output quantities necessitate the non-trivial computation of their (discrete) derivatives with respect to the control variables as wall as the state variables.

4.5. New developments on the code NICE

Participant: Blaise Faugeras.

Developments have been done on the code NICE:

- Implementation of a mode 'without plasma' for magnetostatic computations.
- Implementation of pressure constraints in NICE for IMAS tested on JET data.
- Regular updates of the relased NICE actor in IMAS (EUROfusion / WP13 Code Development for Integrated Modeling)
- A Matlab interface has been developped to run the free boundary direct, evolutive, and inverse static modes of NICE.

4.6. Automatic identification of the plasma equilibrium operating space in tokamaks

Participants: Blaise Faugeras, Xia Song, Eric Nardon, Holger Heumann.

In order to identify the plasma equilibrium operating space for future tokamaks, a new objective function is introduced in the inverse static free-boundary equilibrium code FEEQS.M. This function comprises terms which penalize the violation of the central solenoid and poloidal field coils limitations (currents and forces). The penalization terms do not require any weight tuning. Hence, this new approach automates to a large extent the identification of the operating space. As an illustration, the new method is applied on the ITER 15 and 17MA inductive scenarios, and similar operating spaces compared to previous works are found. These operating spaces are obtained within a few ($\sim$3) hours of computing time on a single standard CPU.

4.7. Automating the design of Tokamak experiment scenarios

Participants: Jacques Blum, Holger Heumann.

The real-time control of plasma position, shape and current in a tokamak has to been sured by a number of electrical circuits consisting of voltage suppliers and axisymmetric coils.Finding good target voltages/currents for the control systems is a very laborious, non-trivial task due to non-linear effects of plasma evolution. We introduce here an optimal control formulation to tackle this task and present in detail the main ingredients for finding numerical solutions:the finite element discretization, accurate linearizations and Sequential Quadratic Programming.Case studies for the tokamaks WEST and HL-2M highlight the flexibility and broad scope of the proposed optimal control formulation.

4.8. Coupling NICE-METIS

Participants: Jean François Artaud, Jacques Blum, Cédric Boulbe, Blaise Faugeras.

The free boundary equilibrium code NICE has been coupled to the fast transport solver METIS in a Matlab worflow. A first test case has been proposed on ITER. This work has been done for the project Eurofusion WPCD.

4.9. Advances in high order mixed finite elements for Maxwell's equations

Participant: Francesca Rapetti.

The implementation of high order curl- or div-conforming finite element spaces is quite delicate, especially in the three-dimensional case. I have worked on an implementation strategy, which has been applied in the open source finite element software FreeFem++. In particular, I have used the inverse of a generalized Vandermonde matrix to build a basis of generators in duality with the degrees of freedom, which then provides in FreeFem++ an easy-to-use but powerful interpolation operator. With Marcella Bonazzoli, now at the Inria Team DEFI in Saclay, I have carefully addressed the problem of applying the same Vandermonde matrix to possibly differently oriented tetrahedra of the mesh over the computational domain. [17]

High order mixed finite element spaces generally lack natural choices of bases but they do have spanning families. I have worked on these FEs for simplicial meshes and proven theoretically their effectiveness. I have also commented on some aspects of a new set of degrees of freedom, the so-called weights on the small simplices, to represent discrete functions in these spaces [11].

4.10. Construction of divergence-free bases

Participants: Francesca Rapetti, Ana Alonso Rodriguez.

I have worked to propose and analyze an efficient algorithm for the computation of a basis of the space of divergence-free Raviart-Thomas finite elements. The algorithm is based on graph techniques. The key point is to realize that, with very natural degrees of freedom for fields in the space of Raviart-Thomas finite elements of degree r + 1 and for elements of the space of discontinuous piecewise polynomial functions of degree $r \geq 0$, the matrix associated with the divergence operator is the incidence matrix of a particular graph. By choosing a spanning tree of this graph, it is possible to identify an invertible square submatrix of the divergence matrix and to compute easily the moments of a field in the space of Raviart-Thomas finite elements with assigned divergence. The analyzed approach is then used to construct a basis of the space of divergence-free Raviart-Thomas finite elements. The numerical tests show that the performance of the algorithm depends neither on the topology of the domain nor or the polynomial degree r [16].

4.11. First steps to polytopal/polyhedral meshes

Participant: Francesca Rapetti.

Merging ideas from compatible discretisations and polyhedral methods, I have worked with D. Di Pietro and J. Droniou to construct novel fully discrete polynomial de Rham sequences of arbitrary degree on polygons and polyhedra. The spaces and operators that appear in these sequences are directly amenable to computer implementation. Besides proving exactness, we have shown that the usual sequence of Finite Element spaces forms, through appropriate interpolation operators, a commutative diagram with other proposed sequence, which ensures suitable approximation properties. A discussion on reconstructions of potentials and discrete L2-products completes the work [14].

4.12. C^1 finite elements on triangular meshes

Participants: Hervé Guillard, Ali Elarif, Boniface Nkonga.

In order to avoid some mesh singularities that arise when using quadrangular elements for complex geometries and flux aligned meshes, the use of triangular elements is a possible option that we have studied in the past years. However due to the appearence of fourth order terms in the PDE systems that we are interested in, pure Galerkin methods require the use of finite element methods with C^1 continuity. The PhD thesis of Ali Elarif that has begun in october 2017 is devoted to the study of these methods for complex PDE models encountered in plasma physics. Relying on the work previously done on steady elliptic PDE, this year we applied these finite element methods to some evolution problems like the incompressible Navier-Stokes and MHD equations in stream-function formulation. Error estimates in H^2 norms have been obtained using standard finite element techniques. The simulation of some instabilities encountered in plasma physics have been done with very satisfactory results.

4.13. Modelling of acoustic streaming

Participants: Hervé Guillard, Argyris Delis [TUC, Crete].

Acoustic streaming is a particularly interesting example of the interaction of phenomena occuring on two different time scales. From a practical point of view, it is mainly used to generate a slow motion in micro-fluidic devices by means of high frequency acoustic sources. Modelling of these interaction is a challenge : taking into account the high frequency phenomena is prohibitively expensive but on the other hand, there is no universal agreement on existing averaged models. In order to have reference simulations, we have constructed a numerical code solving the compressible Navier-Stokes equations with high-order accuracy using compact schemes. Comparison with asymptotic analytical results has been done and shows that the code is able to simulate acoustic waves propagation in a stable way on long time scale, a property that is essential for the study of this phenomenon.

4.14. Mortar finite element methods

Participants: Hervé Guillard, Francesca Rapetti.

Hermite-Bezier finite element modeling is the standard method used to discretize the MHD equations in codes such as JOREK. This finite element family allows for an accurate description of the magnetic topology using flux aligned grids where the iso-parametric curved elements match the magnetic flux level sets. However, the description of complex material geometries is difficult with this family of finite element. We have begun to study the use of discretization methods using overlapping meshes where one mesh is composed of quadrangular Hermite-Bezier finite element while the second one is made of triangular elements.

4.15. Collisions in gyrokinetic equation

Participants: Afeintou Sangam, Vladimir T. Tikhonchuk.

Charged particles in plasma in strong magnetic fields undergo a complicated motion, which is a combination of a fast cyclotron gyration around the magnetic field lines and a relatively slow dynamics along and across the magnetic field lines. Gyrokinetic equations, devised to describe plasma under such conditions, eliminate the fast cyclotron gyration from the equation of motion, thus reducing the space-velocity phase space dimension from six to five.

Originally, the gyrokinetic formulation was devised for a collisionless plasmas. The quest for retaining collisions in gyrokinetic equations is ongoing. Collisions are important if one wants to describe the transport properties of a magnetized plasma on a macroscopic level. A description of the transport of energy and momentum was proposed in Refs. [18], [20], [19], [22], [21]. However, mathematical description of collisions in these works is too complicated for numerical implementation. We develop a simplified description of collision operators in the gyrokinetic formulation that preserve the pertinent conservation features and suitable for numerical modeling. A comparison of these operators with several test cases is under investigation.

4.16. Singular solutions of dispersive systems

Participants: S. Gavrilyuk, B. Nkonga, K-M Shyue, L. Truskinovsky.

We study a dispersive regularization of p-system. The governing equations are the Euler- Lagrange equations for a Lagrangian depending not only on the velocity and density, but also on the first material derivative of density. Such regularization arises, in particular, in the modeling of waves in solids, in bubbly fluids as well as in the theory of water waves. We show that such terms are not always regularizing. The solution can develop shocks even in the presence of dispersive terms. In particular, we construct such a shock solution that connects a constant state to a periodic wave train. The corresponding shock speed coincides with the velocity of the wave train. The generalized Rankine-Hugoniot relations (jump relations) are also obtained. The numerical evidence of the existence of such shocks is demonstrated in the case of the Serre-Green-Naghdi equations describing long surface water waves. In particular, it has been shown that such waves can dynamically be formed

4.17. A path conservative finite volume method for a shear shallow water model

Participants: P. Chandrashekar, B. Nkonga, A. K. Meena, A. Bhole.

The shear shallow water model provides a higher order approximation for shallow water flows by including the effect of vertical shear in the model. This model can be derived from the depth averaging process by including the second order velocity fluctuations, which are neglected in the classical shallow water approximation. The resulting model has a non-conservative structure, which resembles the 10-moment equations from gas dynamics. This structure facilitates the development of path conservative schemes and we construct HLL, 3-wave and 5-wave HLLC-type solvers. An explicit and semi-implicit MUSCL-Hancock type second order scheme is proposed for the time integration. Several test cases including roll waves show the performance of the proposed modeling and numerical strategy.

4.18. Full MHD Modeling of Shattered Pellet Injection

Participants: B. Nkonga, P. Chandrashekar, A. Bhole.

To avoid disruptions, the first thing to do is to operate as far as possible from disruptions operational limits. It means that plasma scenarios must be designed taking these limits into account. The challenge is to deal with peeling-ballooning instabilities called Edge Localized Modes (ELMs) which are characterized by the quasi-periodic relaxation of the pressure pedestal profile which results in the expelling of particles and energy from the bulk plasma to the edge. Injecting of impurities is one of the solutions to change the pedestal profile and mitigate MHD instabilities. The current design of the ITER DMS(Disruption Mitigation System) is a hybrid system using Massive Gas Injection (MGI) and Shattered Pellet Injection (SPI), methods which have demonstrated their efficiency on current tokamaks (JET, DIIID, ...). Considering that the plasma is composed of impurities, main ion core and set of electrons, premixed “Full MHD” formulation has been proposed. This model assumes that, for any control volume, the plasma is locally neutral and at the thermal and coronal equilibrium. Properties of this model are under analysis, according to the tabulated equation of state. A numerical approximation in the Jorek Code is also under progress. This work has been done in the context of the JET program 2019.

5. Partnerships and Cooperations

5.1. National Initiatives

5.1.1. ANR Sistem

Member of the ANR SISTEM, Oct. 2019 - Sept. 2023 coordinated by the M2P2 Institute of Aix-Marseille Univ. "SImulations with high-order schemes of tranSport and TurbulencE in tokaMak" programme Modeles numeriques 2019

- Participants: Francesca Rapetti, Blaise Faugeras, Didier Auroux, Jacques Blum, Cédric Boulbe

Contact: F. Rapetti

5.2. European Initiatives

5.2.1. FP7 & H2020 Projects

EuroFusion Consortium

CASTOR participates to the following EuroFusion consortium projects :

EUROfusion WPCD (Working Package Code Development):

- EWE-2: Enabling Workflow Exploitation Area - Enabling the exploitation of the equilibrium reconstruction and MHD stability workflow (participation)
- WDEV-2: Workflow Development Area - Free boundary equilibrium and feedback control (participation and coordination)

EuroFusion Enabling Research CfP-AWP19-ENR-01, Strengthening the non-linear MHD code JOREK for application to key questions of the fusion roadmap.

EUROfusion WPSA(Work Package JT-60SA) 2018-2010

5.3. International Initiatives

5.3.1. Informal International Partners

The team collaborates with TUC (Technical University of Crete, Prof. Argyris Delis) on the modelling of acoustic streaming phenomena. In this framework, Argyris Delis has visited the Castor team in November 2019.

6. Dissemination

6.1. Promoting Scientific Activities

6.1.1. Journal

6.1.1.1. Member of the Editorial Boards

- J. Blum is member of the editorial board of the Journal Scientific Computing.
- F. Rapetti is member of the editorial board of the Advances in Computational Mathematics (ACOM) journal by Springer
- C. Boulbe is managing editor of the SMAI Journal of Computational Mathematics

6.1.1.2. Reviewer - Reviewing Activities

- H. Guillard has been reviewer for the Journal of Computational physics, Computers and Fluids and International Journal for Numerical methods in Fluids.

6.1.2. Invited Talks

- F. Rapetti: Keynote speaker at the Enumath conference (Egmond aan Zee), oct 2019, "High-order Whitney forms on simplices"

6.1.3. Leadership within the Scientific Community

- H. Guillard is coordinator of the topic “Turbulence and transport of edge plasma” within the Fédération FR-FCM

6.2. Teaching - Supervision - Juries

6.2.1. Teaching

Licence : F. Rapetti, Mathématiques 2,30h équivalent TD, L2, Université Cote d’Azur, France

Master : F. Rapetti, Méthodes numériques, 70h équivalent TD, M1, Université Cote d’Azur, France

Ecole d’ingénieur, C. Boulbe, Analyse Numérique 2, 45 équivalent TD, niveau L3, Université Cote d’Azur

Ecole d’ingénieur, C. Boulbe, Analyse numérique 1, 71h équivalent TD, niveau L3, Université Cote d’Azur

Ecole d’ingénieur, C. Boulbe, Algèbre linéaire et Scilab, 26h équivalent TD, Université Cote d’Azur

Ecole d’ingénieur, C. Boulbe, Projet 1, 41h équivalent TD, Université Cote d’Azur

Licence: A. Sangam, Mathématiques Fondements 1, 60h, Semestre 1 de la Licence, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Méthodes Mathématiques - Approche Continue, 30h, Semestre 1 de la Licence, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Mathématiques Compléments 1, 5h, Semestre 1 de la Licence, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Mathématiques Fondements 2, 6h, Semestre 2 de la Licence, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Analyse 2, 2h, L2, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Analyse Numérique, 70h, L3, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Calcul Différentiel, 20h, L3, Université Nice Sophia Antipolis, France

Ecole d’ingénieur/Master: B. Nkonga, Méthode des éléments finis, 24h, M2, Polytech Nice Sophia, France

Ecole d'ingénieur/Master: B. Nkonga, Eléments finis mixtes, 24h, M2, Polytech Nice Sophia, France

6.2.2. Supervision

PhD : Xiao Song, Model-based Control-oriented Scenario Construction in Tokamaks, Université Cote d'Azur, 6 décembre 2019, Blaise Faugeras, Holger Heumann

PhD in progress : Ali Elarif, "Simulation numérique des instabilités magnétohydrodynamique dans les Tokamaks", October 2017, Hervé Guillard

6.2.3. Juries

- Hervé Guillard has been part of the jury for the Phd defence of Corentin Prigent, "Etude numérique et modélisation du modèle d'Euler bi-température : point de vue cinétique", Bordeaux University, 24/10/2019.
- Hervé Guillard was referee for the Phd jury of Clément Colas, "Formulation intégrale implicite pour la modélisation d'écoulements fluides en milieux encombrés", AMU University, 14/11/2019.
- Hervé Guillard has been part of the jury for the Phd defence of Quentin Carmouze, "Modélisation et simulation numérique des écoulements diphasiques denses et dilués", Nice University, 28/12/2019.
- F. Rapetti: Juan Antonio Soler Vasco, Univ. Aix-Marseille, Sep. 2019.
- F. Rapetti: Anouk Nicolopoulos-Salle, Univ. Sorbonne Paris, Déc. 2019.
- B. Faugeras, H. Heumann, H. Guillard and J. Blum: Xiao Song, Université Cote d'Azur, Dec. 2019

7. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journal

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[2] A. BHOLE, B. NKONGA, S. L. GAVRILYUK, K. A. IVANOVA.*Fluctuation splitting Riemann solver for a non-conservative modeling of shear shallow water flow*, in "Journal of Computational Physics", 2019 [*DOI :* 10.1016/J.JCP.2019.04.033], https://hal.archives-ouvertes.fr/hal-01877504

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[15] Y.-C. TAI, J. VIDES, B. NKONGA, C.-Y. KUO.*Multi-Scale Approximation of Thin-Layer Flows on Curved Topographies*, October 2019, working paper or preprint, https://hal.inria.fr/hal-02305269

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Team CHORALE

Collaborative and HeterOgeneous Robots interActing in Live Environment

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Robotics and Smart environments

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Team CHORALE

Creation of the Team: 2018 April 01

CHORALE team is the continuation of the LAGADIC team at Sophia Antipolis.

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A3.1.10. - Heterogeneous data
A3.2.3. - Inference
A3.4.1. - Supervised learning
A3.4.3. - Reinforcement learning
A3.4.8. - Deep learning
A5.4.2. - Activity recognition
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A5.4.7. - Visual servoing
A5.10.2. - Perception
A5.10.3. - Planning
A5.10.4. - Robot control
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1. Team, Visitors, External Collaborators

Research Scientists

Philippe Martinet [Team leader, Inria, Senior Researcher, HDR]
Patrick Rives [Inria, Senior Researcher, HDR]
Paolo Salaris [Inria, Researcher, until Aug 2019]

External Collaborators

Guillaume Allibert [Univ de Nice - Sophia Antipolis]
Nesrine Chedly [Univ de Nice - Sophia Antipolis, until Jun 2019]
Ahmed Khalifa [École centrale de Nantes, until Aug 2019]
Beatriz Pascual Escudero [Univ de Nantes, until Mar 2019]

Technical Staff

John Thomas [Inria, Engineer, from Dec 2019]

PhD Students

Mohamed Boussaha [IGN, PhD Student]
Luis Federico Contreras Samane [École centrale de Nantes, PhD Student, until Mar 2019]
Franco Fusco [Univ de Nantes, PhD Student]
Dayana Hassan [AXYN, PhD Student, granted by CIFRE]
Ihab Mohamed [Univ Côte d'Azur, PhD Student]
David Perez Morales [École centrale de Nantes, PhD Student, until December 2019]

Post-Doctoral Fellow

Renato Martins [Inria, Post-Doctoral Fellow, from Apr 2019]

Visiting Scientist

Enric Cervera [Jaume I University (Spain), from May 2019 until Aug 2019]

Administrative Assistant

Patricia Riveill [Inria, Administrative Assistant, from April 2018]

2. Overall Objectives

2.1. Overall Objectives

The main objective is to study autonomous robotic systems, from the perception and the control point of views, interacting and evolving among the human beings in live and dynamic environments. By autonomous robotic systems, we refer to Autonomous Vehicles, Mobile robots, UAV and combination of them. Our research ambition is to explore new paradigms and concepts allowing autonomous robotic systems i) to acquire and share a task-oriented representation of the world (accounting for interactions with humans) ii) to act and interact in human-like environments (accounting for interactions with humans) in a safe and efficient way. Task specification, world and interaction modelling, situation awareness, multi sensor based perception and control, the coupling between perception and action, and hybrid model based/deep learning based architectures will be the main focuses of our researches. Although the underlying concepts could be potentially applied to manipulator arms, we have voluntarily restricted the scope of the project to mobile robotic applications that sound more topical and challenging.

3. Research Program

3.1. Task based world modeling and understanding

Executing a robotic task needs to specify a task space and a set of objective functions to be optimized. One research issue will be to define a framework allowing to represent the tasks in a generic canonic space in order to make their design and their analysis easier thanks to the control theory tools (observability, controllability, robustness…). All along the execution of the task, autonomous robotics systems have to acquire and maintain a model of the world and of the interactions between the different components involved in the task (heterogeneous robots, human beings, changes in the environment…). This model evolves in time and in space. In this research axis, we will investigate novel task-oriented world multi-layers representations (photometry, geometry, semantic) embedded in a short/long term memory framework able to handle static and dynamic events (long term mapping). A particular attention will be also paid to integrate human-robot interactions in shared environment (social skills). Another ambition of the project will be to build a bridge between model-based and machine learning methods. Understanding the world evolution is one of the key of autonomy. In this aim, we will focus on situation awareness.

3.2. Multi-sensory perception and control

Multi-sensory based perception and control is an area that starts from one single robot evolving in the environment with a set of sensors, up to a set of heterogeneous robots collaborating for the execution of a global shared task. We will address problems such as the active selection of the most suitable source of information (e.g. sensors and features) during the execution of the task and the active sensing control in order to maximize the collected information about the world modeling (including calibration and environment parameters, exogenous disturbances), allowing the task-driven sensor-based control framework to be more efficiently and robustly executed. Another issue will be the execution of a task defined by another robot or human, and to be replicated with a robot with different capabilities in perception, control and level of autonomy (i.e. heterogeneous robots). Last issues will come from the collaboration of different autonomous and heterogeneous robots in order to accomplish a shared task (mapping, robust localization, calibration, tracking, transporting, moving, …)

4. Application Domains

4.1. Transportation of people and goods

The researches developed in CHORALE can be applied in different applications fields. We are particularly interested in *transportation of people and goods*. CHORALE contribute to the development of Autonomous Connected Vehicles (e.g. Learning, Mapping, Localization, Navigation) and the associated services (e.g. towing, platooning, taxi).

4.2. Assistance and services robots

We are also interested in *assistance and service robotics*. By adding the social level in the representation of the environment, CHORALE develops social and proactive navigation.

4.3. Survey and monitoring of environments

CHORALE studies multi-robots systems to explore, survey and monitor different kind of environments (e.g. agricultural space, forest space, destroyed space), which are of particular importance in the field of *Exploration and monitoring of poorly structured environments*.

5. New Software and Platforms

5.1. Perception360

Perception360 is an integration software platform for all perception developments in the Inria CHORALE team. All functions have been coded in a modular and scalable ROS environment by including a generic model to take into account the different sensors (monocular perspective vision (RGB), vision stereo perspective (RGB-D), spherical vision (RGB and RGB-D).

The main application concerns representation of the environment (multi-layers topological and spherical representation of the environment), Localization, SLAM and Navigation.

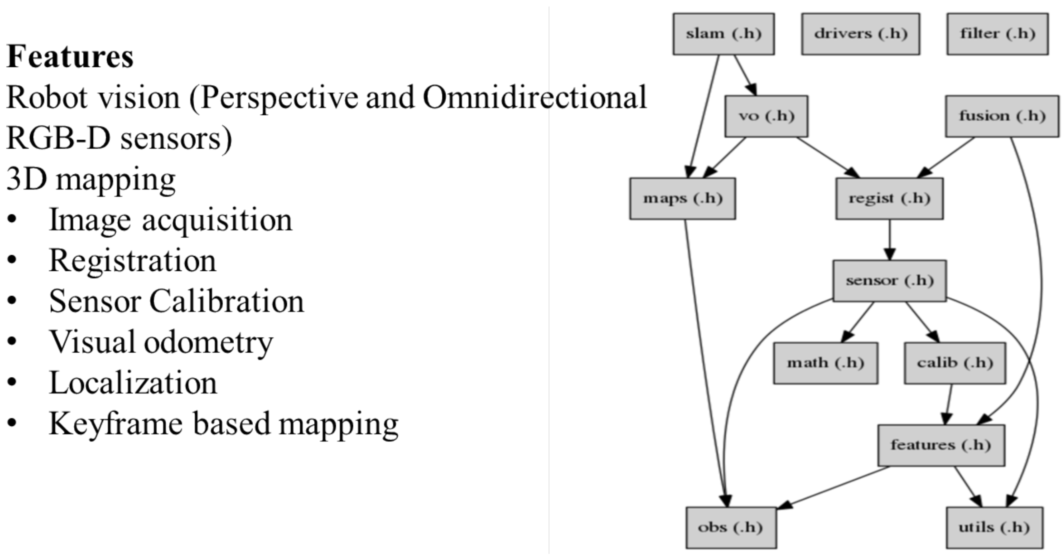

Figure 1. PERCEPTION360

5.2. ICAV

ICAV is an Intelligent and Connected Autonomous Vehicle. It is composed of a Renault ZOE robotized by Ecole Centrale of Nantes (by the team setup by Philippe Martinet in LS2N/ARMEN).

Figure 2. ICAV plateform and its web interface

The robotization allows to have access to the control of:

- Steering angle (or steering torque)
- Braking torque
- Acceleration
- Gear box
- Blinking light

In its original version, it is composed of embedded sensors:

- Car odometry and velocity
- Low cost GPS (Ublox 6)
- Low cost IMU
- Lidar VLP16 from Velodyne
- Two front cameras in the bumper
- One rear camera in the bumper

and one embedded computer, with a web interface connected to a simple tablet. All the equipments are connected to the existing comfort battery. This equipment has been funded by UCA (Digital Reference Centre) and delivered late 2018.

In addition, in the framework of a collaboration between CHORALE and LS2N/ARMEN one global application of Mapping/Localization/Navigation/Parking is installed in the vehicle. This application is using LIDAR VLP16 based mapping algorithm developed in Nantes including the last two years collaboration work between CHORALE and ARMEN. In January 2019, we have done the map of the Inria Sophia Antipolis Center, and other places of Sophia Antipolis. On all places, it is possible to localize the vehicle, register a path and then proceed to autonomous navigation (if we obtain the authorization to make it). Fast prototyping tools environment called ICARS is available for both simulation and development purposes.

In december 2019, we have evaluated the navigation algorithm on the new experimental site made available by CASA.

Figure 3. CASA experimental site in Sophia Antipolis

In the near future, in the framework of the project SPHERE we will integrate a novel 360 degree camera system with the Perception360 platform and embed this system in ICAV. A global 360 degree navigation system will be developed.

5.3. DRONIX

In 2019, we have defined and installed a capture motion system composed of 6 cameras coming from the QUALISYS company. This system allows to track and localize a multi robot system.

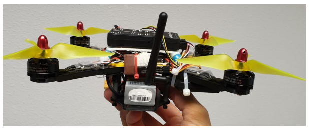

Figure 4. DRONIX plateform

In our applications, we will consider the use of UAVs and possibly the collaboration between UAVs and AGV. The DRONIX platform will be used for real time navigation, and as a ground truth system. The system has a central computer and each robots will have possible access to the global information by wifi.

6. New Results

6.1. Task based world modeling and understanding

6.1.1. Hidden robot

Participants: John Thomas (Master student), Philippe Martinet, Paolo Salaris, Sébastien Briot (LS2N-ARMEN)

When robots want to execute a task, they require to have an adequate representation of the environment where they will evolve. In model based approach, it is classical to describe environment using Metric Map where the function of perception (localization) and control (Path or trajectory tracking) refer to Cartesian state. In sensor based control, the methodology "teaching by showing" has been developed during the last 30 years. The concept of sensory memory has been then introduced in order to represent the task to be executed in sensor space. This concept is used in order to represent the task directly in the sensor space for a particular set of sensors. In summary, building the representation of the task (or the environment) is building the sensory memory, defining a particular motion (or trajectory) is defining a particular occurrence of sensor features, and executing the task is done when a control is designed to perceive the same as stored in the sensory memory. This approach has shown great ability in terms of robustness. However, it is still difficult to analyze the singularities and to demonstrate the stability property for those approaches (mainly when it is necessary to control 6 degree of freedom). In 2013, Sébastien Briot and Philippe Martinet have studied the visual servoing scheme of a Gough-Stewart Platform [18] and shown that it exists an hidden robot in the controller that can be used to study the behaviour and properties of it. The Hidden robot allows to transform the analysis of the controller by viewing it as a parallel robot. Recently, this concept has been applied to study the singularities of the visual servoing scheme of points and of lines [19]. This work continues in the framwork of the ANR project SESAME.

The idea of the new initial work done in 2019, is to find a methodology to design a task by using the Hidden robot concept. Navigation of a mobile robot has been considered in a first time. The followed methodology considers a topological navigation framework where a successive interaction situation are modelled by using an hidden robot: in some words, navigation is done by using a set of successive hidden parallel robots holding the robot when moving. At least two main question have been identified: What is the structure of the virtual robot which fits to task to be done? and Where to fix (or How to select) the anchors of this virtual robots?

For the first question, the idea is, considering different kind of features, to define a virtual parallel robot based on virtual legs. These virtual legs are directly linked to the considered feature. We have studied two cases, distance and angle, considering that existing sensors allow us to obtain the corresponding extracted features. After the modeling of sensors features, different control laws have been investigated allowing to produce motion of the mobile plateform. The corresponding hidden robots and the properties have been studied.
For the second question, two methods have been investigated using selection matrix of features or weighted features. The main used criteria is the transmibility index which relates the faculty of motion transmission of the virtual parallel mecanism.
This work [52] is preliminary and on going. We already have obtained preliminary results in simulation allowing a mobile plateform to evolve in a dedicated environment. It was the work done by John Thomas under the supervision of Philippe Martinet and Paolo Salaris.

6.1.2. End to end navigation

Participants: Renato Martins (Post-doc), Patrick Rives

This research deals with the problem of end-to-end learning for navigation in dynamic and crowded scenes solely from visual information. We investigate the problem of navigating an unknown space to reach a target of interest, for instance “doors", exploring the possibilities given by data-driven based models in the context of ANR MOBI-Deep project around the guidance of visually impaired people. A successful agent navigation policy requires learning general relationships between the agent actions, safety rules and its surrounding environment. We started studying a simple guidance model (turn left, right or stop), whose guidance task is to remain inside a specific region of the scene (to avoid collusion). This is equivalent to take the action to stay in the center of a corridor (indoor scene) or road (outdoor scenario). We first evaluate a relatively small supervised net composed of sixteen ResNet convolutional layers. This model was trained with real images from the Udacity autonomous driving challenge, but presented limited generalization when tested in either non-structured scenes or in scenes with humans. In order to overcome these limitations, we plan to train an A3C agent (Asynchronous Actor-Critic Agent) to learn the action policies in a reinforcement learning scheme, using data acquired of virtual environments with crowds. We also plan to evaluate the use of inputs from different levels as: scene semantic segmentation; depth inference from monocular images; and human and object detection information in the learning scheme.

6.1.3. Semantization of scene

Participants: Mohammed Boussaha (PhD, IGN), E. Fernandez-Moral, R. Martins, Patrick Rives

The work carried out in the ANR PlaTINUM project concerns the semantic labeling of images [17] acquired by agents (autonomous vehicles or pedestrians) moving in an urban-like environment and their accurate localization and guidance. A semantic labeling based on a machine learning approach (CNN) was developed. A same methodology is used to semantize virtual images built from a textured 3D mesh representation of the environment and images from the camera handled by the agents. Several strategies have been studied to exploit complementary information, such as color and depth for improving the accuracy of semantization. Our results show that exploiting this complementarity requires to perfectly align the different sources of informations. We proposed a new approach to the problem of calibration of heterogeneous multi sensors systems [41], [44]. We also looked for evaluating a new metric to quantify the accuracy of semantization provided by the CNN by taking into account the boundaries of semantized objects during the learning step. As a consequence, we show that weighting the boundary pixels in the images allows to segment more clearly the navigable areas used by different agents such as pedestrians (sidewalks) and cars (road). The results of this research were published in [29], [30]. The CNN used for labeling imagesacquired by different image sensors (perspective and spherical) was pre-trained from public datasets with perspective images of urban-like environments (simulated or real). In the context of the Platinum ANR project, a fine-tuning was done with some spherical images acquired in Rouen by the IGN Stereopolis vehicle and then hand-labelled. A Docker version of the software has been made available on the project server in order to be used by the other partners.

A localization method has also been implemented to exploit information of color, depth and semantics (when this information is available). An estimation of the agent position (6DOV, rotation and translation) is computed thanks to a dense method that minimizes the geometric, photometric and semantic differences between a spherical view provided by a SIG (Système d'Information Géographique) data base hosted in a cloud server and the current view of the agent.

During the last year of the project, the methods developed in PlaTINUM were consolidated and validated on the data acquired in Rouen. As originally planned in the project, Inria enlisted the help of iXblue-division Robopec to integrate the various functions developed during the project. This software, called Perception360, will be from now the software platform for all perception developments in the Inria CHORALE team.

6.1.4. Optical Flow Estimation Using Deep Learning In Spherical Images

Participants: Haozhou Zhang (Master), Cédric Demonceaux (Vibot), Guillaume Allibert

In a complex environment such as in a forest, the autonomous navigation is a challenging problem due to many constraints such as the loss of GPS signals because dense and unstructured environments (branches, foliage, ...) reduce the visibility. Without GPS signals, a vision system with the ability to capture everything going on around you seems more valuable than ever and crucial to navigate in this environment. Spherical images offer great benefits over classical cameras wherever a wide field of view is essential.

The equirectangular projection is a popular representation of images taken by spherical cameras. In this projection, the latitude and longitude of the spherical images are projected to horizontal and vertical coordinates on a 2D plane. However, this equirectangular projection suffers from distortions, especially in polar regions. In this case, the density of features is no longer regular at different latitudes of the images. As a result, traditional image processing methods that have been used for perspectives images do not have good performance when they are applied to equirectangular images.

Optical flow estimation is a basic problem of computer vision [50]. It is generally used as input of algorithm for autonomous navigation. Given two successive images, it estimates the motion vector in 2D (in x and y direction) for each pixel from between the two input images. Optical flow is usually considered as a good approximation of the true physical motion mapped on the image plane. It provides a concise description of the direction and velocity of the motion. In [24] and [36], CNNs which are capable of solving the optical flow estimation problem as a supervised learning task are proposed and became the standard for optical flow estimation. However, the dataset used to train [24], [36] is only based on perspective images. Even if they can be used directly with spherical images as input, the high distortions coming from equirectangular projection drastically reduce the global performance of these networks. One possible way to solve this issue is to train the networks proposed in [24], [36] with spherical images. Unfortunately, these databases do not exist and generating them would be a long and costly process.

In the Master's Hoazhou [55], we have proposed a solution to overcome this issue in proposing an adaptation of FlowNet networks to deal with the distortions in the equirectangular projection of spherical images. The proposed approach lies a distortion aware convolution used as convolution layers in the network to deal with distortions in equirectangular images. The proposed networks allows the models to be trained by perspective images and be applied to spherical images using an adapted convolution which is coherent with the spherical image. This solution avoids training a large number of spherical images which is not available and costly to generate.

6.2. Multi-sensory perception and control

6.2.1. Autonomous Parking Maneuvers

Participants: David Perez Morales (PhD, LS2N-ARMEN), Olivier Kermorgant (LS2N-ARMEN), Salvador Dominguez Quijada (LS2N-ARMEN), Philippe Martinet

Automated parking is used as new functionality to sell different model of cars right now. Mainly, the different versions of parking abilities are not autonomous and are based on motion planning only. There is no ability to evolve in dynamic environment: it remains automated in static environment, or even an assistant to park under the control of the driver. The purpose of the PhD work of David Perez Morales was to investigate how the problem of autonomous parking by using different sensor based techniques is able to handle any kind of parking situations (parallel, perpendicular, diagonal) for parking an unparking (backward and forward).

Two different frameworks has been developed. The first framework, using a Multi-Sensor-Based Control (MSBC) approach [47], [48], [46], [45] allows to formalize different parking and unparking operations in a single maneuver with either backward or forward motions. Building upon the first one and by using an MPC strategy [49], a Multi-Sensor-Based Predictive Control (MSBPC) framework has been developed, allowing the vehicle to park autonomously (with multiple maneuvers, if required) into perpendicular and diagonal parking spots with both forward and backward motions and into parallel ones with backward motions in addition to unpark from parallel spots with forward motions. These frameworks have been tested extensively using a robotized Renault ZOE with positive outcomes and now they are part of the autonomous driving architecture being developed at LS2N.

In 2019, the main focus was on MSBPC, and on taking into account the dynamic aspect in the environment (mainly pedestrians). Detection and tracking for pedestrian has been included in the perception aspect, in parallel to the detection of empty spots for parking. An additional terms has been added as a contraint in the cost function to be minimized in order to take into account the dynamic aspect, and a mecanism has been put in place in order to switch automatically the maneuver. In presence of pedestrian, an additional maneuver is engaged, which is what human are generally doing if place is enough for performing safely the maneuver. Comparison with state of the art motion planning approach have been done in simulation. The proposed method have demonstrated the efficiency while the others fails in a very long set of maneuvers. Real experiments have been done also in presence of pedestrians.

6.2.2. Platoon control and observer

Participants: Ahmed Khalifa (Post-Doc, LS2N-ARMEN), Olivier Kermorgant (LS2N-ARMEN), Salvador Dominguez Quijada (LS2N-ARMEN), Philippe Martinet

In the framework of the ANR Valet project, we are interested in platooning control of cars for a service of VALET Parking where it is necessary to join a platoon (after unparking), to evolve among the platoon, and leave the platoon (for parking). We are considering the case when the leader is autonomous (following an already defined path) or manually driven by a human (the path must be build on line). The lateral controller to follow a path has been designed earlier [23] and the localization technique largelly evaluated experimentally [33]. The main exteroceptive sensor is the Velodyne VLP16.

The first work [38] [15] concerned the design of a distributed longitudinal controller for car-like vehicles platooning that travel in an urban environment. The presented control strategy combines the platoon maintaining, gap closure, and collision avoidance functionality into a unified control law. A consensus-based controller designed in the path coordinates is the basis of the proposed control strategy and its role is to achieve position and velocity consensus among the platoon members taking into consideration the nature of the motion in an urban environment. For platoon creation, gap closure scenario is highly recommended for achieving a fast convergence of the platoon. For that, an algorithm is proposed to adjust the controller parameters online. A longitudinal collision between followers can occur due to several circumstances. Therefore, the proposed control strategy considers the assurance of collision avoidance by the guarantee of a minimum safe inter-vehicle distance. Convergence of the proposed algorithm is proved in the different modes of operations. Finally, studies are conducted to demonstrate and validate the efficiency of the proposed control strategy under different driving conditions. To better emulate a realistic setup, the controller is tested by an implementation of the car-like vehicles platoon in a vehicular mobility simulator called ICARS, which considers the real vehicle dynamics and other platooning staff in urban environments.

The second work [14] adresses the problem of controlling the longitudinal motion of car-like vehicles platoon navigating in an urban environment that can improve the traffic flow with a minimum number of required communication links. To achieve a higher traffic flow, a constant-spacing policy between successive vehicles is commonly used but this is at a cost of increased communication links as the leader information must broadcast to all the followers. Therefore, we propose a distributed observer-based control law that depends on a hybrid source of neighbours information in which a sensor-based link is used to get the predecessor position while the leader information is acquired through a communication-based link. Then, an observer is designed and integrated into the control law such that the velocity information of the predecessor can be estimated. We start by presenting the platoon model defined in the Curvilinear coordinates with the required transformation between that coordinate and the Cartesian Coordinates so that one can design the control law directly in the Curvilinear coordinates. After that, internal and string stability analysis are conducted. Finally, we provide simulation results, through dynamic vehicular mobility simulator called ICARS, to illustrate the feasibility of the proposed approach and corroborate our theoretical findings.
Both work have been tested in real with a platoon of 3 up to 4 cars.

6.2.3. High speed visual servoing

Participants: Franco Fusco (PhD, LS2N-ARMEN), Olivier Kermorgant (LS2N-ARMEN), Philippe Martinet

Controlling high speed robot with visual feedback may require to develop more complex models including the dynamics of the robots and the environment. Some previous work done in the field of dynamic visual feedback of parallel robots [42] have demonstrated the efficiency regarding the classical Joint computed torque control. Also, it has been shown that it is also possible to develop more complex interaction models [20].

In recent years, many efforts have been dedicated to extend Sampling-based planning algorithms to solve problems involving constraints, such as geometric loop-closure, which lead the valid Configuration Space to collapse to a lower-dimensional manifold. One proposed solution considers an approximation of the constrained Configuration Space that is obtained by relaxing constraints up to a desired tolerance. The resulting set has then non-zero measure, allowing therefore to exploit classical planning algorithms to search for a path that connects two given states. When the constraints involve kinematic loops in the system, relaxation generally bears to undesired contact forces, which needs to be compensated during execution by a proper control action. We propose a new tool that exploits relaxation to plan in presence of constraints [32]. Local motions inside the approximated manifold are found as the result of an iterative scheme that uses Quadratic Optimization to proceed towards a new sample without falling outside the relaxed region. By properly guiding the exploration, paths are found with smaller relaxation factors and the need of a dedicated controller to compensate errors is reduced. We complete the analysis by showing the feasibility of the approach with experiments on a real manipulator platform.

The commonly exploited approach in visual servoing is to use a model that expresses the rate of change of a set of features as a function of sensor twist. These schemes are commonly used to obtain a velocity command, which needs to be tracked by a low-level controller. Another approach that can be exploited consists in going one step further and to consider an acceleration model for the features. This strategy allows also to obtain a natural and direct link with the dynamic model of the controlled system. The work done in [13] aims at comparing the use of velocity and acceleration-based models in feed-back linearization for Visual Servoing. We consider the case of a redundant manipulator and discuss what this implies for both control techniques. By means of simulations, we show that controllers based on features acceleration give better results than those based on velocity in presence of noisy feedback signals.

We are working to propose new prediction models for Visual Predictive Control that can lead to both better motions in the feature space and shorter sensor trajectories in 3D. Contrarily to existing local models based only on the Interaction Matrix, it is proposed to integrate acceleration information provided by second-order models. This helps to better estimate the evolution of the image features, and consequently to evaluate control inputs that can properly steer the system to a desired configuration. By means of simulations, the performances of these new predictors are shown and compared to those of a classical model. Real experiments confirm the validity of the approach and show that the increased complexity.

6.2.4. *Proactive and social navigation*

Participants: Maria Kabtoul (PhD), Wanting Jin (Master), Anne Spalanzani (CHROMA), Philippe Martinet, Paolo Salaris

In the last decade, many works have been done concerning navigation of robots among humans [34], [27] or human robots interaction [22], [31]. In very few cases, a robot can realize an intention to move.

In this work, we would like that robots can express their needs for sharing spaces with humans in order to perform their task (i.e. navigation in crowdy environments). This requires to be proactive and adapt to the behavior by exploiting the potential collaborative charcateritics of the nearby environment of the robots.

In the framework of the ANR project HIANIC, Maria Kabtoul is doing her PhD on the topic Proactive Social navigation for autonomous vehicles among crowds. We consider shared spaces where humans and cars are able to evolve simultaneously. The first step done in this way is to introduce a pedestrian to vehicle interaction behavioral model. The model estimates the pedestrian's cooperation with the vehicle in an interaction scenario by a quantitative time-varying function. Then, the trajectory of the pedestrian is predicted based on its cooperative behavior. Both parts of the model are tested and validated using real-life recorded scenarios of pedestrian-vehicle interaction. The model is capable of describing and predicting agents' behaviors when interacting with a vehicle in both lateral and frontal crossing scenarios.

In the framework of the ANR project MOBI-DEEP, we have addressed the problem of navigating a robot in a constrained human-like environment. We provide a method to generate a control strategy that enables the robot to proactively move in order to induce desired and socially acceptable cooperative behaviors in neighboring pedestrians. Contrary to other control strategies that simply aim to passively avoid neighboring pedestrians, this approach greatly simplifies the navigation task for both robots and humans, especially in crowded and constrained environments. In order to reach this objective, the co-navigation process between humans and robots is formalized as a multi-objective optimization problem and a control strategy for the robot is obtained by using the Model Predictive Control (MPC) approach. The Social Force Model (SFM) is used to predict the human motion in cooperative situations. Different social behaviors of humans when moving in a group are also taken into account to generate the proper robot motion. Moreover, a switching strategy between purely reactive (if cooperation is not possible) and proactive-cooperative planning depending on the evaluation of the human intentions is also provided. Simulations under different navigation scenarios show how the proactive-cooperative planner enables the robot to generate more socially and understandable behaviors.

This work has been done by Wanting Jin during her Master thesis [37].

6.2.5. *Safe navigation*

Participants: Luiz Guardini (PhD), Anne Spalanzani (CHROMA), Christian Laugier (CHROMA), Philippe Martinet, Anh-Lam Do (Renault), Thierry Hermitte (Renault)

Today, car manufacturer are selling systems to brake in presence of obstacle. Those systems are based on the fact that the risk of collision is always detected and well evaluated. Their action are limited on brake only, which is in some case not sufficient to limit the risk. A global and safe system must be more efficient in environment perception awareness and also in action to be decided (break, steer, acceleration). In such a case, it is very complicated to find the best solution as long as we have to evaluate the different solutions in a near horizon in terms of risk of colisions and severity injuries. Car manufacturer are interested to find solution (i.e evaluation of trajectories (planification and action) in terms of risks and injuries.

Evaluating a scene to perform a collision avoidance maneuver is a hard task for both humans and (semi-) autonomous vehicles. There are some cases though that collision avoidance is inevitable. Interpreting the scene for a possible collision avoidance is difficult already a difficult task. Choosing how to mitigate the damage seems even harder, specially when humans have only a split of second to decide how to proceed.

Intending to decrease the reaction time and to increase safety on dangerous driving situations, one can rely on intelligent systems. Nevertheless, autonomous vehicles simulation and testing usually focus on risk assessment and path planing on regular driving conditions [40]. For instance, Waymo from Google, still do not have the full capability of avoiding collision initiated by other vehicles [28].

Developing Advanced Driver Assistance Systems (ADAS) technologies is one alternative for these emergency scenarios. It includes systems such as Active Braking System (ABS), Forward Collision Warning (FCW) and Collision Avoidance (CA). The latter is one of the most complex systems developed in order to assure safety. It perceives technologies such as Advanced Emergency Braking (AEB) and Autonomous Emergency Steering (AES) System. Those systems attempt to avoid the crash or at least reduce its severity. Developing a CA system starts by assessing the available information in the scene. This is made by establishing safe zones that the vehicle can access. The notion of safety of severity is usually addressed by the concept of risk. Risk can be intuitively understood as the likelihood and severity of the damage that an object of interest may suffer or cause in the future. Threat Assessment (also referred as Risk Assessment or Hazard Assessment) makes use of such concept.

The excellence of the data evidenced in the scene plays a major role in risk assessment and mitigation. Up to date, objects in the scene are not contextualized. For instance, pedestrians are treated as forbidden zones whereas cars are allowed to be collided when mitigation is necessary. This might be a correct assessment in some cases, but not always. The injury risk changes independently to each object according to aspects on the scene, such as the impact velocity and angle of collision.

This work focus on the development of a probabilistic cost map that expresses the Probability of Collision with Injury Risk (PCIR). On top of the information gathered by sensors, it includes the severity of injury in the event of a collision between ego and the objects in the scene. This cost map provides enhanced information to perform vehicle motion planning in emergency trajectories where collision is impending.

We represent the environment though probabilistic occupancy grids. It endures agile and robust sensor interpretation mechanisms and incremental discovery procedures. It also handles uncertainty thanks to probabilistic reasoning [25].

We use the Conditional Monte Carlo Dense Occupancy Tracker (CMCDOT developed in CHROMA). It is a generic spatial occupancy tracker that infers dynamics of the scene through a hybrid representation of the environment. The latter consists of static and dynamic occupancy, empty spaces and unknown areas. This differentiation enables the use of state-specific models as well as relevant confidence estimation and management of dataless areas [51].

Although CMCDOT occupancy grid leads to a very reliable global occupancy of the environment, it works on a sub-object level, meaning that the grid by itself does not carry the information on object classification. To overcome this, Erkent et al [26] proposes a method, which estimates an occupancy grid containing detailed semantic information. The semantic characteristics include classes like road, car, pedestrian, sidewalk, building, vegetation, etc.

The proposed Probabilistic risk map has been built and validation has been done in simulation using Gazebo using different scenarios (identified by the car manufacturer).

6.2.6. 3D Autonomous navigation using Model Predictive Path Integral approach

Participants: Ihab Mohamed (PhD), Guillaume Allibert, Philippe Martinet

Having a safe and reliable system for autonomous navigation of autonomous systems such as Unmanned Aerial Vehicles (UAVs) is a highly challenging and partially solved problem for robotics communities, especially for cluttered and GPS-denied environments such as dense forests, crowded offices, corridors, and warehouses. Such a problem is very important for solving many complex applications, such as surveillance, search-and-rescue, and environmental mapping. To do so, UAVs should be able to navigate with complete autonomy while avoiding all kinds of obstacles in real-time. To this end, they must be able to (i) perceive their environment, (ii) understand the situation they are in, and (iii) react appropriately.

To solve this problem, the applications of the path-integral control theory have recently become more prevalent. One of the most noteworthy works is Williams's iterative path integral method, namely, Model Predictive Path Integral (MPPI) control framework Williams et al. [53]. In this method, the control sequence is iteratively updated to obtain the optimal solution based on importance sampling of trajectories. In Williams et al [54], authors derived a different iterative method in which the control- and noise-affine dynamics constraints, on the original MPPI framework, are eliminated. This framework is mainly based on the information-theoretic interpretation of optimal control using KL-divergence and free energy, while it was previously based on the linearization of Hamilton-Jacob Bellman (HJB) equation and application of Feynman-Kac lemma.

The attractive features of MPPI controller, over alternative methods, can be summarized as: (i) a derivative-free optimization method, i.e., no need for derivative information to find the optimal solution; (ii) no need for approximating the system dynamics and cost functions with linear and quadratic forms, i.e., non-linear and non-convex functions can be naturally employed, even that dynamics and cost models can be easily represented using neural networks; (iii) planning and execution steps are combined into a single step, providing an elegant control framework for autonomous vehicles.

In the context of autonomous navigation, it is observed that the MPPI controller has been mainly applied to the tasks of aggressive driving and UAVs navigation in cluttered environments. For instance, to navigate in cluttered environments, the obstacle map is assumed to be known (either available a priori or built off-line), and only static 2D floor-maps are used. Conversely, in practice, the real environments are often partially observable, with dynamic obstacles. Moreover, only 2D navigation tasks are performed, which limits the applicability of the control framework.

For this reason, our work focuses on MPPI for 2D and 3D navigation tasks in cluttered environments, which are inherently uncertain and partially observable. To the best of our knowledge, this point has not been reported in the literature, presenting a generic MPPI framework that opens up new directions for research.

We propose a generic Model Predictive Path Integral (MPPI) control framework that can be used for 2D or 3D autonomous navigation tasks in either fully or partially observable environments, which are the most prevalent in robotics applications. This framework exploits directly the 3D-voxel grid, e.g., OctoMap [35], acquired from an on-board sensing system for performing collision-free navigation.We test the framework, in realistic RotorS-based simulation, on goal-oriented quadrotor navigation tasks in a 2D/3D cluttered environment, for both fully and partially observable scenarios. Preliminary results demonstrate that the proposed framework works perfectly, under partial observability, in 2D and 3D cluttered environments.

We demonstrate our proposed framework on a set of simulated quadrotor navigation tasks in a 2D and 3D cluttered environment, assuming that: (i) there is a priori knowledge about the environment (namely, fully observable case); (ii) there is not any a priori information (namely, partially observable case); here, the robot is building and updating the map, which represents the environment, online as it goes along.

6.2.7. Perception-aware trajectory generation for robotic systems

Participant: Paolo Salaris, Marco Cognetti (PostDoc, RAINBOW), Valerio Paduano (Master, RAINBOW), Paolo Robuffo Giordano (RAINBOW)

We now focus on our planned research activities on task-oriented perception and control of a robotic system engaged in executing a task. The main objective is to improve the execution of a given task by fruitfully *coupling action and perception*. We aim at finding the correct balance between efficient task execution and quality of the information content since the amount of the latter has an impact on the possibility of correctly executing the task. Indeed, a robot needs to solve an estimation problem in order to safely move in unstructured environments and accomplishing a task. For instance, it has to self-calibrate and self-localize w.r.t. the environment while, at the same time, a map of the surroundings may be built. These possibilities are highly influenced by the quality and amount of sensor information (i.e., available measurements), especially in case of limited sensing capabilities and/or low cost (noisy) sensors.

For nonlinear systems (i.e., the most of the robotics systems of our interest) the amount and quality of the collected information depends on the robot trajectories. It is hence important to find, among all possible trajectories able to accomplish a task, the most informative ones. One crucial point in this context, also known as *active sensing control*, is the choice of an appropriate *measure of information* to be optimized. The Observability Gramian (OG) measures the level of observability of the *initial state* and hence, its maximization (e.g. by maximizing its smallest eigenvalue) actually increase the amount of information about the initial state and hence improves the performances in estimating (observing) the initial state of the robot. However, when the objective is to estimate the current/future state of the robot (which is implicitly the goal of most of the previous literature in this subject, and of our research too), the OG is *not* the right metric even if is often used in the literature for this goal. Recently, in [12], we showed that, the right metric is instead the *Constructibility Gramian* (CG) that indeed quantifies the amount of information about the current/future state, which is obviously the state of interest for the sake of motion control/task execution. We then propose an *online* optimal sensing control problem whose objective is to determine at *runtime*, i.e. anytime a new estimate is provided by the employed observer (an EKF in our case), the future trajectory that maximizes the smallest eigenvalue of the CG. We applied our machinery to two robotics platforms: a unicycle vehicle and a quadrotor UAV moving on a vertical plane, both measuring two distances w.r.t. two markers located in the environment. Results show the effectiveness of our solution not only for pure robot's state estimation, but also with instances of active self-calibration and map building.

The proposed solution is not able to cope with the process/actuation noise as CG is not able to measure its degrading effects on the current amount of the collected information and by consequence its negative effects in the estimation process. For all the cases where an EKF is used as an observer, we overcame this issue in [21] where we minimized the largest eigenvalue of the covariance matrix of the EKF that is the solution of the Riccati differential equation.

We also extended the methodology to the problem of shared control by proposing a shared control active perception method aimed at fusing the high-level skills of a human operator in accomplishing complex tasks with the capabilities of a mobile robot in maximizing the acquired information from the onboard sensors for improving its state estimation (localization). In particular, a persistent autonomous behaviour, expressed in terms of a cyclic motion represented by a closed B-Spline, is executed by the robot. The human operator is in charge of modifying online some geometric properties of this path for executing a given task (e.g., exploration). The path is then autonomously processed by the robot, resulting in an actual path that tries to follow the human's commands while, at the same time, maximizing online the acquired information from the sensors. This work has been done by Valerio Paduano during his Master thesis [43] and submitted to ICRA 2020.

Recently we are also working on extending the methodology to Multiple Robot Systems (in particular a group of quadrotor UAVs). In this context, the goal is to propose an optimal and *online* trajectory planning framework for addressing the localization problem of a group of multiple robots without requiring the rigidity condition. In particular, by leveraging our recent work on optimal online active estimation, we will propose the use of CG for quantifying the localization accuracy, and develop an *online* decentralized optimal trajectory planning able to optimize the CG during the robot motion. We particularly focus on the *online* component, since the planned trajectory are *continuously refined* during the robot motion by exploiting the (continuously converging) decentralized estimation of the robot relative poses. In order to illustrate the approach, we will consider the localization problem for a group of quadrotor UAVs measuring relative distances with maximum range sensing constraints and a decentralized Extended Kalman Filter [39] that estimates the relative configuration of each robot in the group w.r.t. a special one (randomly chosen in the group).

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. AXYN (2017 - 2021)

Participants: Patrick Rives and Paolo Salaris

This contract (30k€) is linked to the PhD Thesis of Dyanna Hassan (Cifre Thesis). The objective is to develop assistive navigation techniques.

7.1.2. Renault (2018 - 2021)

Participant: Philippe Martinet (in collaboration with A. Spalanzani and C. Laugier from CHROMA)

This contract (CHROMA 45k€, CHORALE (15k€ for supervision)) is linked to the PhD Thesis of Luiz Guardini (Cifre Thesis). The objective is to develop contextualized emergency trajectory planning with minimum criticality by employing dynamic probabilistic occupancy grid.

7.2. Bilateral Grants with Industry

7.2.1. AXYN (2017 - 2021)

Phd Student: Dayanna Hassan
Dayanna Hassan is employed by AXYN (Cifre Thesis).
Title of the PhD: Plate-forme robotisée d'assistance aux personnes à mobilité réduite

7.2.2. Renault (2018 - 2021)

Phd Student: : Luiz Guardini
Luiz Guardini is employed by Renault (Cifre Thesis).
Title of the PhD: Autonomous car driving: use of dynamic probabilistic occupancy grids for contextualized planning of emergency trajectory with minimal criticity

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. SPHERE ADT Inria project, 2019-20

Participants: Philippe Martinet, Patrick Rives, Renato Martins. The project SPHERE is an Inria ADT coordinated by Philippe Martinet. The aim is to put in place the PERCEPTION360 framework embedded inside the vehicle ICAV in order to map, localize and navigate autonomously in urban areas. It funds an Inria expert engineer position in CHORALE (John Thomas, 12/19-05/20) focusing on instrumentation, control and software development around the autonomous vehicle ICAV.

8.1.2. E-WHEELED ATT Inria project, 2019-21

Participants: Philippe Martinet. The project E-WHEELED is an Inria ATT coordinated by Philippe Martinet. The aim is to provide mobility to things by implementing connectivity techniques. It makes available an Inria expert engineer (Nicolas Chleq) in CHORALE in order to demonstrate the Proof of Concept using a small size demonstrator.

8.1.3. Local initiatives

CHORALE is in touch with local government CASA (Communauté d'Agglomération de Sophia Antipolis) in order to have access to the experimental site dedicated to Autonomous Vehicle demonstration. The first demonstration of autonomous driving has been done mid December. This site will be inaugurated during spring 2020.
Contacts with local companies involved in connected and autonomous driving have been made (including Renault Software Lab and Hitachi). CHORALE has participated to the GetTogether meetings organized by the local initiative SmartVehicles06.

8.2. National Initiatives

8.2.1. ANR Platinum (14-19)

The ANR Platinum (ended in november 2019), led locally by P. Rives, aims to develop methods and algorithms to map an urban environment, enrich it and automatically update it using visual sensors that communicate and are embedded by system users. The consortium is made of 4 academic partners: LITIS, Le2I (VIBOT), Inria-LAGADIC (CHORALE) et IGN-MATIS. One Phd (Mohammed Boussaha) is working on semantization of urban scenes.

8.2.2. ANR Mobi-Deep (17-22)

The ANR MOBI-Deep project, led locally by P. Rives (then P. Martinet since December 2019) aims to develop technologies that enable (or help) autonomous navigation in open and unknown environments using low-cost sensors such as digital cameras. The consortium is made of 2 academic partners: GREYC, Inria-LAGADIC (CHORALE), one association INJA and 3 industrial partners SAFRAN, SAFRAN Electronic & Defence and NAVOCAP. Philippe Martinet took the coordination of the project in December 2019. One master student (Wanting Jin) has worked (6 months) on proactive navigation, and one post-doc (Renato Martins) has been recruted in April 2019 for two years to work on End to End deep learning navigation.

8.2.3. ANR CLARA (19-22)

The ANR CLARA project, led and coordinated by G. Allibert, is focused in autonomous navigation of an aerial drone, equipped with 360-degree cameras, evolving in a forest to provide 3D mapping using deep learning techniques. The consortium is made of 3 academic partners: I3S/Inria CHORALE, LITIS, ViBot. One PhD student (Ihab Mohamed) is working on autonomous navigation using MPPI technics and one master (Haozhou Zhang) has investigated Optical Flow Estimation in Spherical Images.

8.2.4. Collaboration with LS2N-ARMEN

Philippe Martinet as a strong collaboration with the ARMEN team at LS2N. This mainly concerns autonomous parking maneuvers (with Olivier Kermorgant and Salvador Dominguez; we had a phd student), platoon control and observers (with Olivier Kermorgant and Salvador Dominguez; we had 1 post-doc), high speed visual servoing (with Olivier Kermorgant; we have one phd student), collaborative SLAM (with Olivier Kermorgant; we had one phd student), and Control based design (Sébastien Briot; we had one phd student and have one postdoc). These collaborations are mainly funded by ANR projects (initialized and/or prepared when I was in Nantes).

8.2.4.1. ANR Valet (15-19)

The ANR VALET (coordinated by F. Nashashibi from Inria RITS) proposes the development of an automatic redistribution system for sharing vehicles in urban environments. The principle is based on the creation of automated vehicle platoons guided by manually driven vehicles. The collected vehicles are transported to a charging centre or to a car park; here, each vehicle is assigned a parking space to which it must go and then in which it must park fully autonomously. Throughout the movement of platoons and vehicles, they must interact with other road users, including vehicle-type obstacles and pedestrians. The consortium is made of 2 academic partners: Inria (RITS, Chroma, Prima) and Ircyyn (LS2N) Ecole Centrale de Nantes and the AKKA company. One phD student (David Perez Morales) has worked on autonomous parking. One post doc (Ahmed Khalifa) has worked on observer and control design for platoon applications. CHORALE is working inside Hianic via the collaboration with ARMEN.

8.2.4.2. ANR Hianic (18-21)

The HIANIC project (coordinated by A. Spalanzani from Inria CHROMA) proposes to endow autonomous vehicles with smart behaviors (cooperation, negotiation, socially acceptable movements) that better suit complex shared space situations. It integrates models of human behaviors (pedestrian, crowds and passengers), social rules, as well as smart navigation strategies that will manage interdependent behaviors of road users and of cybercars. The consortium is made of 3 academic partners: Inria (RITS, Chroma, Pervasive Interaction teams), Lig Laboratory (Magma team) and LS2N laboratory (ARMEN and PACCE teams). CHORALE is working inside Hianic via the collaboration with CHROMA and ARMEN. One phd student (Maria Kabtoul) is working on proactive navigation of a vehicle among the crowd.

8.2.4.3. ANR SESAME (19-22)

The ANR SESAME (coordinated by S. Briot from LS2N ARMEN) aims to study singularities and stability of sensor-based controllers The consortium is made of 3 academic partners: LS2N (ARMEN and OGRE), Inria (RAINBOW), LIP6 (POLSYS). One master student (John Thomas) has worked on the design of controller based on the concept of hidden robot. One post doc (Abhilash Nayak) is working of the determination of singularities. CHORALE is working inside SESAME via the collaboration with ARMEN.

8.2.5. *Collaboration with VIBOT*

Guillaume Allibert has a strong collaboration with Pr Cédric Demonceaux from the ERL VIBOT. This mainly concerns activities around perception for robotics. Specifically, we are interested in how to integrate model-based knowledge into deep learning approaches. Two Master students have been involved in 2019: Haozhou Zhang (Optical Flow Estimation In Spherical Images) and Yanis Marchand (New Convolution for Spherical Images Using Depth Information).

8.2.6. *Collaboration with RAINBOW Inria Team*

Paolo Salaris has a strong collaboration with the RAINBOW Inria team about the research field on active sensing control for robotic platforms where the objective is to determine the robot trajectories that maximise the amount of information coming from sensors. In this activity was involved 1 PostDoc (2017-2019) and recently 1 Master student. This collaboration gave raise to 1 journal and 3 conference papers (one of them under review in the procedeeing of ICRA 2020).

8.3. FP7 & H2020 Projects

Program: H2020

Project acronym: CROWDBOT

Project title: Safe Navigation of Robots in Dense Human Crowds

Duration: Jan 2018 - Jun 2021

Coordinator: Julien Pettré

Other partners: ETHZ (Switzerland), EPFL (Switzerland), UCL (UK), RWTH (Germany), Softbank (France), Locomotec (Germany)

Abstract: CrowdBot will enable mobile robots to navigate autonomously and assist humans in crowded areas. Today's robots are programmed to stop when a human, or any obstacle is too close, to avoid coming into contact while moving. This prevents robots from entering densely frequented areas and performing effectively in these high dynamic environments. CrowdBot aims to fill in the gap in knowledge on close interactions between robots and humans during navigation tasks.

8.4. International Initiatives

8.4.1. *Collaboration with Universidade Federal de Minas Gerais, San Paolo*

Patrick Rives and Renato Martins have strong collaborations with two research groups at Universidade Federal de Minas Gerais (UFMG), Brazil. The research topics of CHORALE have a large coverage and share common interests with ongoing projects at these groups.

In this context, Patrick Rives spent two months (Nov-Dec 2018) on a Chair Position at UFMG conjointly funded by Le Ministère des Affaires étrangères (France) and UFMG (Brazil). During his stay, he worked with Prof. Alessandro Correa Victorino in the domain of advanced perception for autonomous vehicles.

One objective of his visit was to initiate a long-term scientific collaboration between UFMG and Inria, based on scientific internships of researchers and PhD students (co-tutelle). Originally, this collaboration should be funded by the CAPES-COFECUB International Program. Unfortunately, due to the political changes in Brazil, this project of collaboration is still pending.

Renato Martins, for his part, is a former postdoctoral researcher in the Computer Vision and Robotics Laboratory - VeRLab (UFMG), where he is currently an external collaborator. He actively collaborates on computer vision, perception and robotic vision with Prof. Erikson R. Nascimento, whose research interests and expertise spans from Computer Vision to Computer Graphics.

8.4.2. *Inria International Partners*

8.4.2.1. *Informal International Partners*

Universidade Federal de Minas Gerais (UFMG), Brazil

Jaume I University (UJI), Spain
National University of Singapore, Singapore (Marcelo H. Ang)
Universidade de Sao Paulo, Brazil

8.5. Visits of International Scientists

Enric Cervera Associated Professor at the Jaume I University (SPAIN). He is working in visual servoing application. During his stay (May-July 2019) as invited professor, he has worked on 360 degree view visual perception for autonomous navigation.

8.5.1. Visits to International Teams

8.5.1.1. Research Stays Abroad

Patrick Rives spent two months (Nov-Dec 2018) on a Chair Position at UFMG conjointly funded by Le Ministère des Affaires étrangères (France) and UFMG (Brazil).

9. Dissemination

9.1. Scientific Events: Organisation

9.1.1. General Chair, Scientific Chair

Philippe Martinet the corresponding chair for the PPNIV19 IRO19 workshop (https://project.inria.fr/ppniv19). He has managed the reviewing process, the website update and the general publicity. More than 300 attendees for this 11th edition.

9.1.2. Member of the Organizing Committees

Philippe Martinet has co-organized the IROS19-PPNIV19 (https://project.inria.fr/ppniv19) workshop with Christian Laugier, Marcelo H. Ang, Christoph Stiller and Miguel Sotelo (over 300 attendees).
Philippe Martinet has co-organized the Cutting edge Forum on Autonomous Driving (https://project.inria.fr/ad19/) with Christian Laugier, Marcelo H. Ang, Christoph Stiller and Miguel Sotelo (more than 150 attendees).

9.1.3. Scientific Events: Selection

9.1.3.1. Chair of Conference Program Committees

Philippe Martinet was Regional Chair for CISRAM 2019.

9.1.3.2. Member of the Conference Program Committees

Philippe Martinet was member for the IPC for ICINCO 2019.
Patrick Rives was Program Committee member of the Conférence Française de Photogrammétrie et de Télédétection 2019 (CFPT)

9.1.3.3. Reviewer

Philippe Martinet was Associated Editor for ITSC 2019, and reviewer for ICINCO19, PPNIV19.
Guillaume Allibert has reviewed papers for ICRA, IROS, IFAC WC, CDC, ACC.
Paolo Salaris has reviewed papers for ICRA, CDC, RSS.
Patrick Rives has reviewed papers for ICRA, IROS, IV, ICAR.
Renato Martins has reviewed papers for WACV, ICRA, IROS, ITSC, ICAR, PPNIV19.

9.1.4. Journal

9.1.4.1. Member of the Editorial Boards

Philippe Martinet is member of the Editorial Board of the Springer ISCA Book Series since 2014.

Philippe Martinet is co-Editor of the Springer book collection “Parallel Robots : Theory and Applications” setup in january 2015.

9.1.4.2. Reviewer - Reviewing Activities

Philippe Martinet is Associate Editor of the journal IEEE-Transactions on Intelligent Vehicles.
Guillaume Allibert has reviewed papers for RA-L and IEEE Trans. on Mechatronics.
Paolo Salaris has reviewed: RA-L, TRO, AURO
Renato Martins has reviewed papers for RA-L and Elsevier JVCI.

9.1.5. Invited Talks

Patrick Rives gave a Plenary Talk at the Universidade Federal de Minas Gerais (UFMG), Brazil
Title: Towards new sensors and representations for autonomous navigation in large scale human-like environments

9.1.6. Scientific Expertise

- International:
  - Philippe Martinet is corresponding chair and co-chair with C. Laugier and Christoph Stiller, of the IEEE RAS Technical Committee on “Autonomous Ground Vehicles and Intelligent Transportation Systems (AGVITS)”.
  - Philippe Martinet is Deputy director of the GdR Robotique.
  - Philippe Martinet was member of CNU 61 from 2011 until September 2019.
  - H2020: Philippe Martinet has participated of the ICT-2019-2 call (4 projects were evaluated)
  - STIC Amsud: Philippe has evaluated one proposal in 2019
  - Skywin (Aerospace Cluster of Wallonia): Patrick Rives has evaluated one proposal
  - Program BRIDGE Discovery (Swiss National Science Foundation): Patrick Rives has evaluated one proposal
- National:
  - Philippe Martinet is deputy director of the GdR robotics.
  - ANR: Guillaume Allibert was part of the CES33 in 2019. He has participated to the evaluation of the pre-projects and to the final projects evaluation.
  - ANR: Patrick Rives has evaluated one proposal in 2019
  - HCERES: Philippe has participated of the evaluation of LAAS (November 2019), IFFSTAR AME department (March 2019) and ONERA DTIS Department (December 2019).
  - ISITE-NEXT in Nantes: Philippe Martinet has evaluated one Talent application in 2019
  - ANRT: Philippe Martinet has evaluated one application for CIFRE grant in 2019
  - Philippe Martinet is coordinator of the ANR MOBI-Deep project
  - Guillaume Allibert is coordinator of the ANR CLARA project
- Local:
  - Paolo Salaris was member of CSD (Comité de Suivi Doctoral) in Inria Sophia Antipolis until end of August 2019.

9.1.7. Research Administration

Guillaume Allibert is the SIS team deputy head at I3S since 2017. This team is composed of 57 people (18 teacher-researchers, 11 researchers, 6 ATER & post doc, 3 emeritus and 19 PhD students).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Guillaume Allibert is assistant professor at the Cote-d'Azur-University. He teaches at the GEII department of the IUT of Nice Côte d'Azur. He is in charge of two complete teaching modules: control and computer science. He also participates in the mathematics course.
Philippe Martinet managed four main actions in 2019 in relation with the education system:

- EIT Digital AUS: Participation in the definition of the educational program. This master program will be done at Polytech Sophia.
- New engineering track on autonomous system: Participation in the discussion to put in place a new engineering track between Polytech Sophia and Ecole des Mines. This Engineering track will start in 2021.
- EMJMD MIR (Erasmus Mundus Joint Master Degree on Marine and Maritime Intelligent Robotics): Jean-Pierre Merlet and Philippe Martinet have discussed with the coordinator of the master Vincent Hugel in order that Inria become an associated partner for this new educational program in robotic.
- Philippe Martinet, Jean-Pierre Merlet and Guillaume Allibert have co-organized the first GdR Robotics Winter school on Robotics Principia (https://project.inria.fr/roboticsprincipia/). An HAL collection has been setup (https://hal.inria.fr/ROBOTICA-PRINCIPIA).

9.2.2. Supervision

PhD : David Perez Morales, Multisensor based control in intelligent parking applications, Ecole Centrale de Nantes, December 6th 2019, P. Martinet, O. Kermorgant, S. Dominguez

PhD : Luis Contreras, SLAM collaboratif dans des environnements extérieurs, Ecole Centrale de Nantes, April 10th 2019, P. Martinet, O. Kermorgant

PhD in progress : Mohammed Boussaha, Hybrid urban scene analysis from mobile mapping images and laser scan, Université Paris Est -MSTIC, 15/10/2016, Bruno Vallet (IGN-Matis), Patrick Rives

PhD in progress : Dyanna Hassan, Plate-forme robotisée d'assistance aux personnes à mobilité réduite, Univ Côte d'Azur, 1/01/2017, P. Rives, P. Salaris

PhD in progress : Ihab Mohammed, Coupling Deep Learning and Advanced Control in UAV Navigation, Univ Côte d'Azur, 1/12/2018, P. Martinet, G. Allibert, P. Salaris

PhD in progress: Franco Fusco, High-speed visual servoing, Ecole Centrale de Nantes, 1/9/2017, P. Martinet, O. Kermorgant

PhD in progress : Maria Kabtoul, Proactive Social navigation for autonomous vehicles among crowds, Univ Grenoble Alpes, 1/09/2018, A. Spalanzani, P. Martinet

PhD in progress : Luiz Alberto Serafim Guardini, Autonomous car driving: use of dynamic probabilistic occupancy grids for contextualized planning of emergency trajectory with minimal criticity, Univ Grenoble Alpes, 1/10/2018, A. Spalanzani, P. Martinet, C. Laugier

PhD in progress : Zongwei Wu, New convolution for spherical images using depth, Université de Bourgogne Franche Comté, 1/10/19, C. Demonceaux, G. Allibert,

9.2.3. Juries

HdR : Guillaume Caron, Vision robotique directe, Univ Picardie Jules Verne, December 10th 2019 (P. Martinet, reviewer)

PhD : David Sierra Gonzales, Towards Human like prediction and decision making for automated vehicles on highway scenarios, Univ Grenoble Alpes, April 1st 2019, (P. Martinet, reviewer)

PhD : Soler Ulun, Multi-robot relative localization using computer vision, NTU Singapore, 2019, (P. Martinet, reviewer)

PhD : Jiang Xiaoyue, Visual and Lidar based SLAM by variational Bayesian method, NTU Singapore, 2019, (P. Martinet, reviewer)

PhD : Michel Moukari, Estimation de profondeur à partir d'images monoculaires par apprentissage profond, Univ de Caen, July 1st 2019, (P. Martinet, reviewer)

PhD : Pavan Vasishta, Building and Leveraging prior knowledge for predicting pedestrain behavior around autonomous vehicles, Univ Grenoble Alpes, September 30th 2019, (P. Martinet, examinator)

PhD : David Perez Morales, Multisensor based control in intelligent parking applications, Ecole Centrale de Nantes, December 6th 2019 (G. Allibert, examinator)

PhD : Thibaut Tezenas du Montcel, Evitement d'obstacles pour quadrirotors en utilisant un capteur de profondeur, Univ Grenoble Alpes, December 16th 2019 (G. Allibert, examinator)

PhD : Jose Juan Tellez, Teleoperation of an UAV for navigation in unstructured environments using a portable haptic interface, Univ Grenoble Alpes, June 26th 2019 (G. Allibert, examinator)

PhD : Kevin Giraud Esclasse, Towards reactive motion generation on exteroceptive feedback for generalized locomotion of humanoid robots, Univ Toulouse Midi-Pyrénées, December 18th 2019 (G. Allibert, examinator)

PhD : Thiago L. Gomes. Transferring human motion and appearance in monocular videos, PhD Qualifying Exam on Computer Science, Universidade Federal de Minas Gerais, Brazil, July 12th 2019 (R. Martins, examinator)

9.3. Popularization

9.3.1. Articles and contents

Philippe Martinet and Renato Martins have been interviewed in December 2019 by France 3 Côte d'Azur in order to popularize the work of CHORALE in the field of Connected Autonomous Vehicles. Real demonstrations of autonomous driving have been done at Inria Sophia Antipolis, and another one at CASA experimental site. An FR3 magazine will be launched in february 2020.

9.3.2. Interventions

- Patrick Rives has presented the topic of Autonomous vehicle during the day "Formation IA pour les professeurs des lycées", Sophia Antipolis, 14/11/2019

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Major publications by the team in recent years

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Project-Team COATI

Combinatorics, Optimization and Algorithms for Telecommunications

IN COLLABORATION WITH: Laboratoire informatique, signaux systèmes de Sophia Antipolis (I3S)

IN PARTNERSHIP WITH:
CNRS

Université Nice - Sophia Antipolis

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Networks and Telecommunications

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Project-Team COATI

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B7.2. - Smart travel

1. Team, Visitors, External Collaborators

Research Scientists

David Coudert [Team leader, Inria, Senior Researcher, HDR]
Jean-Claude Bermond [CNRS, Emeritus, HDR]
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Francesco d'Amore [Inria, from Oct 2019]
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Zhejiayu Ma [CIFRE EasyBroadcast, from Oct 2019]
Fionn Mc Inerney [Inria, until Aug 2019]
Thi Viet Ha Nguyen [Inria]
Andrea Tomassilli [Univ de Nice - Sophia Antipolis, until Sep 2019]
Thibaud Trolliet [Inria, from Oct 2019]

Post-Doctoral Fellows

Emilio Cruciani [Univ Côte d'Azur, from Nov 2019]
Francois Dross [Univ de Nice - Sophia Antipolis, until Aug 2019]

Visiting Scientists

Hossein Baktash [Sharif University, Téhéran, from Jul 2019 until Sep 2019]
Jorgen Bang-Jensen [University of Southern Denmark, until Jan 2019]
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Administrative Assistant

Patricia Riveill [Inria]

2. Overall Objectives

2.1. Overall Objectives

COATI is a joint team between Inria Sophia Antipolis - Méditerranée and the I3S laboratory (Informatique Signaux et Systèmes de Sophia Antipolis) which itself belongs to CNRS (Centre National de la Recherche Scientifique), UNS (Univ. Nice Sophia Antipolis) and Univ. Côte d'Azur. Its research fields are Algorithmics, Discrete Mathematics, and Combinatorial Optimization, with applications mainly in telecommunication networks.

The main objectives of the COATI project-team are to design networks and communication algorithms. In order to meet these objectives, the team studies various theoretical problems in Discrete Mathematics, Graph Theory, Algorithmics, and Operations Research and develops applied techniques and tools, especially for Combinatorial Optimization and Computer Simulation. In particular, COATI used in the last years both these theoretical and applied tools for the design of various networks, such as SDN (software defined networks), WDM, wireless (radio), satellite, and peer-to-peer networks. This research has been done within various industrial and international collaborations.

COATI also investigates other application areas such as bio-informatics and transportation networks.

The research done in COATI results in the production of advanced software such as GRPH, and in the contribution to large open source software such as Sagemath.

3. Research Program

3.1. Research Program

Members of COATI have a strong expertise in the design and management of wired and wireless backbone, backhaul, broadband, software defined and complex networks. On the one hand, we cope with specific problems such as energy efficiency in backhaul and backbone networks, routing reconfiguration in connection oriented networks (MPLS, WDM), traffic aggregation in SONET networks, compact routing in large-scale networks, survivability to single and multiple failures, etc. These specific problems often come from questions of our industrial partners. On the other hand, we study fundamental problems mainly related to routing and reliability that appear in many networks (not restricted to our main fields of applications) and that have been widely studied in the past. However, previous solutions do not take into account the constraints of current networks/traffic such as their huge size and their dynamics. COATI thus puts a significant research effort in the following directions:

- **Service Function Chains (SFC):** we study the placement of Service Function Chains within the network considering the ordering constraints. Then, we focus firstly on energy efficiency and secondly on reliability and protection mechanisms. In a last step, we study reconfiguration of the SFCs in case of dynamic traffic with a make-before-break approach.
- **Larger networks:** Another challenge one has to face is the increase in size of practical instances. It is already difficult, if not impossible, to solve practical instances optimally using existing tools. Therefore, we have to find new ways to solve problems using reduction and decomposition methods, characterization of polynomial instances (which are surprisingly often the practical ones), or algorithms with acceptable practical performances.
- **Stochastic behaviors:** Larger topologies mean frequent changes due to traffic and radio fluctuations, failures, maintenance operations, growth, routing policy changes, etc. We aim at including these stochastic behaviors in our combinatorial optimization process to handle the dynamics of the system and to obtain robust designs of networks.

The methods and tools used in our studies come from discrete mathematics and combinatorial optimization, and COATI contributes to their improvements. Also, COATI works on graph-decomposition methods and various games on graphs which are essential for a better understanding of the structural and combinatorial properties of the problems, but also for the design of efficient exact or approximate algorithms. We contribute to the modelling of optimization problems in terms of graphs, study the complexity of the problems, and then we investigate the structural or metric properties of graphs that make these problems hard or easy. We exploit these properties in the design of algorithms in order to find the most efficient ways for solving the problems.

COATI also focuses on the theory of *directed graphs*. Indeed, graph theory can be roughly partitioned into two branches: the areas of undirected graphs and directed graphs. Even though both areas have numerous important applications, for various reasons, undirected graphs have been studied much more extensively than directed graphs. It is worth noticing that many telecommunication problems are modelled with directed graphs. Therefore, a deeper understanding of the theory of directed graphs will benefit to the resolution of telecommunication networks problems. For instance, the problem of finding disjoint paths becomes much more difficult in directed graphs and understanding the underlying structures of actual directed networks would help us to propose solutions.

Last, we have recently started investigating how tools from multi-agents based systems and machine learning theory could help solving some optimization problems in networks. The arrival of Emanuele Natale as a Junior Researcher (CNRS) in the team and of two new PhD students (Franceso D'Amore and Hicham Lesfari) will foster these investigations.

4. Application Domains

4.1. Telecommunication Networks

COATI is mostly interested in telecommunications networks but also in the network structure appearing in social, molecular and transportation networks.

We focus on the design and management of heterogeneous physical and logical networks. The project has kept working on the design of backbone networks (optical networks, radio networks, IP networks). However, the fields of Software Defined Networks and Network Function Virtualization are growing in importance in our studies. In all these networks, we study routing algorithms and the evolution of the routing in case of any kind of topological modifications (maintenance operations, failures, capacity variations, etc.).

4.2. Other Domains

Our combinatorial tools may be well applied to solve many other problems in various areas (transport, biology, resource allocation, chemistry, smart-grids, speleology, etc.) and we collaborate with experts of some of these domains.

For instance, we collaborate with project-team ABS (Algorithms Biology Structure) from Sophia Antipolis on problems from Structural Biology (co-supervision of a PhD student). In the area of transportation networks, we collaborate with SMEs Benomad and Instant-System on dynamic car-pooling combined with multi-modal transportation systems in the context of ANR project Multimod started in January 2018. Last, we have started a collaboration with GREDEG (Groupe de Recherche en Droit, Economie et Gestion, Univ. Nice Sophia Antipolis) on the analysis of collaboration networks.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

- Julien Bensmail: “Jeunes Talents France-Chine” funding for one travel to China in 2019;
- Christelle Caillouet: UCA Excellence award;
- Emilio Cruciani: recipient of a 2019 Testing and Verification research award;
- François Dross: recipient of an accessit to the PhD prize Graphes "Charles Delorme" 2019 for his PhD entitled *Vertex partition of sparse graphs* [87];

- William Lochet: recipient of the PhD prize Graphes "Charles Delorme" 2019 for his PhD entitled *Substructures in digraphs* [92];
- Emanuele Natale: awarded the "Best Italian Young Researcher in Theoretical Computer Science" by the Italian Chapter of the EATCS.

5.1.2. Promotions

- Patricia Riveill: promoted to Administrative Engineer.

BEST PAPERS AWARDS :
[47]
C. CAILLOUET, T. RAZAFINDRALAMBO, D. ZORBAS.*Optimal placement of drones for fast sensor energy replenishment using wireless power transfer*, in "WD 2019 - Wireless Days 2019", Manchester, United Kingdom, April 2019, Best Paper Award, https://hal.inria.fr/hal-02043123

6. New Software and Platforms

6.1. GRPH

The high performance graph library for Java

KEYWORDS: Graph - Graph algorithmics - Java

FUNCTIONAL DESCRIPTION: Grph is an open-source Java library for the manipulation of graphs. Its design objectives are to make it portable, simple to use/extend, computationally/memory efficient, and, according to its initial motivation: useful in the context of graph experimentation and network simulation. Grph also has the particularity to come with tools like an evolutionary computation engine, a bridge to linear programming solvers, a framework for distributed computing, etc.

Grph offers a very general model of graphs. Unlike other graph libraries which impose the user to first decide if he wants to deal with directed, undirected, hyper (or not) graphs, the model offered by Grph is unified in a general class that supports mixed graphs made of undirected and directed simple and hyper edges. Grph achieves great efficiency through the use of multiple code optimization techniques such as multi-core parallelism, caching, adequate data structures, use of primitive objects, exploitation of low-level processor caches, on-the-fly compilation of specific C/C++ code, etc. Grph attempts to access the Internet in order to check if a new version is available and to report who is using it (login name and hostname). This has no impact whatsoever on performance and security.

- Participants: Aurélien Lancin, David Coudert, Issam Tahiri, Luc Hogie and Nathann Cohen
- Contact: Luc Hogie
- URL: http://www.i3s.unice.fr/~hogie/grph/

6.2. BigGraphs

KEYWORDS: Graph algorithmics - Distributed computing - Java - Graph processing

FUNCTIONAL DESCRIPTION: The objective of BigGraphs is to provide a distributed platform for very large graphs processing. A typical data set for testing purpose is a sample of the Twitter graph : 240GB on disk, 398M vertices, 23G edges, average degree of 58 and max degree of 24635412.

We started the project in 2014 with the evaluation of existing middlewares (GraphX / Spark and Giraph / Hadoop). After having tested some useful algorithms (written according to the Bulk Synchronous Parallel (BSP) model) we decided to develop our own platform.

This platform is based on the existing BIGGRPH library and we are now working on improving the quality of the code. In particular we have designed strong test suites and some non trivial bugs have been fixed. We also have solved problems of scalability, in particular concerning the communication layer with billions of messages exchanged between BSP steps. We also have implemented specific data structures for BSP and support for distributed debugging. This comes along with the implementation of algorithms such as BFS or strongly connected components that are run on the NEF cluster.

In 2017 we have developed a multi-threaded shared-memory parallel version of the BSP framework. This new version uses advanced synchronization mechanisms and strategies to minimize the congestion of multiple threads working on the same graph. Using the NEF cluster (Inria Sophia Antipolis), this parallel version exhibits speed-ups up to 6.5 using 8 nodes (16 cores each) when computing a BFS on the 23 G edges Twitter graph sample.

- Participants: Luc Hogie, Michel Syska and Nicolas Chleq
- Partner: CNRS
- Contact: Luc Hogie
- URL: http://www.i3s.unice.fr/~hogie/software/?name=biggrph

6.3. JMaxGraph

KEYWORDS: Java - HPC - Graph algorithmics

FUNCTIONAL DESCRIPTION: JMaxGraph is a collection of techniques for the computation of large graphs on one single computer. The motivation for such a centralized computing platform originates in the constantly increasing efficiency of computers which now come with hundred gigabytes of RAM, tens of cores and fast drives. JMaxGraph implements a compact adjacency-table for the representation of the graph in memory. This data structure is designed to 1) be fed page by page, à-la GraphChi, 2) enable fast iteration, avoiding memory jumps as much as possible in order to benefit from hardware caches, 3) be tackled in parallel by multiple-threads. Also, JMaxGraph comes with a flexible and resilient batch-oriented middleware, which is suited to executing long computations on shared clusters. The first use-case of JMaxGraph allowed F. Giroire, T. Trolliet and S. Pérennes to count K2,2s, and various types of directed triangles in the Twitter graph of users (23G arcs, 400M vertices). The computation campaign took 4 days, using up to 400 cores in the NEF Inria cluster.

- Contact: Luc Hogie
- URL: http://www.i3s.unice.fr/~hogie/software/?name=jmaxgraph

6.4. Sagemath

SageMath

KEYWORDS: Graph algorithmics - Graph - Combinatorics - Probability - Matroids - Geometry - Numerical optimization

SCIENTIFIC DESCRIPTION: SageMath is a free open-source mathematics software system. It builds on top of many existing open-source packages: NumPy, SciPy, matplotlib, Sympy, Maxima, GAP, FLINT, R and many more. Access their combined power through a common, Python-based language or directly via interfaces or wrappers.

FUNCTIONAL DESCRIPTION: SageMath is an open-source mathematics software initially created by William Stein (Professor of mathematics at Washington University). We contribute the addition of new graph algorithms along with their documentations and the improvement of underlying data structures.

RELEASE FUNCTIONAL DESCRIPTION: See http://www.sagemath.org/changelogs/

NEWS OF THE YEAR: 1) Improvement of shortest path computation algorithms. Done in the context of Google Summer of Code 2019. 2) Main contributor for making the graph module (more than 100,000 lines of code) of SageMath compatible with Python3. Version 9.0 of Sagemath, released on January 1st, 2020, is 100% Python3 compliant.

- Participant: David Coudert
- Contact: David Coudert
- URL: http://www.sagemath.org/

7. New Results

7.1. Network Design and Management

Participants: Julien Bensmail, Jean-Claude Bermond, Christelle Caillouet, David Coudert, Frédéric Giroire, Frédéric Havet, Nicolas Nisse, Stéphane Pérennes, Joanna Moulierac, Foivos Fioravantes, Adrien Gausseran, Andrea Tomassilli.

Network design is a very wide subject which concerns all kinds of networks. In telecommunications, networks can be either physical (backbone, access, wireless, ...) or virtual (logical). The objective is to design a network able to route a (given, estimated, dynamic, ...) traffic under some constraints (e.g. capacity) and with some quality-of-service (QoS) requirements. Usually the traffic is expressed as a family of requests with parameters attached to them. In order to satisfy these requests, we need to find one (or many) paths between their end nodes. The set of paths is chosen according to the technology, the protocol or the QoS constraints.

We mainly focus on the following topics: Firstly, we study Software Defined Networking (SDN) and Network Function Virtualization (NFV) and how to exploit their potential benefits. We propose algorithms for the Provisioning Service Function Chains (SFC) and algorithms to reconfigure the SFC in order to improve the network operational costs without any interruption (with a *make-before-break approach*) and Virtual Network Functions (VNF) placement algorithms to address the mono- and multi-tenant issues in edge and core networks. We also propose algorithms for distributed Mininet [0] in order to improve the performance, and also bandwidth-optimal failure recovery scheme for robust programmable networks. Secondly, we study optimization problems within optical networks: wavelength reconfiguration for seamless migration and spectrum assignment in elastic optical tree-networks. Thirdly, we study the scheduling of network tasks within a data center while taking into account the communication between the network resources. We also study distributed link scheduling in wireless networks. Finally, we investigate on the placement of drones for maximizing the coverage of a landscape by drones in order to localize targets or collect data from sensors.

7.1.1. *Software Defined Networks and Network Function Virtualization*

Recent advances in networks such as Software Defined Networking (SDN) and Network Function Virtualization (NFV) are changing the way network operators deploy and manage Internet services. On the one hand, SDN introduces a logically centralized controller with a global view of the network state. On the other hand, NFV enables the complete decoupling of network functions from proprietary appliances and runs them as software applications on general purpose servers. In such a way, network operators can dynamically deploy Virtual Network Functions (VNFs). SDN and NFV, both separately, bring to network operators new opportunities for reducing costs, enhancing network flexibility and scalability, and shortening the time-to-market of new applications and services. Moreover, the centralized routing model of SDN jointly with the possibility of instantiating VNFs on demand may open the way for an even more efficient operation and resource management of networks. For instance, an SDN/NFV-enabled network may simplify the Service Function Chain (SFC) deployment and provisioning by making the process easier and cheaper. We addressed several questions in this context.

[0] Mininet provides a virtual test bed and development environment for software-defined networks (SDN). See http://mininet.org.

In [15], we aim at investigating how to leverage both SDN and NFV in order to exploit their potential benefits. We took steps to address the new opportunities offered in terms of network design, network resilience, and energy savings, and the new problems that arise in this new context, such as the optimal network function placement in the network. We show that a symbiosis between SDN and NFV can improve network performance and significantly reduce the network's Capital Expenditure (CapEx) and Operational Expenditure (OpEx).

In [50], [57], [58], we consider the problem of reconfiguring SFC with the goal of bringing the network from a sub-optimal to an optimal operational state. We propose optimization models based on the *make-before-break* mechanism, in which a new path is set up before the old one is torn down. Our method takes into consideration the chaining requirements of the flows and scales well with the number of nodes in the network. We show that, with our approach, the network operational cost defined in terms of both bandwidth and installed network function costs can be reduced and a higher acceptance rate can be achieved, while not interrupting the flows.

In [59], we consider the placement of functions in 5G networks in which functions must not only be deployed in large central data centers, but also in the edge. We propose an algorithm that solves the Virtual Network Function Chain Placement Problem allowing a fine management of these rare resources in order to respond to the greatest number of requests possible. Because networks can be divided into several entities belonging to different tenants who are reluctant to reveal their internal topologies, we propose a heuristic that allows the NFV orchestrator to place the function chains based only on an abstract view of the infrastructure network. We leverage this approach to address the complexity of the problem in large mono- or multi-tenant networks. We analyze the efficiency of our algorithm and heuristic with respect to a wide range of parameters and topologies.

In [53], [80], [69], we rethink the network dimensioning problem with protection against Shared Risk Link Group (SLRG) failures in the SDN context. We propose a path-based protection scheme with a global rerouting strategy, in which, for each failure situation, there may be a new routing of all the demands. Our optimization task is to minimize the needed amount of bandwidth. After discussing the hardness of the problem, we develop a scalable mathematical model that we handle using the Column Generation technique. Through extensive simulations on real-world IP network topologies and on random generated instances, we show the effectiveness of our method. Finally, our implementation in OpenDaylight demonstrates the feasibility of the approach and its evaluation with Mininet shows that technical implementation choices may have a dramatic impact on the time needed to reestablish the flows after a failure takes place.

Finally, in [49], [78], [79], we consider the problem of performing large scale SDN networks simulations in a distributed environment. Indeed, networks have become complex systems that combine various concepts, techniques, and technologies. Hence, modelling or simulating them is now extremely complicated and researchers massively resort to prototyping techniques. Among other tools, Mininet is the most popular when it comes to evaluate SDN propositions. It allows to emulate SDN networks on a single computer. However, under certain circumstances experiments (e.g., resource intensive ones) may overload the host running Mininet. To tackle this issue, we propose Distrinet [49], [78], [79], a way to distribute Mininet over multiple hosts. Distrinet uses the same API than Mininet, meaning that it is compatible with Mininet programs. Distrinet is generic and can deploy experiments in Linux clusters or in the Amazon EC2 cloud. Thanks to optimization techniques, Distrinet minimizes the number of hosts required to perform an experiment given the capabilities of the hosting infrastructure, meaning that the experiment is run in a single host (as Mininet) if possible. Otherwise, it is automatically deployed on a platform using a minimum amount of resources in a Linux cluster or with a minimum cost in Amazon EC2.

7.1.2. Optimization of optical networks operation

7.1.2.1. Wavelength Defragmentation for Seamless Migration

Dynamic traffic in optical networks leads to spectrum fragmentation, which significantly reduces network performance, i.e., increases blocking rate and reduces spectrum usage. Telecom operators face the operational challenge of operating non-disruptive defragmentation, i.e., within the make-before-break paradigm when dealing with lightpath rerouting in wavelength division multiplexed (WDM) fixed-grid optical networks.

In [39], we propose a make-before-break (MBB) Routing and Wavelength Assignment (RWA) defragmentation process, which provides the best possible lightpath network provisioning, i.e., with minimum bandwidth requirement. We tested extensively the models and algorithms we propose on four network topologies with different GoS (Grade of Service) defragmentation triggering events. We observe that, for a given throughput, the spectrum usage of the best make-before-break lightpath rerouting is always less than 2.5% away from that of an optimal lightpath provisioning.

7.1.2.2. On spectrum assignment in elastic optical tree-networks

To face the explosion of the Internet traffic, a new generation of optical networks is being developed; the Elastic Optical Networks (EONs). EONs use the optical spectrum efficiently and flexibly, but that gives rise to more difficulty in the resource allocation problems. In [31], we study the problem of Spectrum Assignment (SA) in Elastic Optical Tree-Networks. Given a set of traffic requests with their routing paths (unique in the case of trees) and their spectrum demand, a spectrum assignment consists in allocating to each request an interval of consecutive slots (spectrum units) such that a slot on a given link can be used by at most one request. The objective of the SA problem is to find an assignment minimizing the total number of spectrum slots to be used. We prove that SA is NP-hard in undirected stars of 3 links and in directed stars of 4 links, and show that it can be approximated within a factor of 4 in general stars. Afterwards, we use the equivalence of SA with a graph coloring problem (interval coloring) to find constant-factor approximation algorithms for SA on binary trees with special demand profiles.

7.1.3. Scheduling

7.1.3.1. When Network Matters: Data Center Scheduling with Network Tasks

We consider in [51] the placement of jobs inside a data center. Traditionally, this is done by a task orchestrator without taking into account network constraints. According to recent studies, network transfers represent up to 50% of the completion time of classical jobs. Thus, network resources must be considered when placing jobs in a data center. In this paper, we propose a new scheduling framework, introducing network tasks that need to be executed on network machines alongside traditional (CPU) tasks. The model takes into account the competition between communications for the network resources, which is not considered in the formerly proposed scheduling models with communication. Network transfers inside a data center can be easily modeled in our framework. As we show, classical algorithms do not efficiently handle a limited amount of network bandwidth. We thus propose new provably efficient algorithms with the goal of minimizing the makespan in this framework. We show their efficiency and the importance of taking into consideration network capacity through extensive simulations on workflows built from Google data center traces.

7.1.3.2. Distributed Link Scheduling in Wireless Networks

In [55], we investigate distributed transmission scheduling in wireless networks. Due to interference constraints, “neighboring links” cannot be simultaneously activated, otherwise transmissions will fail. Here, we consider any binary model of interference. We use the model described by Bui, Sanghavi, and Srikant in [85], [93]. We assume that time is slotted and during each slot there are two phases: one control phase which determines what links will be activated and a data phase in which data are sent. We assume random arrivals on each link during each slot, so that a queue is associated to each link. Since nodes do not have a global knowledge of the network, our aim (like in [85], [93]) is to design for the control phase a distributed algorithm which determines a set of non-interfering links. To be efficient the control phase should be as short as possible; this is done by exchanging control messages during a constant number of mini-slots (constant overhead). In this paper, we design the first fully distributed local algorithm with the following properties: it works for any arbitrary binary interference model; it has a constant overhead (independent of the size of the network and the values of the queues), and it does not require any knowledge of the queue-lengths. We prove that this algorithm gives a maximal set of active links, where in each interference set there is at least one active link. We also establish sufficient conditions for stability under general Markovian assumptions. Finally, the performance of our algorithm (throughput, stability) is investigated and compared via simulations to that of previously proposed schemes.

7.1.3.3. Backbone colouring and algorithms for TDMA scheduling

We investigate graph colouring models for the purpose of optimizing TDMA link scheduling in Wireless Networks. Inspired by the BPRN-colouring model recently introduced by Rocha and Sasaki, we introduce a new colouring model, namely the BMRN-colouring model, which can be used to model link scheduling problems where particular types of collisions must be avoided during the node transmissions.

In [25], we initiate the study of the BMRN-colouring model by providing several bounds on the minimum number of colours needed to BMRN-colour digraphs, as well as several complexity results establishing the hardness of finding optimal colourings. We also give a special focus on these considerations for planar digraph topologies, for which we provide refined results. Some of these results extend to the BPRN-colouring model as well. We notably prove that every planar digraph can be 8-BMRN*-coloured, while there exist planar digraphs for which 8 colours are needed in a BMRN*-colouring [72]. We also proved that the problem of deciding whether a planar digraph can be k-BMRN*-coloured is NP-hard for every $k \in \{3, ..., 6\}$.

7.1.4. Optimizing drone coverage

7.1.4.1. Self-organized UAV-based Supervision and Connectivity

The use of drones has become more widespread in recent years. Many use cases have been developed involving these autonomous vehicles, ranging from simple delivery of packages to complex emergency situations following catastrophic events. The miniaturization and very low cost of these machines make it possible today to create large meshes to ensure network coverage in disaster areas, for instance. However, the problems of scaling up and self-organization are necessary to solve problems in these use cases.

In the position paper [45], we first present different new requirements for the deployment of unmanned aerial vehicles (UAV) networks, involving the use of many drones. Then, we introduce solutions from distributed algorithms and real-time data processing to ensure quasi-optimal solutions to the raised problems.

In [44], [65], we propose VESPA, a distributed algorithm using only one-hop information of the drones, to discover targets with unknown location and auto-organize themselves to ensure connectivity between them and the sink in a multi-hop aerial wireless network. We prove that connectivity, termination and coverage are preserved during all stages of our algorithm, and we evaluate the algorithm performances through simulations. Comparison with a prior work shows the efficiency of VESPA both in terms of discovered targets and number of used drones.

7.1.4.2. Optimal placement of drones for fast sensor energy replenishment using wireless power transfer

Lifetime is the main issue of wireless sensors networks. Since the nodes are often placed in inaccessible places, the replacement of their battery is not an easy task. Moreover, the node maintenance is a costly and time consuming operation when the nodes are high in numbers. Energy harvesting technologies have recently been developed to replenish part or all of the required energy that allows a node to function. In [47], [48], we use dedicated chargers carried by drones that can fly over the network and transmit energy to the nodes using radio-frequency (RF) signals. We formulate and optimally solve the Optimal Drone Placement and Planning Problem (OD3P) by using a given number of flying drones, in order to efficiently recharge wireless sensor nodes. Unlike other works in the literature, we assume that the drones can trade altitude with coverage and recharge power, while each drone can move across different positions in the network to extend coverage. We present a linear program as well as a fast heuristic algorithm to meet the minimum energy demands of the nodes in the shortest possible amount of time. Our simulation results show the effectiveness of our approaches for network scenarios with up to 50 sensors and a 50×50m terrain size.

7.1.4.3. Efficient Data Collection and Tracking with Flying Drones

Data collection is an important mechanism for wireless sensor networks to be viable. In [34], we address the Aerial Data Collection Problem (ADCP) from a set of mobile wireless sensors located on the ground, using a fleet of flying devices. The objective is i) to deploy a set of UAVs in a 3D space to cover and collect data from all the mobile wireless sensors at each time step through a ground-to-air communication, ii) to send these data to a central base station using multi-hop wireless air-to-air communications through the network of UAVs, iii) while minimizing the total deployment cost (communication and deployment) over time. The Aerial Data

Collection Problem (ADCP) is a complex time and space coverage, and connectivity problem. We first present a mixed-integer linear program solving ADCP optimally for small instances. Then, we develop a second model solved by column generation for larger instances, with optimal or heuristic pricing programs. Results show that our approach provides very accurate solutions minimizing the data collection cost. Moreover, only a very small number of columns are generated throughout the resolution process, showing the efficiency of our approach.

7.1.5. Other results

7.1.5.1. The Structured Way of Dealing with Heterogeneous Live Streaming Systems

In peer-to-peer networks for video live streaming, peers can share the forwarding load in two types of systems: unstructured and structured. In unstructured overlays, the graph structure is not well-defined, and a peer can obtain the stream from many sources. In structured overlays, the graph is organized as a tree rooted at the server and parent-child relationships are established between peers. Unstructured overlays ensure robustness and a higher degree of resilience compared to the structured ones. Indeed, they better manage the dynamics of peer participation or churn. Nodes can join and leave the system at any moment. However, they are less bandwidth efficient than structured overlays. In [54], we propose new simple distributed repair protocols for video live streaming structured systems. We show, through simulations and with real traces from Twitch, that structured systems can be very efficient and robust to failures, even for high churn and when peers have very heterogeneous upload bandwidth capabilities.

7.1.5.2. Optimal SF Allocation in LoRaWAN Considering Physical Capture and Imperfect Orthogonality

In [46], we propose a theoretical framework for maximizing the long range wide-area networks (LoRaWAN) capacity in terms of the number of end nodes, when they all have the same traffic generation process. The model optimally allocates the spreading factor to the nodes so that attenuation and collisions are optimized. We use an accurate propagation model considering Rayleigh channel, and we take into account physical capture and imperfect spreading factors (SF) orthogonality while guaranteeing a given transmission success probability to each served node in the network. Numerical results show the effectiveness of our SF allocation policy. Our framework also quantifies the maximum capacity of single cell networks and the gain induced by multiplying the gateways on the covered area. We finally evaluate the impact of physical capture and imperfect SF orthogonality on the SF allocation and network performances.

7.2. Graph Algorithms

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COATI is interested in the algorithmic aspects of Graph Theory. In general we try to find the most efficient algorithms to solve various problems of Graph Theory and telecommunication networks. We use Graph Theory to model various network problems. We study their complexity and then we investigate the structural properties of graphs that make these problems hard or easy.

7.2.1. Complexity of graph problems

7.2.1.1. Fully Polynomial FPT Algorithms for Some Classes of Bounded Clique-width Graphs.

Recently, hardness results for problems in P were achieved using reasonable complexity theoretic assumptions such as the Strong Exponential Time Hypothesis. According to these assumptions, many graph theoretic problems do not admit truly subquadratic algorithms. A central technique used to tackle the difficulty of the above mentioned problems is fixed-parameter algorithms with polynomial dependency in the fixed parameter (P-FPT). Applying this technique to clique-width, an important graph parameter, remained to be done. In [35], we study several graph theoretic problems for which hardness results exist such as cycle problems, distance problems and maximum matching. We give hardness results and P-FPT algorithms, using clique-width and some of its upper bounds as parameters. We believe that our most important result is an algorithm in $O(k^4 \cdot n + m)$-time for computing a maximum matching where k is either the modular-width of the graph or the P_4-sparseness. The latter generalizes many algorithms that have been introduced so far for specific subclasses such as cographs. Our algorithms are based on preprocessing methods using modular decomposition and split decomposition. Thus they can also be generalized to some graph classes with unbounded clique-width.

7.2.1.2. Explicit Linear Kernels for Packing Problems

During the last years, several algorithmic meta-theorems have appeared (Bodlaender et al. [83], Fomin et al. [88], Kim et al. [90]) guaranteeing the existence of linear kernels on sparse graphs for problems satisfying some generic conditions. The drawback of such general results is that it is usually not clear how to derive from them constructive kernels with reasonably low explicit constants. To fill this gap, we recently presented [89] a framework to obtain explicit linear kernels for some families of problems whose solutions can be certified by a subset of vertices. In [37], we enhance our framework to deal with packing problems, that is, problems whose solutions can be certified by collections of *subgraphs* of the input graph satisfying certain properties. $\mathcal{F}$-Packing is a typical example: for a family $\mathcal{F}$ of connected graphs that we assume to contain at least one planar graph, the task is to decide whether a graph G contains k vertex-disjoint sub-graphs such that each of them contains a graph in $\mathcal{F}$ as a minor. We provide explicit linear kernels on sparse graphs for the following two orthogonal generalizations of $\mathcal{F}$-Packing: for an integer $\ell \geq 1$, one aims at finding either minor-models that are pairwise at distance at least ℓ in G (-$\mathcal{F}$-Packing), or such that each vertex in G belongs to at most ℓ minors-models ($\mathcal{F}$-Packing with-Membership). Finally, we also provide linear kernels for the versions of these problems where one wants to pack *subgraphs* instead of minors.

7.2.1.3. Low Time Complexity Algorithms for Path Computation in Cayley Graphs.

We study the problem of path computation in Cayley Graphs (CG) from an approach of word processing in groups. This approach consists in encoding the topological structure of CG in an automaton called Diff, then techniques of word processing are applied for computing the shortest paths. In [17], we present algorithms for computing the K-shortest paths, the shortest disjoint paths and the shortest path avoiding a set of nodes and edges. For any CG with diameter D, the time complexity of the proposed algorithms is $O(KD|\text{Diff}|)$, where $|\text{Diff}|$ denotes the size of Diff. We show that our proposal outperforms the state of art of topology-agnostic algorithms for disjoint shortest paths and stays competitive with respect to proposals for specific families of CG. Therefore, the proposed algorithms set a base in the design of adaptive and low-complexity routing schemes for networks whose interconnections are defined by CG.

7.2.1.4. Convex hull in graphs.

In [40], we prove that, given a closure function the smallest preimage of a closed set can be calculated in polynomial time in the number of closed sets. This implies that there is a polynomial time algorithm to compute the convex hull number of a graph, when all its convex subgraphs are given as input. We then show that deciding if the smallest preimage of a closed set is logarithmic in the size of the ground set is LOGSNP-hard if only the ground set is given. A special instance of this problem is to compute the dimension of a poset given its linear extension graph, that is conjectured to be in P.
The intent to show that the latter problem is LOGSNP-complete leads to several interesting questions and to the definition of the isometric hull, i.e., a smallest isometric subgraph containing a given set of vertices S. While for $|S| = 2$ an isometric hull is just a shortest path, we show that computing the isometric hull of a set of vertices is NP-complete even if $|S| = 3$. Finally, we consider the problem of computing the isometric hull number of a graph and show that computing it is Σ_2^P complete.

7.2.2. Combinatorial games in graphs

7.2.2.1. Graph searching and combinatorial games in graphs.

The Network Decontamination problem consists of coordinating a team of mobile agents in order to clean a contaminated network. The problem is actually equivalent to tracking and capturing an invisible and arbitrarily fast fugitive. This problem has natural applications in network security in computer science or in robotics for search or pursuit-evasion missions. Many different objectives have been studied: the main one being the minimization of the number of mobile agents necessary to clean a contaminated network.

Many environments (continuous or discrete) have also been considered. In the book chapter [61], we focus on networks modeled by graphs. In this context, the optimization problem that consists of minimizing the number of agents has a deep graph-theoretical interpretation. Network decontamination and, more precisely, *graph searching* models, provide nice algorithmic interpretations of fundamental concepts in the Graph Minors theory by Robertson and Seymour.

For all these reasons, graph searching variants have been widely studied since their introduction by Breish (1967) and mathematical formalizations by Parsons (1978) and Petrov (1982). The book chapter [61] consists of an overview of the algorithmic results on graph decontamination and graph searching. Moreover, [19] is the preface to the special issue of TCS on the 8th Workshop on GRAph Searching, Theory and Applications, Anogia, Crete, Greece, April 10 - April 13, 2017.

In [52], we focus on another game with mobile agents in a graph. Precisely, in the eternal domination game played on graphs, an attacker attacks a vertex at each turn and a team of guards must move a guard to the attacked vertex to defend it. The guards may only move to adjacent vertices on their turn. The goal is to determine the eternal domination number γ_{all}^{∞} of a graph which is the minimum number of guards required to defend against an infinite sequence of attacks. [52] continues the study of the eternal domination game on strong grids $P_n \boxtimes P_m$. Cartesian grids $P_n \square P_m$ have been vastly studied with tight bounds existing for small grids such as $k \times n$ grids for $k \in \{2,3,4,5\}$. It was recently proven that $\gamma_{all}^{\infty}(P_n \square P_m) = \gamma(P_n \square P_m) + O(n+m)$ where $\gamma(P_n \square P_m)$ is the domination number of $P_n \square P_m$ which lower bounds the eternal domination number [91]. We prove that, for all $n,m \in \mathbb{N}^*$ such that $m \geq n$, $\lfloor \frac{nm}{9} \rfloor + \Omega(n+m) = \gamma_{all}^{\infty}(P_n \boxtimes P_m) = \lceil \frac{nm}{9} \rceil + O(m\sqrt{n})$ (note that $\lceil \frac{nm}{9} \rceil$ is the domination number of $P_n \boxtimes P_m$). Our technique may be applied to other “grid-like" graphs.

In [66], we adapt the techniques of [91] to prove that the eternal domination number of strong grids is upper bounded by $\frac{mn}{7} + O(m+n)$. While this does not improve upon a recently announced bound of $\lceil \frac{m}{3} \rceil \lceil \frac{n}{3} \rceil + O(m\sqrt{n})$ [52] in the general case, we show that our bound is an improvement in the case where the smaller of the two dimensions is at most 6179.

7.2.2.2. The Orthogonal Colouring Game

In [18], we introduce the Orthogonal Colouring Game, in which two players alternately colour vertices (from a choice of $m \in N$ colours) of a pair of isomorphic graphs while respecting the properness and the orthogonality of the colouring. Each player aims to maximize her score, which is the number of coloured vertices in the copy of the graph she owns. Our main result is that the second player has a strategy to force a draw in this game for any $m \in N$ for graphs that admit a strictly matched involution. An involution σ of a graph G is strictly matched if its fixed point set induces a clique and any non-fixed point $v \in V(G)$ is connected with its image $\sigma(v)$ by an edge. We give a structural characterization of graphs admitting a strictly matched involution and bounds for the number of such graphs. Examples of such graphs are the graphs associated with Latin squares and sudoku squares.
In [62], we prove that recognising graphs that admit a strictly matched involution is NP-complete.

7.2.2.3. Complexity of Games Compendium

Since games and puzzles have been studied under a computational lens, researchers unearthed a rich landscape of complexity results showing deep connections between games and fundamental problems and models in computer science. Complexity of Games (CoG, https://steven3k.gitlab.io/isnphard-test/) is a compendium of complexity results on games and puzzles. It aims to serve as a reference guide for enthusiasts and researchers on the topic and is a collaborative and open source project that welcomes contributions from the community.

7.2.3. Algorithms for social networks

7.2.3.1. KADABRA, an ADaptive Algorithm for Betweenness via Random Approximation

In [32], we present KADABRA, a new algorithm to approximate betweenness centrality in directed and undirected graphs, which significantly outperforms all previous approaches on real-world complex networks. The efficiency of the new algorithm relies on two new theoretical contributions, of independent interest. The first contribution focuses on sampling shortest paths, a subroutine used by most algorithms that approximate betweenness centrality. We show that, on realistic random graph models, we can perform this task in time $|E|^{\frac{1}{2}+o(1)}$ with high probability, obtaining a significant speedup with respect to the $\Theta(|E|)$ worst-case performance. We experimentally show that this new technique achieves similar speedups on real-world complex networks, as well. The second contribution is a new rigorous application of the adaptive sampling technique. This approach decreases the total number of shortest paths that need to be sampled to compute all betweenness centralities with a given absolute error, and it also handles more general problems, such as computing the k most central nodes. Furthermore, our analysis is general, and it might be extended to other settings.

7.2.3.2. Distributed Community Detection via Metastability of the 2-Choices Dynamics

In [56], we investigate the behavior of a simple majority dynamics on networks of agents whose interaction topology exhibits a community structure. By leveraging recent advancements in the analysis of dynamics, we prove that, when the states of the nodes are randomly initialized, the system rapidly and stably converges to a configuration in which the communities maintain internal consensus on different states. This is the first analytical result on the behavior of dynamics for non-consensus problems on non-complete topologies, based on the first symmetry-breaking analysis in such setting. Our result has several implications in different contexts in which dynamics are adopted for computational and biological modeling purposes. In the context of Label Propagation Algorithms, a class of widely used heuristics for community detection, it represents the first theoretical result on the behavior of a distributed label propagation algorithm with quasi-linear message complexity. In the context of evolutionary biology, dynamics such as the Moran process have been used to model the spread of mutations in genetic populations [Lieberman, Hauert, and Nowak 2005]; our result shows that, when the probability of adoption of a given mutation by a node of the evolutionary graph depends super-linearly on the frequency of the mutation in the neighborhood of the node and the underlying evolutionary graph exhibits a community structure, there is a non-negligible probability for species differentiation to occur.

7.2.3.3. On the Necessary Memory to Compute the Plurality in Multi-Agent Systems

Consensus and Broadcast are two fundamental problems in distributed computing, whose solutions have several applications. Intuitively, Consensus should be no harder than Broadcast, and this can be rigorously established in several models. Can Consensus be easier than Broadcast?

In models that allow noiseless communication, we prove in [60] a reduction of (a suitable variant of) Broadcast to binary Consensus, that preserves the communication model and all complexity parameters such as randomness, number of rounds, communication per round, etc., while there is a loss in the success probability of the protocol. Using this reduction, we get, among other applications, the first logarithmic lower bound on the number of rounds needed to achieve Consensus in the uniform GOSSIP model on the complete graph. The lower bound is tight and, in this model, Consensus and Broadcast are equivalent.

We then turn to distributed models with noisy communication channels that have been studied in the context of some bio-inspired systems. In such models, only one noisy bit is exchanged when a communication channel is established between two nodes, and so one cannot easily simulate a noiseless protocol by using error-correcting codes. An $\Omega(\epsilon^{-2}n)$ lower bound on the number of rounds needed for Broadcast is proved by Boczkowski et al. [82] in one such model (noisy uniform PULL, where ϵ is a parameter that measures the amount of noise). In such model, we prove a new $\Theta(\epsilon^{-2}n\log n)$ bound for Broadcast and a $\Theta(\epsilon^{-2}\log n)$ bound for binary Consensus, thus establishing an exponential gap between the number of rounds necessary for Consensus versus Broadcast.

7.2.3.4. How long does it take for all users in a social network to choose their communities?

In [30], we consider a community formation problem in social networks, where the users are either friends or enemies. The users are partitioned into conflict-free groups (i.e., independent sets in the conflict graph $G^- = (V,E)$ that represents the enmities between users). The dynamics goes on as long as there exists any set of at most k users, k being any fixed parameter, that can change their current groups in the partition simultaneously, in such a way that they all strictly increase their utilities (number of friends i.e., the cardinality of their respective groups minus one). Previously, the best-known upper-bounds on the maximum time of convergence were $O(|V|\alpha(G^-))$ for $k \leq 2$ and $O(|V|^3)$ for $k = 3$, with $\alpha(G^-)$ being the independence number of G^-. Our first contribution consists in reinterpreting the initial problem as the study of a dominance ordering over the vectors of integer partitions. With this approach, we obtain for $k \leq 2$ the tight upper-bound $O(|V|\min\left\{\alpha(G^-), \sqrt{|V|}\right\})$ and, when G^- is the empty graph, the exact value of order $\frac{(2|V|)^{3/2}}{3}$. The time of convergence, for any fixed $k \geq 4$, was conjectured to be polynomial. In this paper we disprove this. Specifically, we prove that for any $k \geq 4$, the maximum time of convergence is in $\Omega(|V|\Theta(\log|V|))$.

7.2.3.5. A Comparative Study of Neural Network Compression

There has recently been an increasing desire to evaluate neural networks locally on computationally-limited devices in order to exploit their recent effectiveness for several applications; such effectiveness has nevertheless come together with a considerable increase in the size of modern neural networks, which constitute a major downside in several of the aforementioned computationally-limited settings. There has thus been a demand of compression techniques for neural networks. Several proposal in this direction have been made, which famously include hashing-based methods and pruning-based ones. However, the evaluation of the efficacy of these techniques has so far been heterogeneous, with no clear evidence in favor of any of them over the others. In [70], we address this latter issue by providing a comparative study. While most previous studies test the capability of a technique in reducing the number of parameters of state-of-the-art networks, we follow [86] in evaluating their performance on basic architectures on the MNIST dataset and variants of it, which allows for a clearer analysis of some aspects of their behavior. To the best of our knowledge, we are the first to directly compare famous approaches such as HashedNet, Optimal Brain Damage (OBD), and magnitude-based pruning with L1 and L2 regularization among them and against equivalent-size feed-forward neural networks with simple (fully-connected) and structural (convolutional) neural networks. Rather surprisingly, our experiments show that (iterative) pruning-based methods are substantially better than the HashedNet architecture, whose compression doesn't appear advantageous to a carefully chosen convolutional network. We also show that, when the compression level is high, the famous OBD pruning heuristics deteriorates to the point of being less efficient than simple magnitude-based techniques.

7.3. Graph and digraph theory

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COATI studies theoretical problems in graph theory. If some of them are directly motivated by applications, others are more fundamental.

We are putting an effort on understanding better directed graphs (also called *digraphs*) and partitioning problems, and in particular colouring problems. We also try to better the understand the many relations between orientations and colourings. We study various substructures and partitions in (di)graphs. For each of them, we aim at giving sufficient conditions that guarantee its existence and at determining the complexity of finding it.

To ease the reading, we split our results in this section into several subsections dedicated to particular topics.

7.3.1. Graph and digraph colourings

7.3.1.1. Distinguishing labellings and the 1-2-3 Conjecture

We are interested in several distinguishing labelling (or edge-weighting) problems, where the general aim, given a graph, is to label the edges in such a way that certain properties are fulfilled. The main problem we have been considering is the **1-2-3 Conjecture**, which claims that every connected graph different from K_2 admits a labelling with $1, 2, 3$ such that no two adjacent vertices are incident to the same sum of weights. Some of our latest results provide evidence towards the 1-2-3 Conjecture. We also investigated questions inspired from the conjecture, such that the role of the weights $1, 2, 3$ in the statement of the conjecture, the deep connection with proper vertex-colourings and other standard notions of graph theory.

7.3.1.2. A 1-2-3-4 result for the 1-2-3 Conjecture in 5-regular graphs

To date, the best-known result towards the 1-2-3 Conjecture is due to Kalkowski, Karoński and Pfender, who proved that it holds when relaxed to 5-edge-weightings. Their proof builds upon a weighting algorithm designed by Kalkowski for a total version of the problem. In [23], we present new mechanisms for using Kalkowski's algorithm in the context of the 1-2-3 Conjecture. As a main result we prove that every 5-regular graph admits a 4-edge-weighting that permits to distinguish its adjacent vertices via their incident sums.

7.3.1.3. On $\{a,b\}$-edge-weightings of bipartite graphs with odd a,b

For any $S \subset \mathbb{Z}$ we say that a graph G has the S-property if there exists an S-edge-weighting $w : E(G) \rightarrow S$ such that for any pair of adjacent vertices u,v we have $\sum_{e \in E(v)} w(e) \neq \sum_{e \in E(u)} w(e)$, where $E(v)$ and $E(u)$ are the sets of edges incident to v and u, respectively. In general, deciding if a graph G has the $\{a,b\}$-property is NP-complete for every a,b. This question is open for bipartite graphs however. The only known results of this sort are that bipartite graphs without the $\{1,2\}$-property can be recognized easily, and similarly for 2-connected bipartite graphs without the $\{0,1\}$-property. In [28], we focus on $\{a,a+2\}$-edge-weightings where $a \in \mathbb{Z}$ is odd. We show that a 2-connected bipartite graph has the $\{a,a+2\}$-property if and only if it is not a so-called odd multi-cactus. In the case of trees, we show that only one case is pathological. That is, we show that all trees have the $\{a,a+2\}$-property for odd $a \neq -1$, while there is an easy characterization of trees without the $\{-1,1\}$-property.

7.3.1.4. 1-2-3 Conjecture in Digraphs: More Results and Directions

When arc-weighting a digraph, there are, at each vertex, two sums of incident weights: the in-coming sum σ^- and the out-going sum σ^+. Thus, there are many ways for generalizing the 1-2-3 Conjecture to digraphs. In the recent years, four main variants have been considered, where, for every arc $\overrightarrow{uv}$, it is required that one of $\sigma^-(u), \sigma^+(u)$ is different from one of $\sigma^-(v), \sigma^+(v)$. All of these four variants are well understood, except for the one where, for every arc $\overrightarrow{uv}$, it is required that $\sigma^-(u) \neq \sigma^+(v)$. Regarding this version, Horňak, Przybyło and Woźniak recently proved that almost every digraph can be 4-arc-weighted so that, for every arc $\overrightarrow{uv}$, the sum of weights incoming to u is different from the sum of weights outgoing from v. They conjectured a stronger result, namely that the same statement with 3 instead of 4 should also be true. We verify this conjecture in [73]. This work takes place in a recent “quest” towards a directed version of the 1-2-3 Conjecture, the variant above being one of the last introduced ones. We take the occasion of this work to establish a summary of all results known in this field, covering known upper bounds, complexity aspects, and choosability. On the way we prove additional results which were missing in the whole picture. We also mention the aspects that remain open.

7.3.1.5. Edge Weights and Vertex Colours: Minimizing Sum Count

Put differently, the 1-2-3 Conjecture asks whether, via weights with very low magnitude, we can “encode” a proper vertex-colouring of any graph. Note, however, that we do not care about whether such a result colouring is optimal, i.e., whether its number of colours is close to the chromatic number. In [22], we investigate the minimum number of distinct sums/colours we can produce via a neighbour-sum-distinguishing edge-weighting of a given graph G, and the role of the assigned weights in that context. Clearly, this minimum number is bounded below by the chromatic number $\chi(G)$ of G. When using weights of $\mathbb{Z}$, we show that, in general, we can produce neighbour-sum-distinguishing edge-weightings generating $\chi(G)$ distinct sums, except in the peculiar case where G is a balanced bipartite graph, in which case $\chi(G)+1$ distinct sums can be generated. These results are best possible. When using k consecutive weights $1,...,k$, we provide both lower and upper bounds, as a function of the maximum degree Δ, on the maximum least number of sums that can be generated for a graph with maximum degree Δ. For trees, which, in general, admit neighbour-sum-distinguishing 2-edge-weightings, we prove that this maximum, when using weights 1 and 2, is of order $2\log_2 \Delta$. Finally, we also establish the NP-hardness of several decision problems related to these questions.

7.3.1.6. On Minimizing the Maximum Color for the 1-2-3 Conjecture

In the line of the previous investigation, one way to get some sort of progress is to design proper labellings where the maximum color of a vertex is as small as possible. In [64], we investigate the consequences of labeling graphs as in the 1-2-3 Conjecture when it is further required to make the maximum resulting color as small as possible. We first investigate the hardness of determining the minimum maximum color by a labeling for a given graph, which we show is NP-complete in the class of bipartite graphs but polynomial-time solvable in the class of graphs with bounded treewidth. We then provide bounds on the minimum maximum color that can be generated both in the general context, and for particular classes of graphs. Finally, we study how using larger labels permits to reduce the maximum color.

7.3.1.7. Decomposing degenerate graphs into locally irregular subgraphs

A (undirected) graph is locally irregular if no two of its adjacent vertices have the same degree. A decomposition of a graph G into k locally irregular subgraphs is a partition $E_1, ..., E_k$ of $E(G)$ into k parts each of which induces a locally irregular subgraph. Not all graphs decompose into locally irregular subgraphs; however, it was conjectured that, whenever a graph does, it should admit such a decomposition into at most three locally irregular subgraphs. This conjecture was verified for a few graph classes in recent years. It was introduced because it was noticed that, in some contexts, there are connections between locally irregular decompositions and the 1-2-3 Conjecture. In [63], we consider the decomposability of degenerate graphs with low degeneracy. Our main result is that decomposable k-degenerate graphs decompose into at most $3k + 1$ locally irregular subgraphs, which improves on previous results whenever $k \leq 9$. We improve this result further for some specific classes of degenerate graphs, such as bipartite cacti, k-trees, and planar graphs. Although our results provide only little progress towards the leading conjecture above, the main contribution of this work is rather the decomposition schemes and methods we introduce to prove these results.

7.3.1.8. A general decomposition theory for the 1-2-3 Conjecture and locally irregular decompositions

In [21], we propose an approach encapsulating locally irregular decompositions and proper labelings. As a consequence, we get another interpretation of several existing results related to the 1-2-3 Conjecture. We also come up with new related conjectures, to which we give some support.

7.3.1.9. Decomposability of graphs into subgraphs fulfilling the 1-2-3 Conjecture

In particular, one of the side problems we run into is decomposing graphs into subgraphs verifying the 1-2-3 Conjecture. In [29], we prove that every d-regular graph, $d \geq 2$, can be decomposed into at most 2 subgraphs (without isolated edges) fulfilling the 1-2-3 Conjecture if $d \notin \{10, 11, 12, 13, 15, 17\}$, and into at most 3 such subgraphs in the remaining cases. Additionally, we prove that in general every graph without isolated edges can be decomposed into at most 24 subgraphs fulfilling the 1–2–3 Conjecture, improving the previously best upper bound of 40. Both results are partly based on applications of the Lovász Local Lemma.

7.3.1.10. On the 2-edge-coloured chromatic number of grids

The oriented (2-edge-coloured, respectively) chromatic number $\chi_o(G)$ ($\chi_2(G)$, respectively) of an undirected graph G is defined as the maximum oriented (2-edge-coloured, respectively) chromatic number of an orientation (signature, respectively) of G. Although the difference between $\chi_o(G)$ and $\chi_2(G)$ can be arbitrarily large, there are, however, contexts in which these two parameters are quite comparable. In [24], we compare the behaviour of these two parameters in the context of (square) grids. While a series of works has been dedicated to the oriented chromatic number of grids, we are not aware of any work dedicated to their 2-edge-coloured chromatic number. We investigate this throughout this paper. We show that the maximum 2-edge-coloured chromatic number of a grid lies between 8 and 11. We also focus on 2-row grids and 3-row grids, and exhibit bounds on their 2-edge-coloured chromatic number, some of which are tight. Although our results indicate that the oriented chromatic number and the 2-edge-coloured chromatic number of grids are close in general, they also show that these parameters may differ, even for easy instances.

7.3.1.11. From light edges to strong edge-colouring of 1-planar graphs

A strong edge-colouring of an undirected graph G is an edge-colouring where every two edges at distance at most 2 receive distinct colours. The strong chromatic index of G is the least number of colours in a strong edge-colouring of G. A conjecture of Erdős and Nešetřil, stated back in the 80's, asserts that every graph with maximum degree Δ should have strong chromatic index at most roughly $1.25\Delta^2$. Several works in the last decades have confirmed this conjecture for various graph classes. In particular, lots of attention have been dedicated to planar graphs, for which the strong chromatic index decreases to roughly 4Δ, and even to smaller values under additional structural requirements. In [26], we initiate the study of the strong chromatic index of 1-planar graphs, which are those graphs that can be drawn on the plane in such a way that every edge is crossed at most once. We provide constructions of 1-planar graphs with maximum degree Δ and strong chromatic index roughly 6Δ. As an upper bound, we prove that the strong chromatic index of a 1-planar graph with maximum degree Δ is at most roughly 24Δ (thus linear in Δ). In the course of proving the latter result, we prove, towards a conjecture of Hudák and Šugerek, that 1-planar graphs with minimum degree 3 have edges both of whose ends have degree at most 29.

7.3.1.12. Pushable chromatic number of graphs with degree constraints

Pushable homomorphisms and the pushable chromatic number χ_p of oriented graphs were introduced by Klostermeyer and MacGillivray in 2004. They notably observed that, for any oriented graph $\overrightarrow{G}$, we have $\chi_p(\overrightarrow{G}) \leq \chi_o(\overrightarrow{G}) \leq 2\chi_p(\overrightarrow{G})$, where $\chi_o(\overrightarrow{G})$ denotes the oriented chromatic number of $\overrightarrow{G}$. This stands as first general bounds on χ_p. This parameter was further studied in later works.

In [71], we consider the pushable chromatic number of oriented graphs fulfilling particular degree conditions. For all $\Delta \geq 29$, we first prove that the maximum value of the pushable chromatic number of an oriented graph with maximum degree Δ lies between $2^{\frac{\Delta}{2}-1}$ and $(\Delta-3) \cdot (\Delta-1) \cdot 2^{\Delta-1}+2$ which implies an improved bound on the oriented chromatic number of the same family of graphs. For subcubic oriented graphs, that is, when $\Delta \leq 3$, we then prove that the maximum value of the pushable chromatic number is 6 or 7. We also prove that the maximum value of the pushable chromatic number of oriented graphs with maximum average degree less than 3 lies between 5 and 6. The former upper bound of 7 also holds as an upper bound on the pushable chromatic number of planar oriented graphs with girth at least 6.

7.3.2. Graph and digraph decompositions

7.3.2.1. Edge-partitioning a graph into paths: beyond the Barát-Thomassen conjecture

In 2006, Barát and Thomassen conjectured that there is a function f such that, for every fixed tree T with t edges, every $f(t)$-edge-connected graph with its number of edges divisible by t has a partition of its edges into copies of T. This conjecture was recently verified in [81] by, in particular, some members of COATI. In [27], we further focus on the path case of the Barát-Thomassen conjecture. Before the aforementioned general proof was announced, several successive steps towards the path case of the conjecture were made, notably by Thomassen [94], [95], [96], until this particular case was totally solved by Botler, Mota, Oshiro and Wakabayashi [84]. Our goal in this work was to propose an alternative proof of the path case with a weaker hypothesis: Namely, we prove that there is a function f such that every 24-edge-connected graph with minimum degree $f(t)$ has an edge-partition into paths of length t whenever t divides the number of edges. We also show that 24 can be dropped to 4 when the graph is eulerian.

7.3.2.2. Constrained ear decompositions in graphs and digraphs.

Ear decompositions of graphs are a standard concept related to several major problems in graph theory like the Traveling Salesman Problem. For example, the Hamiltonian Cycle Problem, which is notoriously NP-complete, is equivalent to deciding whether a given graph admits an ear decomposition in which all ears except one are trivial (i.e. of length 1). On the other hand, a famous result of Lovász states that deciding whether a graph admits an ear decomposition with all ears of odd length can be done in polynomial time. In [38], we study the complexity of deciding whether a graph admits an ear decomposition with prescribed ear lengths. We prove that deciding whether a graph admits an ear decomposition with all ears of length at most ℓ is polynomial-time solvable for all fixed positive integer ℓ. On the other hand, deciding whether a graph admits an ear decomposition without ears of length in $\mathcal{F}$ is NP-complete for any finite set $\mathcal{F}$ of positive integers. We also prove that, for any $k \geq 2$, deciding whether a graph admits an ear decomposition with all ears of length $0 \mod k$ is NP-complete.

We also consider the directed analogue to ear decomposition, which we call handle decomposition, and prove analogous results : deciding whether a digraph admits a handle decomposition with all handles of length at most ℓ is polynomial-time solvable for all positive integer ℓ; deciding whether a digraph admits a handle decomposition without handles of length in $\mathcal{F}$ is NP-complete for any finite set $\mathcal{F}$ of positive integers (and minimizing the number of handles of length in $\mathcal{F}$ is not approximable up to $n(1-\epsilon)$); for any $k \geq 2$, deciding whether a digraph admits a handle decomposition with all handles of length $0 \mod k$ is NP-complete. Also, in contrast with the result of Lovász, we prove that deciding whether a digraph admits a handle decomposition with all handles of odd length is NP-complete. Finally, we conjecture that, for every set $\mathcal{A}$ of integers, deciding whether a digraph has a handle decomposition with all handles of length in $\mathcal{A}$ is NP-complete, unless there exists $h \in \mathbb{N}$ such that $\mathcal{A} = \{1, \cdots, h\}$.

7.3.3. Substructures in graphs and digraphs

7.3.3.1. Subdivisions in Digraphs of Large Out-Degree or Large Dichromatic Number

In 1985, Mader conjectured the existence of a function f such that every digraph with minimum out-degree at least $f(k)$ contains a subdivision of the transitive tournament of order k. This conjecture is still completely open, as the existence of $f(5)$ remains unknown. In this paper, we show that if D is an oriented path, or an in-arborescence (i.e., a tree with all edges oriented towards the root) or the union of two directed paths from x to y and a directed path from y to x, then every digraph with minimum out-degree large enough contains a subdivision of D. Additionally, we study Mader's conjecture considering another graph parameter. The dichromatic number of a digraph D is the smallest integer k such that D can be partitioned into k acyclic subdigraphs. We show in [16] that any digraph with dichromatic number greater than $4m(n-1)$ contains every digraph with n vertices and m arcs as a subdivision.

7.3.3.2. Bipartite spanning sub(di)graphs induced by 2-partitions

For a given 2-partition (V_1, V_2) of the vertices of a (di)graph G, we study properties of the spanning bipartite subdigraph $BG(V_1, V_2)$ of G induced by those arcs/edges that have one end in each $V_i, i \in \{1, 2\}$. In [20], we determine, for all pairs of non-negative integers k_1, k_2, the complexity of deciding whether G has a 2-partition (V_1, V_2) such that each vertex in V_i (for $i \in \{1, 2\}$) has at least k_i (out-)neighbours in V_{3-i}. We prove that it is NP-complete to decide whether a digraph D has a 2-partition (V_1, V_2) such that each vertex in V_1 has an out-neighbour in V_2 and each vertex in V_2 has an in-neighbour in V_1. The problem becomes polynomially solvable if we require D to be strongly connected. We give a characterization of the structure of NP-complete instances in terms of their strong component digraph. When we want higher in-degree or out-degree to/from the other set the problem becomes NP-complete even for strong digraphs. A further result is that it is NP-complete to decide whether a given digraph D has a 2-partition (V_1, V_2) such that $BD(V_1, V_2)$ is strongly connected. This holds even if we require the input to be a highly connected eulerian digraph.

7.3.3.3. Metric Dimension: from Graphs to Oriented Graphs

The metric dimension $MD(G)$ of an undirected graph G is the cardinality of a smallest set of vertices that allows, through their distances to all vertices, to distinguish any two vertices of G. Many aspects of this notion have been investigated since its introduction in the 70's, including its generalization to digraphs.

In [42], [43], we study, for particular graph families, the maximum metric dimension over all strongly-connected orientations, by exhibiting lower and upper bounds on this value. We first exhibit general bounds for graphs with bounded maximum degree. In particular, we prove that, in the case of subcubic n-node graphs, all strongly-connected orientations asymptotically have metric dimension at most $\frac{n}{2}$, and that there are such orientations having metric dimension $\frac{2n}{5}$. We then consider strongly-connected orientations of grids. For a torus with n rows and m columns, we show that the maximum value of the metric dimension of a strongly-connected Eulerian orientation is asymptotically $\frac{nm}{2}$ (the equality holding when n, m are even, which is best possible). For a grid with n rows and m columns, we prove that all strongly-connected orientations asymptotically have metric dimension at most $\frac{2nm}{3}$, and that there are such orientations having metric dimension $\frac{nm}{2}$.

7.3.4. Bio-informatics motivated problems

7.3.4.1. Overlaying a hypergraph with a graph with bounded maximum degree

A major problem in structural biology is the characterization of low resolution structures of macro-molecular assemblies. One subproblem of this very difficult question is to determine the plausible contacts between the subunits (e.g. proteins) of an assembly, given the lists of subunits involved in all the complexes. This problem can be conveniently modelled by graphs and hypergraphs. Let G and H be respectively a graph and a hypergraph defined on a same set of vertices, and let F be a fixed graph. We say that GF-overlays a hyperedge S of H if F is a spanning subgraph of the subgraph of G induced by S, and that it F-overlays H if it F-overlays every hyperedge of H. Motivated by structural biology, we study in [68] the computational complexity of two problems. The first problem, $(\Delta \leq k)F$-Overlay, consists in deciding whether there is a graph with maximum degree at most k that F-overlays a given hypergraph H. It is a particular case of the second problem Max $(\Delta \leq k)F$-Overlay, which takes a hypergraph H and an integer s as input, and consists in deciding whether there is a graph with maximum degree at most k that F-overlays at least s hyperedges of H. We give a complete polynomial/NP-complete dichotomy for the Max $(\Delta \leq k)F$-Overlay problems depending on the pairs (F, k), and establish the complexity of $(\Delta \leq k)F$-Overlay for many pairs (F, k).

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Oui!Greens, 2019

Participant: Joanna Moulierac.

Duration: January 2019 - February 2019

Coordinator: Joanna Moulierac

Other partners: Dorian Mazauric from EP ABS

Abstract: Supervision of an InriaTech engineer for the development of the algorithm proposed in a previous collaboration with Oui!Greens.

The aim of the algorithm is to propose to clients the adequate products (fruits or vegetables) that are almost out-of-date with the objective of maximizing the satisfaction of the clients, and the diminution of the wastage. During one month, this algorithm has been implemented into the mobile application pepino, owned by Oui!Greens.

8.1.2. MillionRoads, 2019-2020

Participants: David Coudert, Frédéric Giroire, Luc Hogie, Nicolas Nisse, Michel Syska.

Duration: October 2019 - April 2020

Project title: HumanRoads

Coordinator: Nicolas Nisse

Other partners: SME MillionRoads; EP Zenith (Didier Parigot)

Abstract: HumanRoads uses a graph database, in the Neo4j environment, to store and structure its data. This database is already large and is regularly enriched with new data. However, to date, response times to queries are not satisfactory. This Project aims at identifying the limiting factors and to propose alternatives. More precisely, we will work on analyzing the data structure in the graph database to optimize queries, in the Neo4j environment, and on graph algorithms to speed up queries.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. SNIF, 2018-2021

Participants: David Coudert, Frédéric Giroire, Nicolas Nisse, Stéphane Pérennes.

Program: Innovation project of IDEX UCA$^{\text{JEDI}}$.

Project acronym: SNIF

Project title: Scientific Networks and IDEX Funding

Duration: September 2018 - August 2021

Coordinator: Patrick Musso

Other partners: GREDEG, SKEMA, I3S (SigNet) and Inria (COATI), all from UCA.

Abstract: Scientific collaboration networks play a crucial role in modern science. This simple idea underlies a variety of initiatives aiming to promote scientific collaborations between different research teams, universities, countries and disciplines. The recent French IDEX experience is one of them. By fostering competition between universities and granting few of them with a relatively small amount of additional resources (as compare to their global budget), public authorities aim to encourage them to deeply reshape the way academic activities are organized in order to significantly increase the quality of their research, educational programs and innovative activities. The development of new collaboration networks is one of the factors at the heart of this global reorganization. Promoting new international and/or interdisciplinary collaborations is supposed to increase researchers' productivity and industry partnerships. This project aims to question the validity of this line of thought.

9.2. National Initiatives

9.2.1. DGA/Inria Brainside, 2019-2023

Participants: Francesco d'Amore, Emanuele Natale.

Program: DGA/Inria

Project acronym: Brainside

Project title: Algorithms for simplifying neural networks

Duration: October 2019 - March 2023

Coordinator: Emanuele Natale

Other partners: Inria Paris, EP GANG

Abstract: The widespread use of neural networks on devices with computationally-low capabilities, demands for lightweight and energy-efficient networks. Despite such need, and despite the strategies employed to prevent overfitting by removing a substantial part of their edges, the question of how to reduce their size in terms of the number of neurons appears largely unexplored. The aim of the project is to investigate algorithmic procedures to reduce the size of neural networks, in order to improve the speed with which they can be evaluated and to shed light on how much information about the computational problem at hand can be encoded within neural networks of small size.

9.2.2. ANR-17-CE22-0016 MultiMod, 2018-2022

Participants: Mohammed Amine Ait Ouahmed, Ali Al Zoobi, David Coudert, Nicolas Nisse, Michel Syska.

Program: ANR

Project acronym: MultiMod

Project title: Scalable routing in Multi Modal transportation networks

Duration: January 2018 - December 2022

Coordinator: David Coudert

Other partners: Inria Paris, EP GANG; team CeP, I3S laboratory; SME Instant-System; SME Benomad

Abstract: The MultiMod project addresses key algorithmic challenges to enable the fast computation of personalized itineraries in large-scale multi-modal public transportation (PT) networks (bus, tram, metro, bicycle, etc.) combined with dynamic car-pooling. We will use real-time data to propose itineraries with close to real travel-time, and handle user-constraints to propose personalized itineraries. Our main challenge is to overcome the scalability of existing solutions in terms of query processing time and data-structures space requirements, while including unplanned transportation means (car-pooling), real-time data, and personalized user constraints. The combination of car-pooling and PT network will open-up areas with low PT coverage enable faster itineraries and so foster the adoption of car-pooling. We envision that the outcome of this project will dramatically enhanced the mobility and daily life of citizens in urban areas.

Web: https://project.inria.fr/multimod/

9.2.3. PICS DISCO

Program: PICS

Project acronym: DISCO

Project title: DIsjoint Structures and Coverings in Oriented graphs

Duration: January 2018 -December 2020.

Coordinator: Stéphane Bessy (LIRMM)

Other partners: CNRS LIRMM (Montpellier), Syddansk universitet (Odense, Danemark)

Abstract: Directed graphs (digraphs) are much less understood than undirected graphs. Many, seemingly very simple questions remain unsolved for digraphs while the analogous problem for undirected graphs is trivial. At the same time digraphs are a very important modelling tool for practical applications and so a better undestanding of their structure is important. The purpose of DISCO is to advance knowledge on fundamental problems on digraphs, including splitting a digraph into smaller pieces with given properties, problems regarding disjoint paths and trees, finding small certificates for given properties, such as strong spanning subdigraphs with few arcs. The later is important for speeding up certain algorithms.

Through a concerted effort we expect to obtain important results which will lead to a better undestanding of fundamental questions about the structure of digraphs. The participants will meet regularly both in France and in Denmark to work on carefully selected problems.

9.2.4. GDR Actions

9.2.4.1. GDR RSD, ongoing (since 2006)

Members of COATI are involved in the working group RESCOM (*Réseaux de communications*) of GDR RSD, CNRS (http://gdr-rsd.cnrs.fr/pole_rescom). In particular, David Coudert is co-chair of this working group since 2017.

We are also involved in the working group "Energy" of GDR RSD (http://gdr-rsd.cnrs.fr/action_green). In particular, Frédéric Giroire is co-hair of this working group.

9.2.4.2. GDR IM, ongoing (since 2006)

Members of COATI are involved in the working group "Graphes" of GDR IM, CNRS. (http://gtgraphes.labri.fr/). In particular, Frédéric Havet is member of the steering committee.

9.2.4.3. GDR MADICS, ongoing (since 2017)

Members of COATI are involved in the working group GRAMINEES (GRaph data Mining in Natural, Ecological and Environnemental Sciences) of GDR MADICS (Masses de Données, Informations et Connaissances en Sciences). (http://www.madics.fr/actions/actions-en-cours/graminees/).

9.3. International Initiatives

9.3.1. Inria Associate Teams Not Involved in an Inria International Labs

9.3.1.1. EfDyNet

Title: Efficient Dynamic Resource Allocation in Networks

International Partner (Institution - Laboratory - Researcher):

Concordia University (Canada) - Department of Electrical Engineering - Brigitte Jaumard

Start year: 2019

See also: https://team.inria.fr/coati/projects/efdynet/

Networks are evolving rapidly in two directions. On the one hand, new network technologies are developed for different layers, and in particular flexible optical technologies (enabling to allocate a fraction of the optical spectrum rather than a fixed wavelength), Software Defined Networks, and Network Function Virtualization. On the other hand, the traffic patterns evolve and become less predictable due to the increase of cloud and mobile traffic. In this context, there are new possibilities and needs for dynamic resource allocations. We will study this problem mainly in two directions: network reconfiguration and the allocation of virtualized resources. The associated team will build on an already fruitful collaboration between COATI and Concordia. The two teams address design and management optimization problems in networks (WDM, wireless, SDN) with complementary tools and expertise.

9.3.2. Inria International Partners

9.3.2.1. Informal International Partners

Apart from formal collaboration COATI members maintain strong connections with the following international teams, with regular visits of both sides.

Universidade Federal do Ceará (Fortaleza, Brazil), ParGO team;

Universidade Estadual do Ceará (Fortaleza, Brazil), Prof. Leonardo Sampaio;

Univ. of Southern Denmark (Odense, Denmark), Prof. Jørgen Bang-Jensen.

9.3.3. Participation in Other International Programs

9.3.3.1. International Initiatives

GALOP

Program: STICAmSud

Title: Graphs ALgorithms for Optimization Problems

International Partners (Institution - Laboratory - Researcher):

Universidad Diego Portales (Chile) - Facultad de Ingeniería y Ciencias - Karol Suchan

Universidade Federal do Ceará (Brazil) - ParGo team - Julio Araujo

Duration: 2019 - 2020

Start year: 2019

See also: https://team.inria.fr/coati/projects/sticamsud-galop/

This project aims at allowing to continue the fruitful and long-standing collaboration between Inria and UFC and between Inria and UAI. Another goal is to reinforce the collaboration between UFC and UAI that has been recently initiated. Our goal is to study the Computational Complexity of several important problems arising in networks (routing, resources assignment...). In particular, we will focus on the computation of metric or structural properties and parameters of large networks (e.g., transportation and social networks...). We plan to design efficient exact algorithms for solving these problems or to theoretically prove that such algorithms cannot exist. In the latter case, we will then design approximation algorithms, or prove that none exists. In all cases, we aim at implementing our algorithms and use them on real-world instances such as large road networks or huge social networks.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

- Hossein Baktash: Sharif Institute of Technology, Tehran, Iran. July 15 - September 15, 2019.
- Joergen Bang-Jensen: Southern Denmark University, Odense, Denmark, January 7-11 2019.
- Brigitte Jaumard: Concordia University, Montréal, Québec, Canada. June 17-28 and December 7-21, 2019.

- Malgorzata Sulkowska: Faculty of Fundamental Problems of Technology, Wroclaw University of Science and Technology, Wroclaw, Poland. September 23-27th, 2019.
- Karol Suchan: Universidad Diego Portales, Santiago, Chile. December 8-22th, 2019.
- Julio-Cesar Silva Araújo: Universidad do Ceara, Fortaleza, Brazil. December 5-28th, 2019.
- Karol Maia de Oliveira: Universidad do Ceara, Fortaleza, Brazil. December 5-28th, 2019.
- Claudia Linhares Sales: Universidad do Ceara, Fortaleza, Brazil. December 5-28th, 2019.
- Leonardo Sampaio Rocha: Universidad do Ceara, Fortaleza, Brazil. until June 2019.
- Xavier Defago: Tokyo Institute of Technology, Tokyo, Japan. January 7-11, 2019.
- Takako Kodate: Tokyo Woman's Christian University, Tokyo, Japan. March 18-31, 2019.

9.4.2. Visits to International Teams

9.4.2.1. Research Stays Abroad

- Julien Bensmail :

  Indian Statistical Institute, Kolkata, India. January 26-February 9, 2019.

  Universidade Federal do Ceará, Fortaleza, Brazil. May 4-May 17, 2019.

  Xidian University, Xi'an, China. August 31-September 14, 2019.

  Northwestern Polytechnical University, Xi'an, China. October 19-November 2, 2019.
- David Coudert :

  Concordia University, Montréal, Québec, Canada. July 12-27, 2019.
- Adrien Gausseran :

  Concordia University, Montréal, Québec, Canada. September 2 - December 2, 2019.
- Frédéric Giroire :

  Concordia University, Montréal, Québec, Canada. October 8-18th, 2019.
- Joanna Moulierac :

  Concordia University, Montréal, Québec, Canada. October 8-18th, 2019.
- Emanuele Natale :

  Max Planck Institute for Informatics, Sarrebruck, Germany. January 19 - February 28, 2019.

  University of Melbourne, Melbourne, Australia & University of Otago, Dunedin, New Zealand. October 1-30, 2019.

  University of Rome Tor Vergata, Rome, Italy. 1 November 2019 - 31 January 2020.
- Nicolas Nisse :

  Univ. Federal do Ceara, Fortaleza, Brazil, May 4-18th, 2019.

  Xidiang University, Xi'an, China. September 1-15th, 2019.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events: Selection

10.1.1.1. Member of the Conference Program Committees

- Christelle Caillouet :

MiSARN'19: International Mission-Oriented Wireless Sensor, UAV and Robot Networking in conjunction with IEEE INFOCOM 2019.

Wi-DroIT'19: 1st International Workshop on Wireless sensors and Drones in Internet of Things in conjunction with DCOSS 2019

AlgoTel'19: 21ème Rencontre Francophone sur les Aspects Algorithmiques de Télécommunications, Saint Laurent de la Cabrerisse, France, June 4-7, 2019.

- David Coudert :

  ONDM'19: 23rd Conference on Optical Network Design and Management, Athens, Greece, May 13-16, 2019.

  IEEE ICC'19: IEEE International Conference on Communications, Shangai, China, May 20-24, 2019.

  IEEE Globecom'19: IEEE Global Communications Conference, Waikoloa, Hi, USA, December 9-13, 2019.

- Frédéric Giroire :

  Algotel'19: 21ème Rencontre Francophone sur les Aspects Algorithmiques de Télécommunications, Saint-Laurent-de-la-Cabrerisse, France, June 4-7, 2019.

- Frédéric Havet :

  LAGOS'19: X Latin and American Algorithms, Graphs and Optimization Symposium, Belo Horizonte, Brazil, June 2-7 2019.

  JGA'19: Journées Graphes et Algorithmes, Brussels, Belgium, November 15-17 2019.

- Joanna Moulierac :

  CoRes'19: Rencontres Francophones sur la Conception de Protocoles, l'Evaluation de Performance et l'Expérimentation des Réseaux de Communication, Saint Laurent de la Cabrerisse, France, June 3-4, 2019.

- Emanuele Natale :

  SPAA'19: 31st ACM Symposium on Parallelism in Algorithms and Architectures, Phoenix, AZ, USA, June 22-24, 2019 .

- Nicolas Nisse :

  CIAC'19: 11th International Conference on Algorithms and Complexity, Roma, Italy, May 27-29th, 2019.

  LAGOS'19: X Latin and American Algorithms, Graphs and Optimization Symposium, Belo Horizonte, Brazil, June 2-7, 2019.

  WG'19: 45th International Workshop on Graph-Theoretic Concepts in Computer Science, Vall de Núria, Catalonia, Spain, June 19-21, 2019.

10.1.1.2. Reviewer

Members of COATI have reviewed numerous manuscripts submitted to national and international conferences, including:

AlgoTel 2019, CoRes 2019, CSR 2019, EvoApplications 2019, IEEE ICC 2019, IPDPS 2019, IEEE Globecom 2019, LAGOS 2019, MFCS 2019, ONDM 2019, OPODIS 2019, IEEE PIMRC 2019, SPAA 2019, WG 2019.

10.1.2. Journal

10.1.2.1. Member of the Editorial Boards

Jean-Claude Bermond :

Computer Science Reviews, Discrete Mathematics, Discrete Applied Mathematics, Journal of Graph Theory, Journal of Interconnection Networks (Advisory Board), Mathématiques et Sciences Humaines, Networks, Parallel Processing Letters, the SIAM book series on Discrete Mathematics, Transactions on Network Optimization and Control, Algorithms and Applications.

Christelle Caillouet :

Guest Editor of the Special Issue "Optimization and Communication in UAV Networks" of MDPI Sensors Journal with Nathalie Mitton.

Alexandre Caminada :

Sensors — Open Access Journal, MDPI editor, Basel.

Soft Computing, Springer.

Journal of Traffic and Transportation Engineering, Elsevier.

Transactions on Mobile Computing, IEEE.

Transactions on Vehicular Technology, IEEE.

David Coudert :

Discrete Applied Mathematics (Elsevier).

Networks (Wiley).

Frédéric Giroire :

Journal of Interconnection Networks (World Scientific).

Frédéric Havet :

Discrete Mathematics and Theoretical Computer Science.

10.1.2.2. Reviewer - Reviewing Activities

Members of COATI have reviewed numerous manuscripts submitted to international journals, including:

IEEE Access, The American Mathematical Monthly, ACM Journal of Experimental Algorithmics (JEA), Elsevier Ad Hoc Networks, Ars Combinatorica, Computer Communications (ComCom) Computer Networks (COMNET), Computers & Operations Research (COR), Discrete Applied Mathematics (DAM), Discrete Mathematics, Discrete Mathematics and Theoretical Computer Science (DMTCS), Discussiones Mathematicae Graph Theory, European Journal of Combinatorics, European Journal of Operational Research (EJOR), Graphs and Combinatorics, Journal of Computer and System Sciences (JCSS), Journal of Combinatorial Theory, Series B (JCTB), IEEE/OSA Journal of Lightwave Technology (JLT), Opuscula Mathematica, SIAM Journal on Discrete Mathematics (SIDMA), IEEE Transactions on Mobile Computing (TOMC), IEEE/ACM Transactions on Networking (ToN), IEEE Transactions on Network and Service Management (TNSM), IEEE Transactions on Parallel and Distributed Systems (TPDS), IEEE Transaction on Services Computing, Theoretical Computer Science (TCS), Theory of Computing Systems (TOCS), Utilitas Mathematica.

10.1.3. Invited Talks

- Julien Bensmail :

  Sequential Metric Dimension (in trees). Meeting of IFCAM project, Indian Statistical Institute, Kolkata, India. February 2019.

  On the "quest" towards a directed variant of the 1-2-3 Conjecture. Seminar of the Department of Applied Mathematics, Northwestern Polytechnical University, Xi'an, China. October 2019.

On the "quest" towards a directed variant of the 1-2-3 Conjecture. Seminar of the School of Mathematics and Statistics, Xidian University, Xi'an, China. September 2019.

On partitioning graphs into connected subgraphs. Seminar of the Department of Applied Mathematics, Northwestern Polytechnical University, Xi'an, China. September 2019.

A Decompositional Approach to the 1-2-3 Conjecture. Seminar of the Departamento de Matemática, Universidade Federal do Ceará, Fortaleza, Brazil. May 2019.

- David Coudert :

  Scientific objectives of ANR project MULTIMOD. Workshop "Complexité et algorithmes" of GDR IM, Roscoff, France, April 3-5, 2019.

  On the Flinders Hamiltonian Cycle Problem Challenge. Keynote speaker at "21ème Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications" (AlgoTel 2019), Saint Laurent de la Cabrerisse, France, June 3-7, 2019.

  On the Flinders Hamiltonian Cycle Problem Challenge. Department of Computer Science & Software Engineering, Concordia University, Québec, Canada, July 25, 2019.

- Frédéric Giroire :

  Placement de services réseaux virtuels dans le cloud et au-delà. Journées Cloud https://www.irit.fr/journeescloud2019/, Toulouse, France. September, 12, 2019.

  Overview of Networking Challenges for the Placement of Cloud Services. Team seminar. Concordia University, Montréal, Canada.

  Sobriété énergétique des réseaux informatiques. Journée Scientifique "Concilier numérique et environnement ?" de l'Académie RISE / EUR DS4H de l'Université Côte d'Azur, France. December 2, 2019.

- Frédéric Havet :

  Unavoidability and universality of digraphs, WG 2019, Vall de Núria, Catalonia, Spain, June 2019.

  On the unavoidability of trees in tournaments, A tribute to Frédéric Maffray, Grenoble, France, September 2-4, 2019.

- Emanuele Natale :

  From Distributed Computing to Natural Algorithms and Beyond, invited talk at the 20th Italian Conference on Theoretical Computer Science (ICTCS'19) as a recipient of the IC-EATCS Young Researcher Award, Como, Italy, September 9-11, 2019.

- Nicolas Nisse :

  Recovery of disrupted airline operations, seminar team ParGO, Univ. federal do Ceara, Fortaleza, Brazil, May 10th, 2019

  Eternal domination in grid-like graphs, seminar of Northwestern Polytechnical University, Xi'an, China, Sept. 9th, 2019

  Localization GameS in graphs, seminar of Xidian University, Xi'an, China, Sept. 5th, 2019

10.1.4. Leadership within the Scientific Community

Alexandre Caminada :

Member of the administrative board of the Sophia Club Entreprise (club of more than 200 Sophia companies).

David Coudert :

Co-chair of *Pôle RESCOM of GDR RSD of CNRS* since 2017 and member of the steering committee since 2005.

Frédéric Giroire :

Member of the steering committee of *GT Energy of the GDR RSD of CNRS*.

Frédéric Havet :

Member of the steering committee of *GT Graphes of the GDR IM of CNRS*.

Nicolas Nisse :

Member of the "bureau" of the GT CoA of the GDR IM.

10.1.5. Scientific Expertise

- Jean-Claude Bermond :

  Expert for DRTT-MESR Crédit impôt recherche (CIR et agréments).
- Alexandre Caminada :

  Expert for HCERES evaluation of UMR5157 SAMOVAR (Services répartis, Architectures, MOdélisation, Validation, Administration des Réseaux), Telecom Sud Paris.

  Expert for CTI of ENSEA, graduate school on economy and statistics, Abidjan, Côte d'Ivoire.
- David Coudert :

  Expert for ANR
- Frédéric Havet :

  Expert for The Fund for Scientific Research - FNRS, Belgium.
- Nicolas Nisse :

  Expert for ESF (European Science Foundation).

  Expert for National Science Centre, OPUS (Poland)

10.1.6. Research Administration

- Jean-Claude Bermond :

  Responsible for the cooperation between Inria and Greece : setting of grants for master 2 students co-financed by Inria Sophia Antipolis Méditerranée and the French Embassy in Greece (in 2019 the grant was given to Foivos Fioravantes who did his internship in Coati) and getting financial support for internships via the Bodossakis Fundation.
- Christelle Caillouet :

  Elected member of CPRH (Comité Permanent de Ressources Humaines) University of Nice Sophia Antipolis;

  Elected member of I3S laboratory committee since December 2016.
- Alexandre Caminada :

  Head of the graduate school of engineering Polytech Nice Sophia which includes the EA7498 lab (Polytech Lab) of the French Ministry for Education, Research and Innovation, in charge of research in civil engineering and smart building at Université Côte d'Azur.

  Member of the executive board of the Sophia Interdisciplinary Institute of Artificial Intelligence started in 2019.

  Manager of the Chinese Scholarship Council PhD program for the Polytech network (70 Phd subjects proposed in 2019 by the 15 graduate schools).

  Member of the selection committee of the tenure professor position nr552 (section 27, machine learning) at Université Côte d'Azur.
- David Coudert :

Nominated member for Inria at the doctoral school STIC, since September 2017;

Head (since December 2019) and member (since 2009) of the “Comité de Suivi Doctoral” of Inria;

Nominated member for Inria at the steering committee of Academy 1 RISE (Networks, Information, Digital Society) of UCA^{JEDI} since February 2018;

Nominated member for Inria at the steering committee of EUR DS4H since February 2018;

Nominated member for Inria at the steering committee of Labec UCN@Sophia since February 2018;

Member of the steering committee of seminar Forum Numerica of Academy 1 RISE of UCA^{JEDI} since 2018;

Member of the “Bureau du comité des équipe-projets” of Inria research center Sophia Antipolis - Méditerranée since 2018.

- Frédéric Giroire :

  In charge of the internships of stream UbiNet of Master 2 IFI, UNS.

- Frédéric Havet :

  Head of COMRED team of I3S laboratory.

- Luc Hogie :

  Member of the CUMI (comité des utilisateurs des moyens informatiques) of Inria Sophia Antipolis Méditerranée;

  Elected member of I3S laboratory committee since December 2016.

- Joanna Moulierac :

  Member of selection committee MCF 775, IUT Arles, 2019.

- Nicolas Nisse :

  Elected member of "Comité de centre", Inria, Sophia Antipolis.

  Member of “Comité Scientifique et Pédagogique” (CSP) EUR DS4H.

- Michel Syska :

  Elected member of CPRH (Comité Permanent de Ressources Humaines) University of Nice Sophia Antipolis.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching Responsibilities

Julien Bensmail :

2019: In charge of the internships of the 1st-year students of Département QLIO of IUT Nice Côte d’Azur.

Since September 2019: Head of the Licence Professionnelle “Managements des Processus Logistiques” (MPL) of Université Nice-Sophia Antipolis.

Christelle Caillouet :

Elected member of Conseil de département IUT Informatique since September 2017.

Alexandre Caminada :

Head of the graduate school of engineering Polytech Nice Sophia (1500 master grade students, 100 faculty members, 50 staffs).

Member of the executive board of the Polytech network, national network of public graduate school of engineering.

Member of the executive board of Université Côte d’Azur.

Joanna Moulierac :

“Directrice d’études” for the 1st-year students of “Département Informatique” of IUT Nice Côte d’Azur (since September 2017).

Head of the “Conseil de Département Informatique” of IUT Nice Côte d’Azur (since September 2017).

10.2.2. Teaching

IUT: Julien Bensmail, *Recherche opérationnelle*, 90h ETD, Level L2, Département QLIO of IUT Nice Côte d’Azur, UNS, France;

IUT: Julien Bensmail, *Systèmes de gestion de bases de données*, 70h ETD, Level L2, Département QLIO of IUT Nice Côte d’Azur, UNS, France;

IUT: Julien Bensmail, *Sécurité des échanges de données inter-entreprises*, 30h ETD, Level LP, LP MPL of IUT Nice Côte d’Azur, UNS, France;

IUT: Christelle Caillouet, *Object Oriented Programming*, 150h ETD, Level L1, IUT Nice Côte d’Azur, UNS, France;

IUT: Christelle Caillouet, *Introduction to Networks*, 21h ETD, Level L1, IUT Nice Côte d’Azur, UNS, France;

IUT: Christelle Caillouet, *Algorithmics*, 21h ETD, Level L2, IUT Nice Côte d’Azur, UNS, France;

IUT: Adrien Gausseran, *Bases de la conception orientée objet*, 64h ETD, Level L1, IUT Nice Côte d’Azur, UNS, France;

IUT: Adrien Gausseran, *Introduction à l’algorithmique et à la programmation*, 6h ETD, Level L1, IUT Nice Côte d’Azur, UNS, France;

IUT: Luc Hogie, *Distributed programming*, 28h ETD, Level L2, IUT Nice Côte d’Azur, UNS, France;

IUT: Hicham Lesfari, *Réseaux d’opérateurs et réseaux d’accès*, 48h ETD, Level L2, IUT Nice Côte d’Azur, UNS, France;

IUT: Joanna Moulierac, *Introduction à l’algorithmique*, 30h ETD, Level L1, IUT Nice Côte d’Azur, UNS, France;

IUT: Joanna Moulierac, *Introduction aux Réseaux*, 36h ETD, Level L1, IUT Nice Côte d’Azur, UNS, France;

IUT: Joanna Moulierac, *Réseaux avancés*, 60h ETD, Level L2, IUT Nice Côte d’Azur, UNS, France;

IUT: Joanna Moulierac, *Compléments d’algorithmique*, 30h ETD, Level L2, IUT Nice Côte d’Azur, UNS, France;

IUT: Thibaud Trolliet, *Database*, 64h ETD, Level L1, IUT Nice Côte d’Azur, UNS, France;

IUT: Michel Syska, *Tutored Project: Introduction*, Level L1, IUT Nice Côte d’Azur, UNS, France;

IUT: Michel Syska, *Operating Systems: Advanced Programming*, 40h ETD, Level L2, IUT Nice Côte d’Azur, UNS, France;

IUT: Michel Syska, *Data Structures and Algorithms*, 44h ETD, Level L2, IUT Nice Côte d’Azur, UNS, France;

IUT: Michel Syska, *Introduction to Artificial Intelligence*, 40h ETD, Level L2, IUT Nice Côte d’Azur, UNS, France;

IUT: Michel Syska, *Algorithmics*, 52h ETD, Level L2, IUT Nice Côte d’Azur, UNS, France;

IUT: Michel Syska, *Web Security*, 13h ETD, Level L3, IUT Nice Côte d’Azur, UNS, France;

MPSI: Nicolas Nisse, *Option informatique, MPSI*, 24h ETD, classe préparatoire MPSI, Lycée International de Valbonne, France;

Licence: Frédéric Giroire, *Probability and statistics*, 50h ETD, 1st year (L3), Engineer School Polytech Nice;

Licence: Thi Viet Ha Nguyen, *TDs Theoretical computer science 2 (Formal langages and automata)*, 22h ETD, L3, Polytech Nice Sophia, France;

Master: Alexandre Caminada, *Radio location systems*, 20h ETD, Master 2 (in english), Polytech Nice Sophia, France

Master: Alexandre Caminada, *Artificial intelligence*, 40h ETD, Master 2 (in english), Polytech Nice Sophia, France

Master: Alexandre Caminada, Master grade student's internship supervision and assesment, 10h ETD, Master 2, Polytech Nice Sophia, France

Master: David Coudert, *Algorithms for Telecoms*, 36h ETD, M2, Université Nice Sophia Antipolis, France;

Master: Frédéric Giroire, *Graph Algorithms*, 15h ETD, Master 2, International Track Ubinet, Université Côte d'Azur, Nice;

Master: Frédéric Giroire, *Machine learning for networks*, 15h ETD, Master 2, International Track Ubinet, Université Côte d'Azur, Nice;

Master: Emanuele Natale, *Natural Distributed Algorithms*, 20h, Laurea Magistrale, University of Rome Tor Vergata, Italy.

Master: Nicolas Nisse, *Graphes*, 36 ETD, M1 Informatique, UNS/UCA, France;

Master: Nicolas Nisse, *Graphes avancés*, 36 ETD, M2 Informatique, UNS/UCA, France;

Master: Nicolas Nisse, *Algorithmes et Optimisation*, 15 ETD, M2 IFI, Parcours Ubinet, UNS/UCA, France;

Master: Nicolas Nisse, *Algorithmique*, 10 ETD, Formation professeurs de lycée, DIU, UCA, France;

Master: Stéphane Pérennes, *Algorithmes et complexité*, 10h ETD, M1 SI4, Polytech Nice Sophia, France

10.2.3. Supervision

10.2.3.1. PhD thesis

PhD: Brieuc Berruet, *Application des techniques de Machine Learning à la géolocalisation "indoor" des objets connectés dans le contexte de la future 5G*, doctorale school SPIM, Université de Belfort Franche Comté, December 17, 2019. Supervisor: Alexandre Caminada and Oumaya Baala (Orange).

PhD: Emilio Cruciani, *Simple Randomized Distributed Algorithms for Graph Clustering*, Gran Sasso Science Institute, December 19, 2018. Co-supervisors: Gianlorenzo D'Angelo (GSSI), Luca Becchetti (Sapienza University of Rome) and Emanuele Natale.

PhD: Mehdi Katranji, *Utilisation des méthodes de Machine Learning pour apprendre les modèles de mobilité humaine selon leurs attibuts socio-démographiques et géographiques*, doctorale school SPIM, Université de Belfort Franche Comté, December 16, 2019. Supervisor: Alexandre Caminada and Fouad Hadjselem (Orange).

PhD: Fionn McInerney, *Domination and Identification Games in Graphs* [14], Université Côte d'Azur, July 8, 2019. Supervisor: Nicolas Nisse.

PhD: Andrea Tomassilli, *Towards Next Generation Networks with SDN and NFV* [15], June 24, 2019. Supervisors: Stéphane Pérennes and Frédéric Giroire.

PhD in progress: Ali Al Zoobi, *Algorithms for shared on demand public transportation system in the city*, since October 2018. Co-supervisors: David Coudert and Nicolas Nisse.

PhD in progress: Francesco D'Amore, *Dynamics for multi-agent system coordination in noisy and stochastic environments*, since October 2019. Co-supervisors: Emanuele Natale and Nicolas Nisse.

PhD in progress: Giuseppe Di Lena, *Resilience of virtualized networks*, since April 2018. Co-supervisors: Thierry Turletti (DIANA), Chidung Lac (Orange Labs Lannion) and Frédéric Giroire. CIFRE grant with Orange.

PhD in progress: Foivos Fioravantes, *Distinguishing labellings of graphs*, since October 2019. Co-supervisors: Julien Bensmail and Nicolas Nisse.

PhD in progress: Adrien Gausseran, *Optimization Algorithms for Network Slicing for 5G*, since October 2018. Supervisors: Joanna Moulierac and Nicolas Nisse.

PhD in progress: Hicham Lesfari, *Machine learning for dynamic network resource allocation*, since October 2019. Supervisor: Frédéric Giroire.

PhD in progress: Zhejiayu Ma, *Learning problem for the diffusion of multimedia contents*, since October 2018. Co-Supervisors: Guillaume Urvoy-Keller, Frédéric Giroire, Soufiane Rouiba (Easy-broadcast, Nantes). CIFRE grant with Easybroadcast.

PhD in Progress: Thi-Viet-Ha Nguyen, *Graph Algorithms techniques for (low and high) resolution model of large protein assemblies.*, since October 2018. Co-supervisors: Frédéric Havet and Dorian Mazauric (ABS).

PhD in progress: Thibaud Trolliet, *Exploring Trust on Twitter*, since October 2017. Co-supervisors: Arnaud Legout (DIANA) and Frédéric Giroire.

10.2.3.2. Internships

Licence: Paul Bastide, *Density Estimation via Random Walks with Limited Communication*, ENS Rennes, France, from 20 May 2019 until 12 July 2019. Supervisor: Emanuele Natale.

Licence: Gabriel Djebbar, *Collapse and graphs problems*, SI3, Polytech Nice Sophia, France, from July 2018 until August 2018. Co-supervisors: Frédéric Havet and Dorian Mazauric (ABS).

Licence: Solal Gaudin, *Compromis temps-espace dans l'énumération des paires éloignés par distances décroissantes*, L3 ENS Cachan, France, from June 2019 until July 2019. Supervisor: David Coudert.

Licence: Emile Sorci, *Oblivious metric dimension*, L3, ENS Lyon, France, from June 2019 until July 2019. Co-supervisors: Julien Bensmail and Nicolas Nisse.

Licence: Zoé Varin, *Constrained matchings*, L3, ENS Lyon, France, from June 2019 until July 2019. Co-supervisors: Julien Bensmail and Nicolas Nisse.

Master 1 (tutorship): Nitha Sagar Jayanna, *Shortest Path in Multimodal Public Transportation Networks*, M1 Computer Science, Digital Systems for Humans (DS4H) Graduate school - Université Côte d'Azur, France, from October 2018 until June 2019. Supervisor: Michel Syska

Master 1 (tutorship): Shamprikta Mehreen, *Multi Objective Shortest Path Problem*, M1 Computer Science, Digital Systems for Humans (DS4H) Graduate school - Université Côte d'Azur, France, from October 2018 until June 2019. Supervisor: Michel Syska

Master 2 (TER): Haoran Ding, *Machine learning for dynamic network resource allocation*, Master 2 IFI, international track Ubinet, Université Côte d'Azur, France, from October 2019 until December 2019. Co-supervisors: Frédéric Giroire and Hicham Lesfari.

Master 2 (TER): Thomas Dissaux, *Computing treelength*, M2 IFI, Université Côte d'Azur, France, from October 2019 until December 2019. Supervisor: Nicolas Nisse

Master 2 (TER): Igor Dias Da Silva, *Computation and analysis of drone trajectories for effective surveillance and data collection*, Master IFI, Université Côte d'Azur, France, from November 2019 until December 2019. Supervisor: Christelle Caillouet.

Master 2 (TER): Arno Gobbin, *Computational Complexity of Puzzles and Games*, SI5 Polytech Nice Sophia, Université Côte d'Azur, France, from November 2019 until December 2019. Supervisor: Emanuele Natale

Master 2 (TER): Siwar Helaoui, *Distributed simulation of algorithms for the deployment of self-organized UAVs*, SI5 Polytech Nice Sophia, Université Côte d'Azur, France, from November 2019 until March 2020. Supervisor: Christelle Caillouet and David Coudert.

Master 2 (TER): Noueman Khalikine, *Algorithms for studying the evolution over time of the structure of social graphs*, stream Ubinet of M2 IFI, Université Côte d'Azur, France, from November 2019 until December 2019. Supervisor: David Coudert and Frédéric Giroire.

Master 2 (TER): Abdelkrim El Merss, *Algorithms for studying the evolution over time of the structure of social graphs*, stream Ubinet of M2 IFI, Université Côte d'Azur, France, from November 2019 until December 2019. Supervisor: David Coudert and Frédéric Giroire.

Master 2 (TER): Victor Tapissier, *Evolution over time of the structure of social graphs*, SI5 Polytech Nice Sophia, Université Côte d'Azur, France, from November 2019 until December 2019. Supervisor: David Coudert and Frédéric Giroire.

Master 2 (TER): Bruno Tarbes, *Evolution over time of the structure of social graphs*, SI5 Polytech Nice Sophia, Université Côte d'Azur, France, from November 2019 until December 2019. Supervisor: David Coudert and Frédéric Giroire.

Master 2 (apprentissage): Théo Qui, *Implementation and study of Graphs' decompositions*, M2 IFI, Université Côte d'Azur, France, from September 2019 until August 2020. Supervisor: Nicolas Nisse.

Master 2: Athanasia Farmaki, *Implementaiton of algorithms for the dial-a-ride problem with time windows*, in the context of ANR MULTIMOD, Master 2, National Technical University of Athens, Greece, from January 2019 until June 2019. Co-supervisors: David Coudert and Nicolas Nisse.

Master 2: Foivos Fioravantes, *BMRN*-colouring of planar digraphs*, Master 2 IFI, international track Ubinet, Université Côte d'Azur, France, from March 2019 until August 2019. Supervisor: Julien Bensmail.

Master 2: Hicham Lesfari, *Network Anomaly Detection Using Graph Kernels*, Master 2 IFI, international track Ubinet, Université Côte d'Azur, France, from March 2019 until August 2019. Supervisor: Frédéric Giroire.

Master 2: Bai Xin, *Optimization of Drones Trajectory for Optimal Sensor Coverage and Data Collection*, M2 Ubinet, Université Côte d'Azur, France, from March 2019 until August 2019. Supervisor: Christelle Caillouet.

Google Summer of Code: Ritesh K, *Improvement of methods for computing distances in the graph module of Sagemath*, Bachelor of Technology at the Department of Computer Science and Engineering of National Institute of Technology Karnataka, India. from May 2019 until August 2019. Mentor: David Coudert.

Google Summer of Code: Rajat Mittal, *Implementation of algorithms for enumeration of k-shortests simple paths and contribution to the improvement of graph module of Sagemath*, Master at Indian Institute of Technology (BHU) Varanasi, India. from May 2019 until August 2019. Mentor: David Coudert.

Google Summer of Code: Georgios Giapitzakis Tzintanos, *Implementation of new graph traversals (LexBFS, LexDFS, etc.) and contribution to the improvement of graph module of Sagemath*, Bachelor of Science at the National and Kapodistrian University of Athens, Greece. from May 2019 until August 2019. Mentor: David Coudert.

10.2.4. Juries

Jean-Claude Bermond :

President of the PhD prize committee *prix de thèse Graphes "Charles Delorme"*http://gtgraphes.labri.fr/pmwiki/pmwiki.php/PrixTheseDelorme/PrixTheseDelorme;

Christelle Caillouet :

Member of PhD committee of Dorin Rautu, Université de Toulouse, October 1, 2019;

Alexandre Caminada :

Referee for the PhD thesis of Shen Peng, Paris-Sud university, June 17, 2019, Chance Constrained Problem and Its Applications;

Referee for the Pierre Lafitte Price, supported by the Doctoral Schools SFA (Basic and Applied Sciences) and STIC (Sciences and Technologies of Information and Communication) of Université Côte d'Azur and Mines Paris, to enhance the quality of the research work of 2nd year PhD students;

David Coudert :

Referee and member of PhD committee of Valentin Pollet, Université de Montpellier, October 3, 2019;

Referee and member of PhD committee of Francesca Fossati, Sorbonne Université, November 29, 2019;

President of PhD committee of Paul Beaujean, Université Paris Dauphine, December 16, 2019;

Frédéric Havet :

Member of PhD committee Jocelyn Thiébaut, Université de Montpellier, November 19, 2019;

Joanna Moulierac :

Member of PhD committee of Chaopeng Guo, Université de Toulouse, June 14, 2019;

Nicolas Nisse :

Referee and member of PhD committee Valentin Gledel, Université de Lyon (LIRIS), September 24th, 2019;

Referee and member of PhD committee Sébastien Ratel, Université Aix-Marseille (LIS), November 8th, 2019.

10.3. Popularization

10.3.1. Internal or external Inria responsibilities

- Jean-Claude Bermond, Frédéric Havet, Joanna Moulierac, and Nicolas Nisse are involved in Terra Numerica which brings together several popularization groups in order to create a museum of digital sciences.
- Frédéric Havet: Vice-president and member of the scientific committee of the association Institut Esope 21 (https://lewebpedagogique.com/institutesope21/).

10.3.2. Education

- Frédéric Havet, Joanna Moulierac and Nicolas Nisse (responsable) : Participation to Galejade project "Graphes et ALgorithmes : Ensemble de Jeux À Destination des Ecoliers... (mais pas que)" https://galejade.inria.fr/.

  Design of pedagogical resources introducing graphs and algorithms to primary school students.

  Training of primary school teachers, ESPE, Nice (March 22, 2019), Lyon (April 10th, 2019).

Intervention Lycée Carnot (Cannes, March 14, 2019), Lycée Sydney Bechet (Antibes, March 13, 2019), Lycée au Cannet (April 5, 2019)

- Frédéric Havet :
  Training of secondary school teachers on graphs and algorithms. April 23, 2019.

10.3.3. Interventions

- Fête de la Science (Frédéric Havet, Nicolas Nisse, Ali Al Zoobi) :
  Villeneuve-Loubet, October 5, 2019;
  Colline du Château de Nice (stands Inria and I3S laboratory), October 4-6, 2019;
  Collège Lycée Vinon-sur-Verdon, October 8-11, 2019;
  Palais des Congrès de Juan-Les-Pins, October 19-20, 2019.
- Ali Al Zoobi :
  Presentation of posters and combinatorial games during the "Fête des Sciences", Collège Emile Roux, June 5, 2019.
- David Coudert :
  Presentation of the *Flinders Hamiltonian Cycle Problem Challenge* to a group of students from classe préparatoire MPSI, Lycée International de Valbonne, June 24, 2019.
- Frédéric Giroire :
  Accueil de la mission locale de Grasse pour une session de médiation scientifique, 26 avril 2019.
- Frédéric Havet :
  Animation of the exhibition “Animals of the Mediterranean sea” 6 classes, Ecole la Tauriac, Toulon, January 24, 2019.
  Conferences “Birds of Var”, 6 classes, Ecole élémentaire de Rians, February 1, 2019.
  Conference “Be a mathemagician”, Ecole des Pallières, February 2, 2019.
  Animation “Birds of Var”, 6 classes Ecole de la Tauriac and 2 classes Ecole de la Beaucaire, Toulon, Mars 07 2019.
  3 conferences “Les pavages”, “La science du ballon de football”, “Mathémagie” for 10 classes in total. Collège Daudet Nice, April 15, 2019.
  “La magie du binaire”. Conference for six classes in Manosque for the “Jeux fabriqués” day organised by DANE 04. April 2, 2019.
  Training of primary school teachers.
- Frédéric Havet, Joanna Moulierac, and Nicolas Nisse participated to the supervision of twelve schoolchildren (3ème) in internship.
- Nicolas Nisse :
  MathC2+, Sophia Antipolis, June 14, 2019
- Michel Syska :
  Member of the organization of the code competition "*Retro Gaming pico-8*" (55 teams of 3 students), April, 2019.
  Organization and supervision of the local site IUT for the national code competition "*La nuit de l'info*" (156 students = 3.7% of participants), December 5-6, 2019.

10.3.4. Internal action

- Frédéric Havet and Nicolas Nisse participated to the Cafe'In presenting Galejade. April 29, 2019.

11. Bibliography

Major publications by the team in recent years

[1] D. AGARWAL, C. CAILLOUET, D. COUDERT, F. CAZALS. *Unveiling Contacts within Macro-molecular assemblies by solving Minimum Weight Connectivity Inference Problems*, in "Molecular and Cellular Proteomics", April 2015, vol. 14, p. 2274-2284 [*DOI :* 10.1074/MCP.M114.047779], https://hal.inria.fr/hal-01245401

[2] J. BENSMAIL, A. HARUTYUNYAN, T.-N. LE, S. THOMASSÉ.*Edge-partitioning a graph into paths: beyond the Barát-Thomassen conjecture*, in "Combinatorica", April 2019, vol. 39, n^o^ 2, p. 239-263 [*DOI :* 10.1007/S00493-017-3661-5], https://hal.archives-ouvertes.fr/hal-01744515

[3] C. CAILLOUET, F. GIROIRE, T. RAZAFINDRALAMBO.*Efficient Data Collection and Tracking with Flying Drones*, in "Ad Hoc Networks", 2019, vol. 89, n^o^ C, p. 35-46 [*DOI :* 10.1016/J.ADHOC.2019.01.011], https://hal.inria.fr/hal-02043136

[4] N. COHEN, F. HAVET, W. LOCHET, N. NISSE.*Subdivisions of oriented cycles in digraphs with large chromatic number*, in "Journal of Graph Theory", April 2018, vol. 89, n^o^ 4, p. 439-456 [*DOI :* 10.1002/JGT.22360], https://hal.archives-ouvertes.fr/hal-01834779

[5] D. COUDERT, G. DUCOFFE.*Revisiting Decomposition by Clique Separators*, in "SIAM Journal on Discrete Mathematics", January 2018, vol. 32, n^o^ 1, p. 682-694 [*DOI :* 10.1137/16M1059837], https://hal.inria.fr/hal-01753324

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[7] E. CRUCIANI, E. NATALE, G. SCORNAVACCA.*Distributed Community Detection via Metastability of the 2-Choices Dynamics*, in "AAAI 2019 - 33th AAAI Conference Association for the Advancement of Artificial Intelligence", Honolulu, United States, January 2019, https://hal.archives-ouvertes.fr/hal-02002462

[8] F. DROSS, F. HAVET.*On the Unavoidability of Oriented Trees*, in "Electronic Notes in Theoretical Computer Science", August 2019, vol. 346, p. 425-436 [*DOI :* 10.1016/J.ENTCS.2019.08.038], https://hal.inria.fr/hal-02350215

[9] F. GIROIRE, F. HAVET, J. MOULIERAC.*On the Complexity of Compressing Two Dimensional Routing Tables with Order*, in "Algorithmica", January 2018, vol. 80, n^o^ 1, p. 209-233 [*DOI :* 10.1007/S00453-016-0243-7], https://hal.inria.fr/hal-01686641

[10] L. HOGIE, M. SYSKA, N. CHLEQ.*BigGraphs: distributed graph computing*, September 2016, n^o^ IDDN.FR.001.410005.000.S.P.2015.000.31235, https://hal.archives-ouvertes.fr/hal-01360649

[11] W. LOCHET.*Immersion of transitive tournaments in digraphs with large minimum outdegree*, in "Journal of Combinatorial Theory, Series B", May 2018, 4 [*DOI :* 10.1016/J.JCTB.2018.05.004], https://hal.archives-ouvertes.fr/hal-01835124

[12] M. RIFAI, N. HUIN, C. CAILLOUET, F. GIROIRE, J. MOULIERAC, D. LOPEZ PACHECO, G. URVOY-KELLER.*Minnie : An SDN world with few compressed forwarding rules*, in "Computer Networks", July 2017, vol. 121, p. 185-207 [*DOI :* 10.1016/J.COMNET.2017.04.026], https://hal.inria.fr/hal-01576133

[13] A. TOMASSILLI, F. GIROIRE, N. HUIN, S. PÉRENNES.*Provably Efficient Algorithms for Placement of Service Function Chains with Ordering Constraints*, in "IEEE INFOCOM 2018 - IEEE Conference on Computer Communications", Honolulu, United States, IEEE, April 2018 [*DOI :* 10.1109/INFOCOM.2018.8486275], https://hal.inria.fr/hal-01921112

Publications of the year

Doctoral Dissertations and Habilitation Theses

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[15] A. TOMASSILLI.*Towards Next Generation Networks with SDN and NFV*, Université Côte d'Azur, June 2019, https://hal.inria.fr/tel-02373758

Articles in International Peer-Reviewed Journal

[16] P. ABOULKER, N. COHEN, F. HAVET, W. LOCHET, P. F. S. MOURA, S. THOMASSÉ.*Subdivisions in Digraphs of Large Out-Degree or Large Dichromatic Number*, in "The Electronic Journal of Combinatorics", July 2019, vol. 26, P3.19, https://hal.archives-ouvertes.fr/hal-02275082

[17] D. AGUIRRE-GUERRERO, G. DUCOFFE, L. FABREGA, P. VILA, D. COUDERT.*Low Time Complexity Algorithms for Path Computation in Cayley Graphs*, in "Discrete Applied Mathematics", April 2019, vol. 259, p. 218-225 [*DOI :* 10.1016/J.DAM.2018.12.005], https://hal.inria.fr/hal-01973608

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Project-Team COFFEE

COmplex Flows For Energy and Environment

IN COLLABORATION WITH: Laboratoire Jean-Alexandre Dieudonné (JAD)

IN PARTNERSHIP WITH:
CNRS

Université Nice - Sophia Antipolis

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Earth, Environmental and Energy Sciences

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Project-Team COFFEE

Creation of the Team: 2011 July 01, updated into Project-Team: 2013 January 01

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A6.1.4. - Multiscale modeling
A6.1.5. - Multiphysics modeling
A6.2.1. - Numerical analysis of PDE and ODE
A6.2.7. - High performance computing
A6.5. - Mathematical modeling for physical sciences
A6.5.2. - Fluid mechanics
A6.5.3. - Transport

Other Research Topics and Application Domains:

B1.1.8. - Mathematical biology
B3.3.1. - Earth and subsoil
B4.1. - Fossile energy production (oil, gas)
B4.2. - Nuclear Energy Production
B7.1. - Traffic management

1. Team, Visitors, External Collaborators

Research Scientists

Thierry Goudon [Team leader, Inria, Senior Researcher, HDR]
Laurent Monasse [Inria, Researcher]

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Konstantin Brenner [Univ. Côte d'Azur, Associate Professor]
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Post-Doctoral Fellows

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Laurence Beaude [Univ. Côte d'Azur, Post-Doctoral Fellow, until Dec. 2019]
Francesco Bonaldi [Inria, Post-Doctoral Fellow, from Sep 2019]
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El Houssaine Quenjel [Univ Côte d'Azur, Post-Doctoral Fellow, from Feb 2019]
Sean Mcgovern [Inria, Post-Doctoral Fellow, from Dec 2019]

Administrative Assistant

Marie-Cécile Lafont [Inria, Administrative Assistant]

2. Overall Objectives

2.1. Overall Objectives

The project aims at studying mathematical models issued from environmental and energy management questions. We consider systems of PDEs of hydrodynamic type or hybrid fluid/kinetic systems. The problems we have in mind involve unusual coupling, which in turn leads to challenging difficulties for mathematical analysis and the need of original numerical solutions. By nature many different scales arise in the problems, which allows to seek hierarchies of reduced models based on asymptotic arguments. The topics require a deep understanding of the modeling issues and, as far as possible boosted by the mathematical analysis of the equations and the identification of key structure properties, we wish to propose innovative and performing numerical schemes. To this end, the development of innovative Finite Volumes schemes with unstructured meshes on complex geometries will be a leading topic of the team activity.

3. Research Program

3.1. Research Program

Mathematical modeling and computer simulation are among the main research tools for environmental management, risks evaluation and sustainable development policy. Many aspects of the computer codes as well as the PDEs systems on which these codes are based can be considered as questionable regarding the established standards of applied mathematical modeling and numerical analysis. This is due to the intricate multiscale nature and tremendous complexity of those phenomena that require to set up new and appropriate tools. Our research group aims to contribute to bridging the gap by developing advanced abstract mathematical models as well as related computational techniques.

The scientific basis of the proposal is two–fold. On the one hand, the project is "technically–driven": it has a strong content of mathematical analysis and design of general methodology tools. On the other hand, the project is also "application–driven": we have identified a set of relevant problems motivated by environmental issues, which share, sometimes in a unexpected fashion, many common features. The proposal is precisely based on the conviction that these subjects can mutually cross-fertilize and that they will both be a source of general technical developments, and a relevant way to demonstrate the skills of the methods we wish to design.

To be more specific:

- We consider evolution problems describing highly heterogeneous flows (with different phases or with high density ratio). In turn, we are led to deal with non linear systems of PDEs of convection and/or convection–diffusion type.
- The nature of the coupling between the equations can be two–fold, which leads to different difficulties, both in terms of analysis and conception of numerical methods. For instance, the system can couple several equations of different types (elliptic/parabolic, parabolic/hyperbolic, parabolic or elliptic with algebraic constraints, parabolic with degenerate coefficients....). Furthermore, the unknowns can depend on different sets of variables, a typical example being the fluid/kinetic models for particulate flows. In turn, the simulation cannot use a single numerical approach to treat all the equations. Instead, hybrid methods have to be designed which raise the question of fitting them in an appropriate way, both in terms of consistency of the discretization and in terms of stability of the whole computation. For the problems under consideration, the coupling can also arises through interface conditions. It naturally occurs when the physical conditions are highly different in subdomains of the physical domain in which the flows takes place. Hence interface conditions

are intended to describe the exchange (of mass, energy...) between the domains. Again it gives rise to rather unexplored mathematical questions, and for numerics it yields the question of defining a suitable matching at the discrete level, that is requested to preserve the properties of the continuous model.

- By nature the problems we wish to consider involve many different scales (of time or length basically). It raises two families of mathematical questions. In terms of numerical schemes, the multiscale feature induces the presence of stiff terms within the equations, which naturally leads to stability issues. A clear understanding of scale separation helps in designing efficient methods, based on suitable splitting techniques for instance. On the other hand asymptotic arguments can be used to derive hierarchy of models and to identify physical regimes in which a reduced set of equations can be used.

We can distinguish the following fields of expertise

- Numerical Analysis: Finite Volume Schemes, Well-Balanced and Asymptotic-Preserving Methods
  - Finite Volume Schemes for Diffusion Equations and Viscous Flows
  - Finite Volume Schemes for Conservation Laws
  - Well-Balanced and Asymptotic-Preserving Methods
  - Domain Decomposition Methods
- Modeling and Analysis of PDEs
  - Kinetic equations and hyperbolic systems
  - PDEs in random media
  - Interface problems

4. Application Domains

4.1. Multiphase porous media flows and multi-physics coupling

Our research focuses on the numerical modeling of multiphase porous media flows accounting for complex geology and for nonlinear and multi-physics couplings. It is applied to various problems in the field of energy such as the simulation of geothermal systems in collaboration with BRGM, of nuclear waste repositories in collaboration with Andra, and of oil and gas recovery in collaboration with Total. Our research directions include the development of advanced numerical schemes adapted to polyhedral meshes and highly heterogeneous media in order to represent more accurately complex geologies. A special focus is made on the modeling of multiphase flows in network of faults or fractures represented as interfaces of co-dimension one coupled to the surrounding matrix. We also investigate nonlinear solvers adapted to the nonlinear couplings between gravity, capillary and viscous forces in highly heterogeneous porous media. In the same line, we study new domain decomposition algorithms to couple non-isothermal compositional liquid gas flows in a porous medium with free gas flows occurring at the interface between the ventilation gallery and the nuclear waste repository or between a geothermal reservoir and the atmosphere. We have begun exploring the coupling between the multiphase flow in the porous matrix and the solid mechanics involved in opening fractures.

4.2. Particulate and mixture flows

We investigate fluid mechanics models referred to as "multi–fluids" flows. A large part of our activity is more specifically concerned with the case where a disperse phase interacts with a dense phase. Such flows arise in numerous applications, like for pollutant transport and dispersion, the combustion of fuel particles in air, the modelling of fluidized beds, the dynamic of sprays and in particular biosprays with medical applications, engine fine particles emission... There are many possible modelings of such flows: microscopic models where the two phases occupy distinct domains and where the coupling arises through intricate interface conditions; macroscopic models which are of hydrodynamic (multiphase) type, involving non standard state laws, possibly with non conservative terms, and the so–called mesoscopic models. The latter are based on Eulerian–Lagrangian description where the disperse phase is described by a particle distribution function in phase space. Following this path we are led to a Vlasov-like equation coupled to a system describing the evolution of the dense phase that is either the Euler or the Navier-Stokes equations. It turns out that the leading effect in such models is the drag force. However, the role of other terms, of more or less phenomenological nature, deserves to be discussed (close packing terms, lift term, Basset force...). Of course the fluid/kinetic model is interesting in itself and needs further analysis and dedicated numerical schemes. In particular, in collaboration with the Atomic Energy Commission (CEA), we have proposed a semi-Lagrangian scheme for the simulation of particulate flows, extending the framework established in plasma physics to such flows.

We also think it is worthwhile to identify hydrodynamic regimes: it leads to discuss hierarchies of coupled hydrodynamic systems, the nature of which could be quite intriguing and original, while they share some common features of the porous media problems. We are particularly interested in revisiting the modeling of mixture flows through the viewpoint of kinetic models and hydrodynamic regimes. We propose to revisit the derivation of new mixture models, generalizing Kazhikov-Smagulov equations, through hydrodynamic asymptotics. The model is of “hybrid” type in the sense that the constraint reduces to the standard incompressibility condition when the disperse phase is absent, while it involves derivatives of the particle volume fraction when the disperse phase is present.

4.3. Fungal network growth

Members of the team have started an original research program devoted to fungal network growth. We started working on this subject through a collaboration with biologists and physicists at LIED (Université Paris Diderot) and probabilists in CMAP (Ecole Polytechnique) and Université Paris Sud, involving Rémi Catellier and Yves D’Angelo in LJAD in Nice. The motivation is to understand branching networks as an efficient space exploration strategy, with fungus *Podospora Anserina* being the biological model considered. This research is submitted as an ANR-project and has been supported by various local fundings.

5. New Software and Platforms

5.1. AP_PartFlow

FUNCTIONAL DESCRIPTION: We are developing experimental codes, mainly based on Finite Differences, for the simulation of particulate flows. A particular attention is paid to guaranty the asymptotic properties of the scheme, with respect to relaxation parameters.

- Contact: Thierry Goudon

5.2. Mka3d

KEYWORDS: Scientific computing - Elasticity - Elastodynamic equations

FUNCTIONAL DESCRIPTION: The Mka3d method simulates an elastic solid by discretizing the solid into rigid particles. An adequate choice of forces and torques between particles allows to recover the equations of elastodynamics.

- Partners: Ecole des Ponts ParisTech - CEA
- Contact: Laurent Monasse
- URL: http://cermics.enpc.fr/~monassel/Mka3D/

5.3. Compass

Computing Architecture to Speed up Simulation

KEYWORDS: Finite volume methods - Porous media - High performance computing

FUNCTIONAL DESCRIPTION: Compass is a parallel code initiated in 2012 and co-developed by LJAD-Inria Coffee and BRGM since 2015. It is devoted to the simulation of multiphase flows in porous media, it accounts for non isothermal and compositional flows and includes complex network of fractures or faults represented as interfaces of co-dimension one coupled to the surrounding matrix. The discretization is based on vertex and cell unknowns and is adapted to polyhedral meshes and heterogeneous media. The ComPASS code is co-developed since december 2016 by the partners of the ANR CHARMS project including BGRM, LJAD-Inria Coffee, Storengy, MdS and LJLL with the objective to develop a new generation simulator for geothermal systems focusing on fluids and accounting for complex fault networks and wells.

- Participants: Simon Lopez, Farid Smai, Michel Kern, Yacine Ould Rouis, Nabil Birgle, Laurence Beaude, Konstantin Brenner and Roland Masson
- Partners: Université de Nice Sophia Antipolis (UNS) - BRGM
- Contact: Roland Masson
- URL: http://www.anr-charms.org/page/compass-code

5.4. NS2DDV-M

2D Navier-Stokes equations with variable density

KEYWORDS: Partial differential equation - Finite volume methods - Finite element modelling

FUNCTIONAL DESCRIPTION: The NS2DDV Matlab toolbox is an open-source program written in Matlab for simulating 2D viscous, incompressible and inhomogeneous flows. The computation kernel of the code is based on Finite Elements - Finite Volumes hybrid methods applied on the 2D Navier-Stokes equations. It works on unstructured meshes and can include mesh refinements strategies. We develop and freely distribute a new version of the Matlab code NS2DDV-M (equipped with a graphic interface and an accurate documentation) to promote new collaborations in the domain, allow some easy comparisons with concurrent codes on the same benchmark cases, and compare alternative numerical solution methods.

- Partner: Laboratoire Paul Painlevé
- Contact: Caterina Calgaro
- URL: https://wikis.univ-lille1.fr/painleve/ns2ddv

5.5. SimBiof

KEYWORDS: Bioinformatics - Chemistry

FUNCTIONAL DESCRIPTION: We are developing numerical methods, currently by using Finite Differences approaches, for the simulation of biofilms growth. The underlying system of PDEs takes the form of multiphase flows equations with conservation constraints and vanishing phases. The numerical experiments have permitted to bring out the influence of physical parameters on the multidimensional growth dynamics.

- Contact: Thierry Goudon

5.6. CELIA3D

KEYWORDS: Fluid mechanics - Multi-physics simulation

FUNCTIONAL DESCRIPTION: The CELIA3D code simulates the coupling between a compressible fluid flow and a deformable structure. The fluid is handled by a Finite Volume method on a structured Cartesian grid. The solid is handled by a Discrete Element method (Mka3d scheme). The solid overlaps the fluid grid and the coupling is carried out with immersed boundaries (cut cells) in a conservative way.

- Partners: Ecole des Ponts ParisTech - CEA
- Contact: Laurent Monasse
- URL: http://cermics.enpc.fr/~monassel/CELIA3D/

6. Bilateral Contracts and Grants with Industry

6.1. Bilateral Contracts with Industry

- Contract with Andra financing the two year postdoctoral position of Joubine Aghili (october 2017 - september 2019) and dealing with the simulation of compositional liquid gas Darcy flows in highly heterogeneous porous medium with network of fractures using Discrete Fracture Matrix models (DFM). It is applied to the simulation of the desaturation of the nuclear waste storage in the neighbourhood of the galleries. Supervision Roland Masson and Konstantin Brenner from LJAD-Inria, Jean-Raynald de Dreuzy from Geosciences Rennes and Laurent Trenty from Andra.
- The team has also on-going collaboration with Storengy (post-doc of Daniel Constantin-Quiroz).

7. Partnerships and Cooperations

7.1. Regional Initiatives

The team is involved in the IDEX project UCA-JEDI.

7.2. National Initiatives

7.2.1. ANR

- ANR CHARMS (Quantitative Reservoir Models for Complex Hydrothermal Systems), Roland Masson and Konstantin Brenner: december 2016 - december 2020, partners BRGM (leader), LJAD-Inria, Storengy, MdS, LJLL.
- ANR JCJC PRECIS (Effect of a shock wave on a structure with contact using mesh refinement and parallelism), Laurent Monasse: april 2018 - april 2021, partners Inria (leader), Ecole des Ponts, CEA, Université Paris-Est.

7.2.2. National and European networks

- GdR MANU.

  The research group MANU has activities centered around scientific computing, design of new numerical schemes and mathematical modelling (upscaling, homogenization, sensitivity studies, inverse problems,...). Its goal is to coordinate research in this area, as well as to promote the emergence of focused groups around specific projects
- S. Junca is involved in GdR 3437 DYNOLIN “Dynamique non linéaire” and GdR MecaWave.
- LJAD-Inria and BRGM are the French partners of the Norvergian, German French project InSPiRE "International Open Source Simulation Software Partnership in Research and Education” which has just been accepted by the Research Council of Norway with the code ComPASS as one of the softwares of this project together with Dune, Dumux and OPM.

7.3. International Initiatives

7.3.1. Inria Associate Teams Not Involved in an Inria International Labs

7.3.1.1. HDTHM

Title: Mathematical and numerical methods for thermo-hydro-mechanical models in porous media with discontinuities

International Partner (Institution - Laboratory - Researcher):

Monash University (Australia) - School of Mathematics - Jérome Droniou

Start year: 2019

See also: https://math.unice.fr/~massonr/HDTHM/HDTHM.html

The objective of this project is to extend a recent successful joint work between the two project leaders into a tight collaboration between the Monash and the Coffee teams involving several permanent members and students. The present project focuses on challenging directions of research related to the numerical simulation of thermo-hydro-mechanical models in fractured porous media that take advantage of the complementarity of both teams' expertise as well as of the recent arrival of Laurent Monasse in the Coffee team. It is an opportunity to extend our collaborations with the Coffee team industrial partners in geosciences as well as to submit in common a research project to the Australian Research Council toward the end of the project.

7.3.2. Inria International Partners

The team has many interactions abroad: UFRJ, Ut Austin, India, Geneva, ICL,...

7.3.3. Participation in Other International Programs

Coffee is member of the Interdisciplinary Union of Porous Media Research at the University of Stuttgart (NUPUS).

Principal areas of research cooperation to be pursued under this program include free flow and porous medla flow interaction, fracture and fluid flow interactlon, fluid-solid phase change interaction, and simulation methods and tools.

7.4. International Research Visitors

7.4.1. Visits of International Scientists

The team has welcomed Paulo Amorim, from UFRJ, for research on the modeling of self-organization in f population dynamics, Corrado Mascia, from La Sapienza, on the analysis of hyperbolic systems and Martin Gander, from Univ. Geneva, for research on domain decomposition methods.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Journal

8.1.1.1. Member of the Editorial Boards

Thierry Goudon is Co-Ed. in Chief SMAI J. Comput. Math.

8.1.1.2. Reviewer - Reviewing Activities

The team members serve regularly as reviewers for journals in applied mathematics, scientific computing, numerical analysis, mathematical analysis.

8.1.2. Scientific Expertise

T. Goudon has been chair of the international panel of experts for the evaluation of all the Research Units of Mathematics in Portugal, nominated by the **Fundação para a Ciência e a Tecnologia**. Not only the panel had to write an assessment (see https://www.fct.pt/apoios/unidades/avaliacoes/2017/docs/Mathematics.pdf) on the scientific production and activities of the research units, but it was also in charge of the attribution of the funding, PhD and postdoc fellowships, for a total amount of 5.5 MEUR (see https://www.fct.pt/apoios/unidades/avaliacoes/2017/docs/Mathematics_table.pdf).

T. Goudon is Scientific Officer at the Ministry of Research.

T. Goudon is member of the scientific boards of CIRM and FSMP.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Florent Berthelin, Master2 Mathématiques fondamentales, Université Côte d'Azur, 120h.

Florent Berthelin, Chair of the Master 2 Mathématiques fondamentales, Université Côte d'Azur.

Florent Berthelin, Analysis, L2, Université Nice Sophia Antipolis, 72h.

Laurent Monasse, Numerical analysis, L3, Université Nice Sophia Antipolis, 40h.

Thierry Goudon is President of the national competition to hire teachers (agregation de mathematiques).

8.2.2. Supervision

- PhD: Giulia Lissonni, DDFV methods and domain decomposition: applications in fluid mechanics, 04 October 2019, Stella Krell and Thierry Goudon.
- PhD in progress: Kevin Atsou, Mathematical modeling of tumor growth, analysis and simulation, 01 October 2017, Thierry Goudon
- PhD in progress: Billel Guelmame, Conservation laws in mechanics, 01 October 2017, Stéphane Junca
- PhD in progress: Leo Vivion, Dynamical model of a Lorentz gas: kinetic approach, analysis and asymptotic issues, 01 September 2017, Thierry Goudon
- PhD in progress: Frédéric Marazzato, Modeling of fracture and fragmentation using a Discrete Element method, 01 October 2016, Alexandre Ern, Karam Sab and Laurent Monasse.
- PhD in progress: Nadine Dirani, Effect of a shock wave on a structure with contact, 01 November 2018, Thierry Goudon and Laurent Monasse.

8.2.3. Juries

T. Goudon has been reviewer for the PhD theses:

- Z. Karaki, Équations cinétiques avec champ magnétique", Nantes, Dec. 2019.
- M. Mezache, "Processus oscillatoires lors de l'agrégation et la fragmentation des fibres amyloïdes", Sorbonne Univ., Dec. 2019.

9. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] G. LISSONI.*DDFV method : applications to fluid mechanics and domain decomposition*, Université de Nice - Sophia Antipolis ; UCA, LJAD, October 2019, https://tel.archives-ouvertes.fr/tel-02309356

Articles in International Peer-Reviewed Journal

[2] J. AGHILI, K. BRENNER, J. HENNICKER, R. MASSON, L. TRENTY.*Two-phase Discrete Fracture Matrix models with linear and nonlinear transmission conditions*, in "GEM - International Journal on Geomathematics", January 2019 [*DOI :* 10.1007/s13137-019-0118-6], https://hal.archives-ouvertes.fr/hal-01764432

[3] P. AMORIM, T. GOUDON, F. PERUANI.*An ant navigation model based on Weber's law*, in "Journal of Mathematical Biology", 2019, https://hal.archives-ouvertes.fr/hal-01802998

[4] L. BEAUDE, R. MASSON, S. LOPEZ, P. SAMIER.*Combined face based and nodal based discretizations on hybrid meshes for non-isothermal two-phase Darcy flow problems*, in "ESAIM: Mathematical Modelling and Numerical Analysis", July 2019 [*DOI :* 10.1051/M2AN/2019014], https://hal.archives-ouvertes.fr/hal-01832659

[5] F. BERTHELIN, P. GOATIN.*Regularity results for the solutions of a non-local model of traffic*, in "Discrete and Continuous Dynamical Systems - Series A", 2019, vol. 39, n^{o} 6, p. 3197-3213, https://hal.archives-ouvertes.fr/hal-01813760

[6] F. BERTHELIN, J. VOVELLE.*Stochastic isentropic Euler equations*, in "Annales scientifiques de l'Ecole normale supérieure", 2019, vol. 52, n^{o} 1, p. 181–254, https://arxiv.org/abs/1310.8093 , https://hal.archives-ouvertes.fr/hal-00878559

[7] C. CAPUTO, T. GOUDON, A. F. VASSEUR.*Solutions of the 4-species quadratic reaction-diffusion system are bounded and C ∞ -smooth, in any space dimension*, in "Analysis & PDE", 2019, https://hal.inria.fr/hal-01588779

[8] J. GILLERON, T. GOUDON, F. LAGOUTIÈRE, H. MARTIN, B. MAUROY, P. MILLET, M. RIBOT, C. VAGHI.*Modeling and analysis of adipocytes dynamic with a differentiation process*, in "ESAIM: Proceedings and Surveys", 2019, vol. 2019, p. 1 - 10, forthcoming, https://hal.inria.fr/hal-02073788

[9] T. GOUDON, J. BARRE, D. CRISAN.*Two-dimensional pseudo-gravity model: particles motion in a non-potential singular force field*, in "Transactions AMS", 2019, https://hal.inria.fr/hal-02418639

[10] T. GOUDON, S. KRELL, G. LISSONI.*DDFV method for Navier-Stokes problem with outflow boundary conditions*, in "Numerische Mathematik", 2019, https://hal.archives-ouvertes.fr/hal-01842129

[11] T. GOUDON, J. LLOBELL, S. MINJEAUD.*An explicit MUSCL scheme on staggered grids with kinetic-like fluxes for the barotropic and full Euler system*, in "Communications in Computational Physics", 2019, forthcoming, https://hal.archives-ouvertes.fr/hal-02350773

[12] T. GOUDON, S. MINJEAUD, J. LLOBELL.*An asymptotic preserving scheme on staggered grids for the-barotropic Euler system in low Mach regimes*, in "Numerical Methods for Partial Differential Equations", 2019, https://hal.inria.fr/hal-02418641

[13] T. GOUDON, L. MONASSE.*Fokker-Planck approach of Ostwald ripening: simulation of a modified Lifschitz-Slyozov-Wagner system with a diffusive correction*, in "SIAM Journal on Scientific Computing", 2019, forthcoming, https://hal.archives-ouvertes.fr/hal-01959069

[14] T. GOUDON, A. F. VASSEUR.*Statistical Stability for Transport in Random Media*, in "Multiscale Modeling and Simulation: A SIAM Interdisciplinary Journal", January 2019, vol. 17, n^{o} 1, p. 507-530 [*DOI :* 10.1137/18M1184643], https://hal.inria.fr/hal-02418394

[15] T. GOUDON, L. VIVION.*Numerical investigation of Landau damping in dynamical Lorentz gases*, in "Physica D: Nonlinear Phenomena", 2019, https://hal.inria.fr/hal-02418404

[16] B. GUELMAME, S. JUNCA, D. CLAMOND.*Regularizing effect for conservation laws with a Lipschitz convex flux*, in "Communications in Mathematical Sciences", 2019, vol. 17, n^{o} 8, p. 2223-2238, https://hal.archives-ouvertes.fr/hal-01943834

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Other Publications

[19] P. AMORIM, F. BERTHELIN, T. GOUDON.*A non-local scalar conservation law describing navigation processes*, December 2019, working paper or preprint, https://hal.archives-ouvertes.fr/hal-02419349

[20] F. BONALDI, K. BRENNER, J. DRONIOU, R. MASSON.*The Gradient Discretisation Method for Two-phase Discrete Fracture Matrix Models in Deformable Porous Media*, January 2020, working paper or preprint, https://hal.archives-ouvertes.fr/hal-02454360

[21] C. CANCÈS, C. CHAINAIS-HILLAIRET, M. HERDA, S. KRELL.*Large time behavior of nonlinear finite volume schemes for convection-diffusion equations*, November 2019, working paper or preprint, https://hal.archives-ouvertes.fr/hal-02360155

[22] C. CHAINAIS-HILLAIRET, S. KRELL.*Exponential decay to equilibrium of nonlinear DDFV schemes for convection-diffusion equations*, December 2019, working paper or preprint, https://hal.archives-ouvertes.fr/hal-02408212

[23] M. J. GANDER, J. HENNICKER, R. MASSON.*Modeling and Analysis of the Coupling in Discrete Fracture Matrix models*, January 2020, working paper or preprint, https://hal.archives-ouvertes.fr/hal-02437030

[24] T. GOUDON, S. KRELL, G. LISSONI.*Non-overlapping Schwarz algorithms for the Incompressible Navier-Stokes equations with DDFV discretizations*, January 2020, working paper or preprint, https://hal.inria.fr/hal-02448007

[25] T. GOUDON, L. VIVION.*Landau damping in dynamical Lorentz gases*, June 2019, working paper or preprint, https://hal.archives-ouvertes.fr/hal-02155761

[26] F. MARAZZATO, A. ERN, L. MONASSE.*A consistent discrete element method for quasi-static and dynamic elasto-plasticity*, November 2019, https://arxiv.org/abs/1911.00738 - working paper or preprint, https://hal.archives-ouvertes.fr/hal-02343280

Project-Team DIANA

Design, Implementation and Analysis of Networking Architectures

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Networks and Telecommunications

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Project-Team DIANA

Creation of the Team: 2013 January 01, updated into Project-Team: 2015 July 01

Keywords:

Computer Science and Digital Science:

A1.1.13. - Virtualization
A1.2.1. - Dynamic reconfiguration
A1.2.2. - Supervision
A1.2.3. - Routing
A1.2.4. - QoS, performance evaluation
A1.2.5. - Internet of things
A1.2.9. - Social Networks
A1.3. - Distributed Systems
A1.3.4. - Peer to peer
A1.4. - Ubiquitous Systems

Other Research Topics and Application Domains:

B6.2. - Network technologies
B6.2.1. - Wired technologies
B6.2.2. - Radio technology
B6.2.3. - Satellite technology
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B8.5.2. - Crowd sourcing
B9.1.1. - E-learning, MOOC
B9.5.1. - Computer science
B9.5.6. - Data science
B9.8. - Reproducibility
B9.10. - Privacy

1. Team, Visitors, External Collaborators

Research Scientists

Walid Dabbous [Team leader, Inria, Senior Researcher, HDR]
Chadi Barakat [Inria, Senior Researcher, HDR]
Arnaud Legout [Inria, Researcher, HDR]
Damien Saucez [Inria, Researcher, until Sep 2019, on leave at Safran Electrical & Power since Oct 2019]
Thierry Turletti [Inria, Senior Researcher, HDR]

External Collaborators

Mondi Ravi [Self employed, from Jun 2019 until Aug 2019]
Mondi Ravi [Inria, Consultant, from Sep 2019]

Technical Staff

Abdelhakim Akodadi [Inria, Engineer, until Apr 2019]

Zeineb Guizani [Inria, Engineer, until May 2019]
David Migliacci [Inria, Engineer]
Thierry Parmentelat [Inria, Engineer]
Mondi Ravi [Inria, Engineer, until May 2019]

PhD Students

Othmane Belmoukadam [Univ Côte d'Azur, PhD Student]
Yanis Boussad [Univ de Nice - Sophia Antipolis, PhD Student]
Giuseppe Di Lena [Orange Labs, PhD Student]
Mamoutou Diarra [Ekinops, PhD Student, from Sep 2019, granted by CIFRE]
Thibaut Ehlinger [Inria, PhD Student, until Apr 2019]
Houssam Elbouanani [Inria, PhD Student, from Dec 2019]
Imane Fouad [Inria]
Karyna Gogunska [Inria, PhD Student, until Sep 2019]
Muhammad Jawad Khokhar [Inria, PhD Student]
Mohamed Naoufal Mahfoudi [Inria, PhD Student, until Sep 2019]
Ghada Moualla [Inria, PhD Student, until Mar 2019]
Vitalii Poliakov [Univ de Nice - Sophia Antipolis, PhD Student, until Jan 2019]
Imane Taibi [Inria]
Mathieu Thiery [Inria]
Thibaud Trolliet [Inria, PhD Student, until Sep 2019]

Post-Doctoral Fellows

Giulio Grassi [Inria]
Tingting Yuan [Inria, Post-Doctoral Fellow]

Visiting Scientists

Rabi Ahrara [Univ Côte d'Azur, from Nov 2019]
Chanpiseth Chap [Univ Côte d'Azur, from Nov 2019]
Florinda Fragassi [Univ Côte d'Azur, from Nov 2019]
Rossella Franco [Univ Côte d'Azur, from Nov 2019]
Angelo Rodio [Univ Côte d'Azur, from Nov 2019]
Adeel Siddiqui [Univ Côte d'Azur, from Nov 2019]

Administrative Assistant

Christine Foggia [Inria, Administrative Assistant]

2. Overall Objectives

2.1. Presentation of the team

The overall objective of the DIANA project-team is to provide network architectural support for improving citizen rights in the Internet. To do so, we work to provide service transparency and user data control in the context of hundreds of billions of both wired and mobile devices. Our methodology includes advanced measurement techniques, design and implementation of architectural solutions, and their validation in adequate experimental facilities.

The high complexity of the Internet architecture, protocols and services, and the economic interests of the big stakeholders result in a lack of transparency concerning information of high interest to the connected "citizen" such as possible privacy leaks, root cause of service degradation or lock-in behavior. It is therefore important to enhance the network to provide service transparency to citizens.

On the other hand, the ossification of the Internet architecture around the IP protocol makes introduction of new functionalities in the network quite difficult. Users currently have no control on their contents and depend on big companies (e.g., Google drive, iCloud, dropbox, Microsoft OneDrive) to easily access and share data at the expense of their privacy. However, the recent development of software-defined network and network functions virtualization concepts open the perspective of faster deployment of network functionalities, as it abstracts the whole network as a single piece of software, instead of a large number of heterogeneous and dedicated devices to be configured one-by-one.

In the DIANA project-team, we have two main research directions:

- designing and deploying a measurement plane providing network service transparency,
- defining and deploying an open network architecture for user control.

Our research program is presented briefly in the next section.

3. Research Program

3.1. Service Transparency

Transparency is to provide network users and application developers with reliable information about the current or predicted quality of their communication services, and about potential leakages of personal information, or of other information related to societal interests of the user as a “connected citizen” (e.g. possible violation of network neutrality, opinion manipulation). Service transparency therefore means to provide information meaningful to users and application developers, such as quality of experience, privacy leakages, or opinion manipulation, etc. rather than network-level metrics such as available bandwidth, loss rate, delay or jitter.

The Internet is built around a best effort routing service that does not provide any guarantee to end users in terms of quality of service (QoS). The simplicity of the Internet routing service is at the root of its huge success. Unfortunately, a simple service means unpredicted quality at the access. Even though a considerable effort is done by operators and content providers to optimise the Internet content delivery chain, mainly by over-provisioning and sophisticated engineering techniques, service degradation is still part of the Internet. The proliferation of wireless and mobile access technologies, and the versatile nature of Internet traffic, make end users quality of experience (QoE) forecast even harder. As a matter of fact, the Internet is missing a dedicated measurement plane that informs the end users on the quality they obtain and in case of substantial service degradation, on the origin of this degradation. Current state of the art activities are devoted to building a distributed measurement infrastructure to perform active, passive and hybrid measurements in the wired Internet. However, the problem is exacerbated with modern terminals such as smartphones or tablets that do not facilitate the task for end users (they even make it harder) as they focus on simplifying the interface and limiting the control on the network, whereas the Internet behind is still the same in terms of the quality it provides. Interestingly, this same observation explains the existing difficulty to detect and prevent privacy leaks. We argue that the lack of transparency for diagnosing QoE and for detecting privacy leaks have the same root causes and can be solved using common primitives. For instance, in both cases, it is important to be able to link data packets to an application. Indeed, as the network can only access data packets, there must be a way to bind these packets to an application (to understand users QoE for this application or to associate a privacy leak to an application). This is however a complex task as the traffic might be obfuscated or encrypted. Our objectives in the research direction are the following:

- Design and develop measurement tools providing transparency, in spite of current complexity
- Deploy those measurement tools at the Internet’s edge and make them useful for end users
- Propose measurements plane as an overlay or by exploiting in-network functionalities
- Adapt measurements techniques to network architectural change
- Provide measurements as native functionality in future network architecture

3.2. Open network architecture

We are surrounded by personal content of all types: photos, videos, documents, etc. The volume of such content is increasing at a fast rate, and at the same time, the spread of such content among all our connected devices (mobiles, storage devices, set-top boxes, etc) is also increasing. All this complicates the control of personal content by the user both in terms of access and sharing with other users. The access of the personal content in a seamless way independently of its location is a key challenge for the future of networks. Proprietary solutions exist, but apart from fully depending on one of them, there is no standard plane in the Internet for a seamless access to personal content. Therefore, providing network architectural support to design and develop content access and sharing mechanisms is crucial to allow users control their own data over heterogeneous underlying network or cloud services.

On the other hand, privacy is a growing concern for states, administrations, and companies. Indeed, for instance the French CNIL (entity in charge of citizens privacy in computer systems) puts privacy at the core of its activities by defining rules on any stored and collected private data. Also, companies start to use privacy preserving solutions as a competitive advantage. Therefore, understanding privacy leaks and preventing them is a problem that can already find support. However, all end-users do not *currently* put privacy as their first concern. Indeed, in face of two services with one of higher quality, they usually prefer the highest quality one whatever the privacy implication. This was, for instance, the case concerning the Web search service of Google that is more accurate but less privacy preserving than Bing or Qwant. This is also the case for cloud services such as iCloud or Dropbox that are much more convenient than open source solutions, but very bad in terms of privacy. Therefore, to reach end-users, any privacy preserving solutions must offer a service equivalent to the best existing services.

We consider that it will be highly desirable for Internet users to be able to *easily* move their content from a provider to another and therefore not to depend on a content provider or a social network monopoly. This requires that the network provides built-in architectural support for content networking.

In this research direction, we will define a new *service abstraction layer* (SAL) that could become the new waist of the network architecture with network functionalities below (IP, SDN, cloud) and applications on top. SAL will define different services that are of use to all Internet users for accessing and sharing data (seamless content localisation and retrieval, privacy leakage protection, transparent vertical and horizontal handover, etc.). The biggest challenge here is to cope in the same time with large number of content applications requirements and high underlying networks heterogeneity while still providing efficient applications performance. This requires careful definition of the services primitives and the parameters to be exchanged through the service abstraction layer.

Two concurring factors make the concept behind SAL feasible and relevant today. First, the notion of scalable network virtualization that is a required feature to deploy SAL in real networks today has been discussed recently only. Second, the need for new services abstraction is recent. Indeed, more than fifteen years ago the Internet for the end-users was mostly the Web. Only ten years ago smartphones came into the picture of the Internet boosting the number of applications with new functionalities and risks. Since a few years, many discussions in the network communities took place around the actual complexity of the Internet and the difficulty to develop applications. Many different approaches have been discussed (such as CCN, SDN) that intend to solve only part of the complexity. SAL takes a broader architectural look at the problem and considers solutions such as CCN as mere use cases. Our objectives in this research direction include the following:

- Identify common key networking services required for content access and sharing
- Detect and prevent privacy leaks for content communication
- Enhance software defined networks for large scale heterogeneous environments
- Design and develop open Content Networking architecture
- Define a service abstraction layer as the thin waist for the future content network architecture
- Test and deploy different applications using SAL primitives on heterogeneous network technologies

3.3. Methodology

We follow an experimental approach that can be described in the following techniques:

- Measurements: the aim is to get a better view of a problem in quantifiable terms. Depending on the field of interest, this may involve large scale distributed systems crawling tools; active probing techniques to infer the status and properties of a complex and non controllable system as the Internet; or even crowdsourcing-based deployments for gathering data on real-users environments or behaviours.
- Experimental evaluation: once a new idea has been designed and implemented, it is of course very desirable to assess and quantify how effective it can be, before being able to deploy it on any realistic scale. This is why a wide range of techniques can be considered for getting early, yet as significant as possible, feedback on a given paradigm or implementation. The spectrum for such techniques span from simulations to real deployments in protected and/or controlled environments.

4. Highlights of the Year

4.1. Highlights of the Year

4.1.1. Ekinops

We have started a collaboration with EKINOPS on the topic of Multi-access Edge Computing. The activity started with a CIFRE thesis. The PhD student Mamoutou Diarra started his PhD on this topic on November 2019.

4.1.2. ACM CoNEXT 2019 Artefact Evaluation Committee

As a continuation of our long lasting efforts in encouraging reproducibility [17], Damien Saucez and Mohamed Naoufal Mahfoudi from our project-team have co-chaired the ACM CoNEXT 2019 Artefact Evaluation Committee. In 2019, 11 papers out of the 32 accepted at the conference have requested for being evaluated, resulting in 10 artefacts being awarding with a badge. Interestingly, we are witnessing an important improvement in the quality of the artefacts proposed by the SIGCOMM community.

5. New Software and Platforms

5.1. ACQUAmobile

KEYWORDS: Android - Internet access - Performance measure - Quality of Experience

FUNCTIONAL DESCRIPTION: ACQUA is an Application for prediCting QUality of Experience (QoE) at Internet Access [21]. It is developed by the Diana team at Inria Sophia Antipolis – Méditerranée and was supported by Inria under the ADT ACQUA grant. The scientific project around ACQUA is supported by Inria Project Lab BetterNet and the French National Project ANR BottleNet. The project also got the approval of Inria COERLE and French CNIL for the part on experimentation with real users. ACQUA presents a new way for the evaluation of the performance of Internet access. Starting from network-level measurements as the ones we often do today (bandwidth, delay, loss rates, jitter, etc), ACQUA targets the estimated Quality of Experience (QoE) related to the different applications of interest to the user without the need to run them (e.g., estimated Skype quality, estimated video streaming quality).

An application in ACQUA is a function, or a model, that links the network-level and device-level measurements to the expected Quality of Experience. Supervised machine learning techniques are used to establish such link between measurements both at the network level and the device level, and estimations of the Quality of Experience for different Internet applications. The required data for such learning can be obtained either by controlled experiments as we did in [26] on YouTube Quality of Experience, or by soliciting the crowd (i.e. crowdsourcing) for combinations (i.e. tuples) of measurements and corresponding application-level Quality of Experience. Our current work is concentrating on using the ACQUA principle in the estimation and prediction of the Quality of Experience for main user's applications. We refer to the web site of the project for further details.

The ACQUA Android application is supposed to be on one hand the reference application for QoE forecasting and troubleshooting for end users at their Internet access, and on the other hand, the feedback channel that allows end users to report to us (if they are willing) on their experience together with the corresponding network measurements so as to help us calibrating better and more realistic models. For this calibration, we are currently performing extensive, efficient and automatic measurements in the laboratory, we will count on end users to help us completing this dataset with further applications and more realistic network and user conditions.

ACQUA is mainly meant for end users, but it is also of interest to (mobile) network operators and to content providers to estimate the QoE of their customers and their networks without each time having to run expensive application-level traffic and to involve real users.

Assessment: Audience = 3, Software Originality = 4, Software Maturity = 3, Evolution and Maintenance = 3, Software Distribution and Licensing = 5.

- Authors: Thierry Spetebroot and Chadi Barakat
- Contact: Chadi Barakat
- URL: http://project.inria.fr/acqua/

5.2. ElectroSmart

KEYWORDS: Crowd-sourcing - UMTS - GSM - Bluetooth - Wi-Fi - 4G - 3G - 2G - Electromagnetic waves - Android - LTE

FUNCTIONAL DESCRIPTION: The Internet and new devices such as smartphones have fundamentally changed the way people communicate, but this technological revolution comes at the price of a higher exposition of the general population to microwave electromagnetic fields (EMF). This exposition is a concern for health agencies and epidemiologists who want to understand the impact of such an exposition on health, for the general public who wants a higher transparency on its exposition and the health hazard it might represent, but also for cellular operators and regulation authorities who want to improve the cellular coverage while limiting the exposition, and for computer scientists who want to better understand the network connectivity in order to optimize communication protocols. Despite the fundamental importance to understand the exposition of the general public to EMF, it is poorly understood because of the formidable difficulty to measure, model, and analyze this exposition.

The goal of the ElectroSmart project is to develop the instrument, methods, and models to compute the exposition of the general public to microwave electromagnetic fields used by wireless protocols and infrastructures such as Wi-Fi, Bluetooth, or cellular. Using a pluri-disciplinary approach combining crowd-based measurements, in-lab experiments, and modeling using sparse and noisy data, we address challenges such as designing and implementing a measuring instrument leveraging on crowd-based measurements from mobile devices such as smartphones, modeling the exposition of the general public to EMF to compute the most accurate estimation of the exposition, and analyzing the evolution of the exposition to EMF with time. This technological breakthrough will have scientific, technical, and societal applications, notably on public health politics, by providing the scientific community and potential users with a unique measuring instrument, methods, and models to exploit the invaluable data gathered by the instrument.

This project is supported by the UCN@Sophia Labex in 2016/2017/2018 (funding the engineer Mondi Ravi), by an Inria ADT (funding the engineer Abdelhakim Akodadi) 2017/2018, by and Inria ATT (funding the business developer David Migliacci) in 2017/2018, and by the academy 1 of UCAJedi (funding a Ph.D. student Yanis Boussad) 2017/2020.

In August 2016, we released the first stable public release of ElectroSmart. On the 07th January 2020, we acquire 1000 new daily users, and have 20k weekly active users.

Assessment: A-5, SO-4, SM-4, EM-3-up4, SDL-1

We are in a process of creating a startup to commercialize the exposition maps we can build with the data we are collecting.

- Participants: Arnaud Legout, Abdelhakim Akodadi, Hackob Melconian, Inderjeet Singh and Mondi Ravi
- Contact: Arnaud Legout
- URL: https://es.inria.fr/home/index?path_prefix=en

5.3. nepi-ng

KEYWORDS: Wireless network - Experimentation

FUNCTIONAL DESCRIPTION: In the specific context of R2lab, we have created a tool suite for orchestrating network experiments, that for historical reasons we refer to collectively as `nepi-ng`, for NEPI new generation. An umbrella website is available at https://nepi-ng.inria.fr/.

At this point, `nepi-ng` has a much smaller scope than its NEPI ancestor used to have, in that it only supports remote control of network experiments over `ssh`. As a matter of fact, in practice, this is the only access mechanism that we need to have for running experiments on both R2lab, and PlanetLab Europe.

The design of `nepi-ng` of course is modular, so that it will be perfectly possible to add other control mechanisms to this core if and when it becomes necessary.

`nepi-ng` is currently made of two separate Python libraries:

- asynciojobs:
  - URL: http://asynciojobs.readthedocs.io/en/latest/
  - Version: asynciojobs v0.5.4
  - Keywords: networking experimentation, orchestration
  - License: CC BY-SA 4.0
  - Type of human computer interaction: Python library
  - OS/Middleware: Linux
  - Required library or software: Python-3.5 / asyncio
  - Programming language: Python3
- apssh:
  - URL: http://apssh.readthedocs.io/en/latest/
  - Version: apssh v0.7.1
  - Keywords: networking experimentation, orchestration
  - License: CC BY-SA 4.0
  - Type of human computer interaction: Python library
  - OS/Middleware: Linux
  - Required library or software: Python-3.5 / asyncio
  - Programming language: Python3

Assessment: A-2, SO-3, SM-3, EM-3, DSL-4

- Contact: Thierry Parmentelat
- URL: http://nepi-ng.inria.fr

5.4. Distrinet

KEYWORDS: SDN - Emulation - Large-scale Emulators - Network simulator

SCIENTIFIC DESCRIPTION: Networks have become complex systems that combine various concepts, techniques, and technologies. As a consequence, modelling or simulating them is now extremely complicated and researchers massively resort to prototyping techniques. Two experimental techniques are mainly used when it comes to testing a network: simulation and emulation. Emulation provides a good accuracy and allows to test the applications directly in an environment that is similar to a real one. Most of the emulators do not take into account the scalability, because usually they are designed to be executed in a single machine. Among other tools, Mininet is the most popular when it comes to evaluate SDN propositions. It allows to emulate SDN networks on a single computer. Unfortunately, Mininet shows its limitations with resource intensive experiments as the emulating host may become overloaded. To tackle this issue, we propose Distrinet, a distributed implementation of Mininet over multiple hosts. Distrinet uses the same API than Mininet, meaning that it is compatible with Mininet programs. It is generic and can deploy experiments in Linux clusters or in the Amazon EC2 cloud.

Assessment: A5, SO3, SM2, EM2-down, SDL4

FUNCTIONAL DESCRIPTION: Distrinet is an extension of Mininet that relies on LXC to be distributed in the cloud, and particularly in Amazon.

RELEASE FUNCTIONAL DESCRIPTION: First release

- Participants: Damien Saucez, Giuseppe Di Lena, Andrea Tomassilli, Frédéric Giroire, Thierry Turletti and Walid Dabbous
- Partner: Orange Labs
- Contact: Walid Dabbous
- URL: https://distrinet-emu.github.io

5.5. Platforms

5.5.1. Reproducible research Lab - R2lab

Scientific work around network protocols and related software stacks requires experiments, hence experimental conditions, to be reproducible. This is a particularly challenging requirement in the wireless networking area, where characteristics of wireless channels are known to be variable, unpredictable and hardly controllable.

The R2lab wireless testbed was designed with reproducibility as its central characteristics; it is built around an isolated and anechoic chamber, featuring RF absorbers that prevent radio waves reflections, and a Faraday cage blocking external interferences. R2lab thus provides an ideal environment for running reproducible wireless experiments.

R2lab has been operated for 4 years now, in the context of the FIT (Future Internet of Things) Equipment of Excellence project, and as such, it is now federated with the other testbeds that are part of the FIT initiative. As of early 2019, it is now also federated within the Fed4Fire initiative.

Available toolsets, both hardware and software, are mostly stable apart from low noise marginal deployment of new kinds of radio devices, that now encompass among 5G and LoRa, among others. Our focus at this point of the project is to leverage our initial technical and financial investment, and to produce scientific work around reproducibility, particularly from a methodological standpoint, as illustrated by various publications [33], [34].

Worth being mentioned as well, as part of a partnership with the OpenAirInterface initiative, R2lab is used on a daily basis for system-wide regression tests of the OAI stack, which in return allows us to offer up-to-date images for running OAI-based experiments.

Access to R2lab is open 24/7. We currently have around 200 active users from all over the world among them 40 new users registered in 2019. For more details see http://r2lab.inria.fr.

5.5.2. Network simulator for aircrafts

- Keywords: network, simulation, real-time
- Functional Description: In collaboration with Safran Electrical and Power we produced a network design tool for aircrafts. This tool simulates aircraft networks. The tool is about 10,000 lines of code, out of which we produced 2,000.
- Assessment: A-2up,SO-3,SM-2up,EM-4,SDL-3,OC-DA-CD-TPM
- Licence: confidential
- URL: confidential
- Contact: Damien Saucez

6. New Results

6.1. Service Transparency

6.1.1. From Network Traffic Measurements to QoE for Internet Video

Participants: Muhammad Jawad Khokhar, Thibaut Ehlinger, Chadi Barakat.

Video streaming is a dominant contributor to the global Internet traffic. Consequently, monitoring video streaming Quality of Experience (QoE) is of paramount importance to network providers. Monitoring QoE of video is a challenge as most of the video traffic of today is encrypted. In this work, we consider this challenge and present an approach based on controlled experimentation and machine learning to estimate QoE from encrypted video traces using network level measurements only. We consider a case of YouTube and play out a wide range of videos under realistic network conditions to build ML models (classification and regression) that predict the subjective MOS (Mean Opinion Score) based on the ITU P.1203 model along with the QoE metrics of startup delay, quality (spatial resolution) of playout and quality variations, and this is using only the underlying network Quality of Service (QoS) features. We comprehensively evaluate our approach with different sets of input network features and output QoE metrics. Overall, our classification models predict the QoE metrics and the ITU MOS with an accuracy of 63-90% while the regression models show low error; the ITU MOS (1-5) and the startup delay (in seconds) are predicted with a root mean square error of 0.33 and 2.66 respectively. The results of this work were published in [26] and can be found with further details in the PhD manuscript of Muhammad Jawad Khokhar graduated in October 2019.

6.1.2. When Deep Learning meets Web Measurements to infer Network Performance

Participants: Imane Taibi, Chadi Barakat.

Web browsing remains one of the dominant applications of the internet, so inferring network performance becomes crucial for both users and providers (access and content) so as to be able to identify the root cause of any service degradation. Recent works have proposed several network troubleshooting tools, e.g, NDT, MobiPerf, SpeedTest, Fathom. Yet, these tools are either computationally expensive, less generic or greedy in terms of data consumption. The main purpose of this work funded by the IPL BetterNet is to leverage passive measurements freely available in the browser and machine learning techniques (ML) to infer network performance (e.g., delay, bandwidth and loss rate) without the addition of new measurement overhead. To enable this inference , we propose a framework based on extensive controlled experiments where network configurations are artificially varied and the Web is browsed, then ML is applied to build models that estimate the underlying network performance. In particular, we contrast classical ML techniques (such as random forest) to deep learning models trained using fully connected neural networks and convolutional neural networks (CNN). Results of our experiments show that neural networks have a higher accuracy compared to classical ML approaches. Furthermore, the model accuracy improves considerably using CNN. These results were published in [28].

6.1.3. On Accounting for Screen Resolution in Adaptive Video Streaming: A QoE-Driven Bandwidth Sharing Framework

Participants: Othmane Belmoukadam, Muhammad Jawad Khokhar, Chadi Barakat.

Screen resolution along with network conditions are main objective factors impacting the user experience, in particular for video streaming applications. Terminals on their side feature more and more advanced characteristics resulting in different network requirements for good visual experience. Previous studies tried to link MOS (Mean Opinion Score) to video bit rate for different screen types (e.g., CIF, QCIF, and HD). We leverage such studies and formulate a QoE-driven resource allocation problem to pinpoint the optimal bandwidth allocation that maximizes the QoE (Quality of Experience) over all users of a provider located behind the same bottleneck link, while accounting for the characteristics of the screens they use for video playout. For our optimization problem, QoE functions are built using curve fitting on data sets capturing the relationship between MOS, screen characteristics, and bandwidth requirements. We propose a simple heuristic based on Lagrangian relaxation and KKT (Karush Kuhn Tucker) conditions for a subset of constraints. Numerical simulations show that the proposed heuristic is able to increase overall QoE up to 20% compared to an allocation with TCP look-alike strategies implementing max-min fairness. Later, we use a MPEG/DASH implementation in the context of ns-3 and show that coupling our approach with a rate adaptation algorithm can help increasing QoE while reducing both resolution switches and number of interruptions. Our framework and the first validation results were published in [20].

6.1.4. Tuning optimal traffic measurement parameters in virtual networks with machine learning

Participants: Karyna Gogunska, Chadi Barakat.

With the increasing popularity of cloud networking and the widespread usage of virtualization as a way to offer flexible and virtual network and computing resources, it becomes more and more complex to monitor this new virtual environment. Yet, monitoring remains crucial for network troubleshooting and analysis. Controlling the measurement footprint in the virtual network is one of the main priorities in the process of monitoring as resources are shared between the compute nodes of tenants and the measurement process itself. In this paper, first, we assess the capability of machine learning to predict measurement impact on the ongoing traffic between virtual machines; second, we propose a data-driven solution that is able to provide optimal monitoring parameters for virtual network measurement with minimum traffic interference. These results were published in [25] and are part of the PhD manuscript of Karyna Gogunska graduated in December 2019.

6.1.5. Collaborative Traffic Measurement in Virtualized Data Center Networks

Participants: Houssam Elbouanani, Chadi Barakat.

Data center network monitoring can be carried out at hardware networking equipment (e.g. physical routers) and/or software networking equipment (e.g. virtual switches). While software switches offer high flexibility to deploy various monitoring tools, they have to utilize server resources, esp. CPU and memory, that can no longer be reserved fully to service users' traffic. In this work we closely examine the costs of (i) sampling packets ; (ii) sending them to a user-space program for measurement; and (iii) forwarding them to a remote server where they will be processed in case of lack of resources locally. Starting from empirical observations, we derive an analytical model to accurately predict ($R^2 = 99.5\%$) the three aforementioned costs, as a function of the sampling rate. We next introduce a collaborative approach for traffic monitoring and sampling that maximizes the amount of collected traffic without impacting the data center's operation. We analyze, through numerical simulations, the performance of our collaborative solution. The results show that it is able to take advantage of the uneven loads on the servers to maximize the amount of traffic that can be sampled at the scale of a data center. The resulting gain can reach 200% compared to a non collaborative approach. These results were published in [23].

6.1.6. Distributed Privacy Preserving Platform for Ridesharing Services

Participants: Damien Saucez, Yevhenii Semenko.

The sharing economy fundamentally changed business and social interactions. Interestingly, while in essence this form of collaborative economy allows people to directly interact with each other, it is also at the source of the advent of eminently centralized platforms and marketplaces, such as Uber and Airbnb. One may be concerned with the risk of giving the control of a market to a handful of actors that may unilaterally fix their own rules and threaten privacy. Within the Data Privacy project of the UCAJedi Idex Academy 5 and House of Human and Social Sciences, Technologies and Uses Theme, we have proposed a holistic solution to address privacy issues in the sharing economy. We considered the case of ridesharing and proposed a decentralized architecture which gives the opportunity to shift from centralized platforms to decentralized ones. Digital communications in our proposition are specifically designed to preserve data privacy and avoid any form of centralization. A blockchain is used in our proposition to guarantee the essential roles of a marketplace, but in a decentralized way. Our evaluation shows that privacy protection without trusted entities comes at the cost of harder scalability than an approach with a trusted third party. However, our numerical evaluation on real data and our Android prototype shows the practical feasibility of our approach. The results obtained in this activity are published in 12th International Conference on Security, Privacy, and Anonymity in Computation, Communication, and Storage (SpaCCS) 2019, Atlanta [31] and documented in a research report [35].

6.1.7. Missed by Filter Lists: Detecting Unknown Third-Party Trackers with Invisible Pixels

Participants: Imane Fouad, Arnaud Legout, Natasa Sarafijanovic-Djukic.

Web tracking has been extensively studied over the last decade. To detect tracking, previous studies and user tools rely on filter lists. However, it has been shown that filter lists miss trackers. In this paper, we propose an alternative method to detect trackers inspired by analyzing behavior of invisible pixels. By crawling 84,658 webpages from 8,744 domains, we detect that third-party invisible pixels are widely deployed: they are present on more than 94.51% of domains and constitute 35.66% of all third-party images. We propose a fine-grained behavioral classification of tracking based on the analysis of invisible pixels. We use this classification to detect new categories of tracking and uncover new collaborations between domains on the full dataset of 4,216,454 third-party requests. We demonstrate that two popular methods to detect tracking, based on EasyList & EasyPrivacy and on Disconnect lists respectively miss 25.22% and 30.34% of the trackers that we detect. Moreover, we find that if we combine all three lists, 379,245 requests originated from 8,744 domains still track users on 68.70% of websites. This work will appear in PETS 2020 [24].

6.1.8. Privacy implications of switching ON a light bulb in the IoT world

Participants: Mathieu Thiery, Arnaud Legout.

The number of connected devices is increasing every day, creating smart homes and shaping the era of the Internet of Things (IoT), and most of the time, end-users are unaware of their impacts on privacy. In this work, we analyze the ecosystem around a Philips Hue smart white bulb in order to assess the privacy risks associated to the use of different devices (smart speaker or button) and smartphone applications to control it. We show that using different techniques to switch ON or OFF this bulb has significant consequences regarding the actors involved (who mechanically gather information on the user's home) and the volume of data sent to the Internet (we measured differences up to a factor 100, depending on the control technique we used). Even when the user is at home, these data flows often leave the user's country, creating a situation that is neither privacy friendly (and the user is most of the time ignorant of the situation), nor sovereign (the user depends on foreign actors), nor sustainable (the extra energetic consumption is far from negligible). We therefore advocate a complete change of approach, that favors local communications whenever sufficient. The preprint documenting this work has been published as research report [40].

6.1.9. ElectroSmart

Participants: Arnaud Legout, Mondi Ravi, David Migliacci, Abdelhakim Akodadi, Yanis Boussad.
We are currently evaluating the relevance to create a startup for the ElectroSmart project. We are quite advanced in the process and the planned creation is June 2020. There is a "contrat de transfer" ready between Inria and ElectroSmart to transfer the PI from Inria to the ElectroSmart company (when it will be created). Arnaud Legout the future CEO of the company obtained the "autorisation de création d'entreprise" from Inria. ElectroSmart has been incubated in PACA Est in December 2018.

The three future co-founder of ElectroSmart (Arnaud Legout, Mondi Ravi, David Migliacci) followed the Digital Startup training from Inria/EM Lyon.

The goal of ElectroSmart is to help people reduce their exposure to EMF and offer a solution to reduce symptoms associated with exposure to EMF. Electrosensitivity, is known to be a complex and multifactorial syndrome that impacts hundreds of millions of persons worldwide. We aim to commercialize the first treatment of electrosensitivity based on non-deceptive placebo (called open-label placebo). It is known today that placebo are an effective treatment to subjective symptoms (which is the case for several symptoms associated with electrosensitivity). The problem with placebo was that is was assumed that it must be deceptive to be efficient. Kaptchuk et al. showed recently that non-deceptive placebo are as effective as deceptive placebo, so the ethical usage of placebo is now possible. ElectroSmart want to be the first company to commercialize non-deceptive placebo for electrosensitive persons. For details, see https://electrosmart.app/.

6.2. Open Network Architecture

6.2.1. Constrained Software Defined Networks

Participant: Damien Saucez.
The objective of the ANR JCJC DET4ALL project was to offer the ability to multiplex constrained networks with real time and safety requirements on Ethernet network not initially thought for strict constraints. The reason for this move to Ethernet is to reduce the cost of networking solutions in automotive and industrial applications. We advocate that this move requires to rely on Software Defined Networking (SDN) that enables a programmatic approach to networking, hence offering modularity and flexibility. The challenge with SDN is to be able to certify the behaviour of the system while keeping the solution generic. Within DET4ALL we put the first element in place to show that the previous works that proposed programming languages and abstractions for best-effort network could be leveraged to offering safety properties and determinism in real-time industrial and automotive networks. More precisely, we have demonstrated that Linear Temporal Logic (LTL) can be used in real-time networks to demonstrate the that real-time constraints are always respected. We built a strawman to show that the Temporal NetKat language was adapted to express real-time constraints of networks even though it was not initially design for that purpose. Given that Temporal NetKat relies on LTL and an algebra, it is a good candidate to prove the correct behaviour of a SDN network which logic would be implemented with such a language. In the continuation of this work, we have determined what would be necessary to be able to provide provable live network updates in real time network without service degradation.

This work is published in [30] and will be detailed in the next subsection. Due the leave of Damien Saucez to Safran for one year starting October 1st 2019, the activity on this project had to be stopped as it was in the context of an ANR JCJC project.

6.2.2. NUTS: Network Updates in Real Time Systems

Participants: Damien Saucez, Walid Dabbous.

Recent manufacturing trends have highlighted the need to adapt to volatile, fast-moving, and customer-driven markets. To keep pace with ever quicker product lifecycles, shorter order lead times and growing product variants, factories will become distributed modular cyber-physical systems interconnected by complex communication networks. We advocate that the Software Define Networking (SDN) concept with its programmatic approach to networking is a key enabler for the so-called Industry 4.0 because it provides flexibility and the possibility to formally reason on networks. We have identified that a critical point to address is how to support safe network updates of deterministic real-time communication SDN. To achieve this goal 4 elements are required. First a declarative language with LTL support is needed to express the constraints. Second, a programmable data-plane with the ability to provide real-time constraints indications must be provided in order to assess the behaviour of the forwarding elements. Such language does not exist yet however among the data-plane languages currently on the market some provide the ability to add annotations that could be used to reach our objective. Third, we have identified that deterministic algorithms had to be used to provide a verifiable sequence of network updates in order to make live updates without service degradations. Finally, mathematical techniques must be used to provide bounds on the network updates. Network Calculus can be used for that objective. This study was published as a poster in SOSR'19 [30].

6.2.3. A Joint range extension and localization for LPWAN

Participants: Mohamed Naoufal Mahfoudi, Gayatri Sivadoss, Othmane Bensouda Korachi, Thierry Turletti, Walid Dabbous.

We have proposed Snipe, a novel system offering joint localization and range extensions for LPWANs. Although LPWAN systems such as Long Range (LoRa) are designed to achieve high communication range with low energy consumption, they suffer from fading in obstructed environments with dense multipath components, and their localization system is sub-par in terms of accuracy. In this work, MIMO techniques are leveraged to achieve a higher signal-to-noise ratio at both the end device and the gateway while providing an opportunistic accurate radar-based system for localization with limited additional cost. This work has been published at Internet Technology Letters [15].

6.2.4. Online Robust Placement of Service Chains for Large Data Center Topologies

Participants: Ghada Moualla, Thierry Turletti, Damien Saucez.

The trend today is to deploy applications and more generally Service Function Chains (SFCs) in public clouds. However, before being deployed in the cloud, chains were deployed on dedicated infrastructures where software, hardware, and network components were managed by the same entity, making it straightforward to provide robustness guarantees. By moving their services to the cloud, the users lose their control on the infrastructure and hence on the robustness. We propose an online algorithm for robust placement of service chains in data centers. Our placement algorithm determines the required number of replicas for each function of the chain and their placement in the data center. Our simulations on large data-center topologies with up to 30,528 nodes show that our algorithm is fast enough such that one can consider robust chain placements in real time even in a very large data center and without the need of prior knowledge on the demand distribution. This work has been published at IEEE Access [16].

6.2.5. Bandwidth-optimal Failure Recovery Scheme for Robust Programmable Networks

Participants: Giuseppe Di Lena, Damien Saucez, Thierry Turletti.

With the emergence of Network Function Virtualization (NFV) and Software Defined Networking (SDN), efficient network algorithms considered too hard to be put in practice in the past now have a second chance to be considered again. In this context, we rethink the network dimensioning problem with protection against Shared Risk Link Group (SLRG) failures. In this work, we consider a path-based protection scheme with a global rerouting strategy, in which, for each failure situation, there may be a new routing of all the demands. Our optimization task is to minimize the needed amount of bandwidth. After discussing the hardness of the problem, we develop a scalable mathematical model that we handle using the Column Generation technique. Through extensive simulations on real-world IP network topologies and on random generated instances, we show the effectiveness of our method. Finally, our implementation in OpenDaylight demonstrates the feasibility of the approach and its evaluation with Mininet shows that technical implementation choices may have a dramatic impact on the time needed to reestablish the flows after a failure takes place. This work has been presented at the IEEE International Conference on Cloud Networking (CloudNet), November 2019, at Coimbra in Portugal [29] and documented in a research report [36]. A poster version is published in IFIP-Networking in Warsaw [41].

6.2.6. Efficient Pull-based Mobile Video Streaming leveraging In-Network Functions

Participants: Indukala Naladala, Thierry Turletti.

There has been a considerable increase in the demand for high quality mobile video streaming services, while at the same time, the video traffic volume is expected to grow exponentially. Consequently, maintaining high quality of experience (QoE) and saving network resources are becoming crucial challenges to solve. In this work, we propose a name-based mobile streaming scheme that allows efficient video content delivery by exploiting a smart pulling mechanism designed for information-centric networks (ICNs). The proposed mechanism enables fast packet loss recovery by leveraging in-network caching and coding. Through an experimental evaluation of our mechanism over an open wireless testbed and the Internet, we demonstrate that the proposed scheme leads to higher QoE levels than classical ICN and TCP-based streaming mechanisms. This work will be presented at the IEEE Consumer Communications & Networking Conference (CCNC), in January 2020 at Las Vegas, USA [27]. The following link https://github.com/fit-r2lab/demo-cefore includes the artefacts that allows to reproduce performance results shown in the paper.

6.2.7. Low Cost Video Streaming through Mobile Edge Caching: Modelling and Optimization

Participants: Luigi Vigneri, Chadi Barakat.

Caching content at the edge of mobile networks is considered as a promising way to deal with the data tsunami. In addition to caching at fixed base stations or user devices, it has been recently proposed that an architecture with public or private transportation acting as mobile relays and caches might be a promising middle ground. While such mobile caches have mostly been considered in the context of delay tolerant networks, in this work done in collaboration with Eurecom with the support of the UCN@Sophia Labex, we argue that they could be used for low cost video streaming without the need to impose any delay on the user. Users can prefetch video chunks into their playout buffer from encountered vehicle caches (at low cost) or stream from the cellular infrastructure (at higher cost) when their playout buffer empties while watching the content. Our main contributions are: (i) to model the playout buffer in the user device and analyze its idle periods which correspond to bytes downloaded from the infrastructure; (ii) to optimize the content allocation to mobile caches, to minimize the expected number of non-offloaded bytes. We perform trace-based simulations to support our findings showing that up to 60 percent of the original traffic could be offloaded from the main infrastructure. These contributions were published in the IEEE Transactions on Mobile Computing journal [18].

6.2.8. Quality of Experience-Aware Mobile Edge Caching through a Vehicular Cloud

Participants: Luigi Vigneri, Chadi Barakat.

Densification through small cells and caching in base stations have been proposed to deal with the increasing demand for Internet content and the related overload on the cellular infrastructure. However, these solutions are expensive to install and maintain. Instead, using vehicles acting as mobile caches might represent an interesting alternative. In this work, we assume that users can query nearby vehicles for some time, and be redirected to the cellular infrastructure when the deadline expires. Beyond reducing costs, in such an architecture, through vehicle mobility, a user sees a much larger variety of locally accessible content within only few minutes. Unlike most of the related works on delay tolerant access, we consider the impact on the user experience by assigning different retrieval deadlines per content. We provide the following contributions: (i) we model analytically such a scenario; (ii) we formulate an optimization problem to maximize the traffic offloaded while ensuring user experience guarantees; (iii) we propose two variable deadline policies; (iv) we perform realistic trace-based simulations, and we show that, even with low technology penetration rate, more than 60% of the total traffic can be offloaded which is around 20% larger compared to existing allocation policies. These results were published in the IEEE Transactions on Mobile Computing journal [19].

6.2.9. Machine Learning for Next-Generation Intelligent Transportation Systems

Participants: Tingting Yuan, Thierry Turletti, Chadi Barakat.

Intelligent Transportation Systems, or ITS for short, includes a variety of services and applications such as road traffic management, traveler information systems, public transit system management , and autonomous vehicles, to name a few. It is expected that ITS will be an integral part of urban planning and future cities as it will contribute to improved road and traffic safety, transportation and transit efficiency, as well as to increased energy efficiency and reduced environmental pollution. On the other hand, ITS poses a variety of challenges due to its scalability and diverse quality-of-service needs, as well as the massive amounts of data it will generate. In this survey, we explore the use of Machine Learning (ML), which has recently gained significant traction, to enable ITS. In the context of the Drive associated team, we did a comprehensive survey of the current state-of-the-art of how ML technology has been applied to a broad range of ITS applications and services, such as cooperative driving and road hazard warning, and identify future directions for how ITS can use and benefit from ML technology. The survey is documented in [42].

6.3. Experimental Evaluation

6.3.1. Exploiting the cloud for Mininet performance

Participants: Giuseppe Di Lena, Damien Saucez, Thierry Turletti.

Networks have become complex systems that combine various concepts, techniques, and technologies. As a consequence , modelling or simulating them is now extremely complicated and researchers massively resort to prototyping techniques. Among other tools, Mininet is the most popular when it comes to evaluate SDN propositions. It allows to emulate SDN networks on a single computer. However, under certain circumstances experiments (e.g., resource intensive ones) may overload the host running Mininet. To tackle this issue, we propose Distrinet, a way to distribute Mininet over multiple hosts. Distrinet uses the same API than Mininet, meaning that it is compatible with Mininet programs. Distrinet is generic and can deploy experiments in Linux clusters or in the Amazon EC2 cloud. Thanks to optimization techniques, Distrinet minimizes the number of hosts required to perform an experiment given the capabilities of the hosting infrastructure, meaning that the experiment is run in a single host (as Mininet) if possible. Otherwise, it is automatically deployed on a platform using a minimum amount of resources in a Linux cluster or with a minimum cost in Amazon EC2. This work has been presented at the IEEE International Conference on Cloud Networking (CloudNet) [22]. Distrinet has been demonstrated both at the IEEE CloudNet conference and at the ACM CoNEXT conference in Orlando USA in December 2019 [39].

6.3.2. Distributed Network Experiment Emulation

Participants: Giuseppe Di Lena, Damien Saucez, Thierry Turletti, Walid Dabbous.

With the ever growing complexity of networks, researchers have to rely on test-beds to be able to fully assess the quality of their propositions. In the meanwhile, Mininet offers a simple yet powerful API, the goldilocks of network emulators. We advocate that the Mininet API is the right level of abstraction for network experiments. Unfortunately it is designed to be run on a single machine. To address this issue we developed a distributed version of Mininet-Distrinet-that can be used to perform network experiments in any Linux-based testbeds, either public or private. To properly use testbed resources and avoid over-commitment that would lead to inaccurate results, Distrinet uses optimization techniques that determine how to orchestrate the experiments within the testbed. Its programmatic approach, its ability to work on various testbeds, and its optimal management of resources make Distrinet a key element to reproducible research. This work has been presented at the Global Experimentation for Future Internet - Workshop (GeFi) workshop November 2019, at Coimbra in Portugal [38].

6.3.3. Evaluating smartphone performance for cellular power measurement. Under submission

Participants: Yanis Boussad, Arnaud Legout.

From crowdsource data collection to automation and robotics, mobile smartphones are well suited for various use cases given the rich hardware components they feature. Researchers can now have access to various sensors such as barometers, magnetometers, orientation sensors, in addition to multiple wireless technologies all on a single and relatively cheap mobile smartphone. In this work, we study the performance of smartphones to measure cellular wireless power. We performed our experiments inside an anechoic chamber in order to compare the measurements of smartphone to the ones obtained with professional spectrum analyzer. We first evaluate the effect of orientation on the received power, then we propose a way to improve the accuracy of smartphone power measurements by using the orientation sensors. We improve the accuracy of the measurements from 25 dBm RMSE to no more than 6 dBm RMSE. We also show how we can exploit the characteristics of the reception pattern of the smartphone to determine the angle of arrival of the signal. The results of this work are described in a research report under submission [32].

6.3.4. Towards Reproducible Wireless Experiments Using R2lab

Participants: Mohamed Naoufal Mahfoudi, Thierry Parmentelat, Thierry Turletti, Walid Dabbous.

Reproducibility is key in designing wireless systems and evaluating their performance. Trying to reproduce wireless experiments allowed us to identify some pitfalls and possible ways to simplify the complex task of avoiding them. In this research report, we expose a few considerations that we learned are instrumental for ensuring the reproducibility of wireless experiments. Then we describe the steps we have taken to make our experiments easy to reproduce. We specifically address issues related to wireless hardware, as well as varying propagation channel conditions. We show that extensive knowledge of the used hardware and of its design is required to guarantee that the inner state of the system has no negative impact on performance evaluation and experimental results. As for variability of channel conditions, we make the case that a special setup or testbed is necessary so that one can control the ambient wireless propagation environment, using for instance, an anechoic chamber like R2lab. This work is published as research report [33].

6.3.5. A step towards runnable papers using R2lab

Participants: Thierry Parmentelat, Mohamed Naoufal Mahfoudi, Thierry Turletti, Walid Dabbous.

In this research report, we present R2lab, an open, electromagnetically insulated research testbed dedicated to wireless networking. We describe the hardware capabilities currently available in terms of Software Defined Radio, and the software suite made available to deploy experiments. Using a generic experiment example, we show how it all fits into a notebook-based approach to getting closer to runnable papers. This work is published as research report [34].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. Collaboration with Safran

Participant: Damien Saucez.

The research collaboration with Safran on Constrained Software Defined Networks has evolved into a new stage: Damien Saucez took a one year secondment from Inria to join Safran and further develop this activity from “inside”.

7.1.2. Collaboration with Ekinops

Participant: Thierry Turletti, Walid Dabbous.

We have started a collaboration with EKINOPS on the topic of Multi-access Edge Computing. The activity started with a CIFRE thesis. The PhD student Mamoutou Diarra started his PhD on this topic on November 2019.

7.1.3. Collaboration with Orange

Participant: Thierry Turletti, Damien Saucez.

We have a collaboration with Orange on the topic of Network Function Virtualization. The activity includes the CIFRE PhD thesis of Giuseppe Di Lena that started his PhD on resilient NFV/SDN environments on April 2018.

7.2. Bilateral Grants with Industry

7.2.1. QWANT

Participant: Arnaud Legout.

The PIA ANSWER project is led by the QWANT search engine and the Inria Sophia Antipolis Méditerranée research center. This proposal is the winner of the “Grand Challenges du Numérique” (BPI) and aims to develop the new version of the search engine http://www.qwant.com with radical innovations in terms of search criteria, indexed content and privacy of users. In the context of this project, we got with Nataliia Bielova from the INDES project-team a funding for a 3 years Ph.D. working on Web tracking technologies and privacy protection.

8. Partnerships and Cooperations

8.1. Inria Internal Funding

8.1.1. IPL Betternet

Participants: Giuilio Grassi, Imane Taibi, Chadi Barakat.

The DIANA team is part of the Inria Project Lab BetterNet (http://project.inria.fr/betternet/). Within this lab, Inria is funding the PhD of Imane Taibi who is hosted by the Dionysos team in Rennes and is co-supervied by Chadi Barakat from the DIANA project-team and Gerardo Rubino and Yassine Hadjadj-Aoul from the DIONYSOS project-team. The PhD of Imane Taibi started on the 1st of November 2017. Further in 2018, Inria funded a PostDoc position to supervise the experiments planned within the IPL and develop the data analysis part. This PostDoc position is occupied by Giulio Grassi who is co-supervised by Chadi Barakat from the Diana project-team and Renata Teixeira from the MIMOVE project-team. Giulio Grassi started on October 1st, 2018 and is currently located in Paris.

8.2. Regional Initiatives

8.2.1. ElectroSmart

Participants: Arnaud Legout, Mondi Ravi, David Migliacci, Abdelhakim Akodadi, Yanis Boussad.

The ElectroSmart project benefits form the following fundings:

- a 39 months engineering position from the UCN@Sophia Labex for the 2016-2019 period (Ravi Mondi was hired on this position)
- 30KEuros from Academy 1 of UCAJedi
- a two years engineering position from an Inria ADT for 2017/2019 (Abdelhakim Akodadi)
- a 18 months business developer from Inria ATT for june 2017-june 2019 (David Migliacci)
- a 3 years 2017/2020 Ph.D. thesis from Academy 1 of UCAJedi (Yanis Boussad)
- 12 months business developper from Inria ATT for june 2019 - mai 2020 (David Migliacci)
- 12 months engineer from Inria ATT for june 2019 - mai 2020 (Mondi Ravi)

8.2.2. D2D Indoor

Participants: Chadi Barakat, Zeineb Guizani.

This project is joint with the NFCOM startup in Nice, specialized in the development of new services for mobile phones. The project aims at leveraging mobile to mobile communications for offloading the cellular infrastructure, and targets a solution based on algorithms previously developed in the DIANA project-team (BitHoc and HBSD) to achieve networking in a sparse scenario following the multi-hop communication principle. The project got a funding for one year engineer from the Labex UCN@SOPHIA. Zeineb Guizani has worked on this project from July 2018 to May 2019 and has proposed an architecture based on NDN-opp to support such communications.

8.3. National Initiatives

8.3.1. ANR

- **ANR JCJC DET4ALL** (2019-2021): Modern factories and industrial system massively rely on cyber physical systems with digital communications (e.g., to allow collaborative robots, for data analytics...). However, industrial networks are still mostly managed and conceived as collections of independent communicating units instead of one unified piece of software.

  The reason why the shift of paradigm did not occur yet to industrial digital communication networks is because industrial processes generally impose strong determinism and real-time constraints. As a result, industrial networks have a propensity of being physically segregated to contain potential malfunctions and simplify conception.

  With the DET4ALL project, we will apply the concept of network programmability to the world of industrial communicating systems. To that aim, we will construct and prove the essential building blocks that will allow to virtualise industrial networks:

  - algorithms to automatically provision the various components constituting industrial networks;
  - Domain Specific Languages (DSLs) to specify real-time communication schemes;
  - mechanisms to update on-the-fly the production infrastructures without service degradation.

  The impact of the DET4ALL project goes beyond technological advances; it will also bring a new vision on what production tools can become, namely agile systems in perpetual evolution.

- **ANR FIT** (2011-2019): FIT (Future Internet of Things) aims at developing an experimental facility, a federated and competitive infrastructure with international visibility and a broad panel of customers. It will provide this facility with a set of complementary components that enable experimentation on innovative services for academic and industrial users. The project will give French Internet stakeholders a means to experiment on mobile wireless communications at the network and application layers thereby accelerating the design of advanced networking technologies for the Future Internet. FIT is one of 52 winning projects from the first wave of the French Ministry of

Higher Education and Research's Equipements of Excellence (Equipex) research grant programme. The project will benefit from a 5.8 million euro grant from the French government. Other partners are UPMC, IT, Strasbourg University and CNRS. The project was extended for one year and will end in december 2019. See also http://fit-equipex.fr/.

- **ANR BottleNet** (2016-2019): BottleNet aims to deliver methods, algorithms, and software systems to measure Internet Quality of Experience (QoE) and diagnose the root cause of poor Internet QoE. This goal calls for tools that run directly at users' devices. The plan is to collect network and application performance metrics directly at users' devices and correlate it with user perception to model Internet QoE, and to correlate measurements across users and devices to diagnose poor Internet QoE. This data-driven approach is essential to address the challenging problem of modeling user perception and of diagnosing sources of bottlenecks in complex Internet services. ANR BottleNet will lead to new solutions to assist users, network and service operators as well as regulators in understanding Internet QoE and the sources of performance bottleneck.

8.4. European Initiatives

8.4.1. FP7 & H2020 Projects

- Program: FP7 FIRE programme
- Project acronym: Fed4Fire+
- Project title: Federation for FIRE Plus
- Duration: January 2017 - December 2021
- Coordinator: iMinds (Belgium)
- Other partners: 20 european partners including IMEC (Belgium), UPMC (Fr), Fraunhofer (Germany), TUB (Germany), etc.
- Web site: http://www.fed4fire.eu/
- Abstract: The Fed4FIRE+ project has the objective to run and further improve Fed4FIRE as best-in-town federation of experimentation facilities for the Future Internet Research and Experimentation initiative. Federating a heterogeneous set of facilities covering technologies ranging from wireless, wired, cloud services and open flow, and making them accessible through common frameworks and tools suddenly opens new possibilities, supporting a broad range of experimenter communities covering a wide variety of Internet infrastructures, services and applications. Fed4FIRE+ will continuously upgrade and improve the facilities and include technical innovations, focused towards increased user satisfaction (user-friendly tools, privacy-oriented data management, testbed SLA and reputation, experiment reproducibility, service-level experiment orchestration, federation ontologies, etc.). It will open this federation to the whole FIRE community and beyond, for experimentation by industry and research organisations, through the organization of Open Calls and Open Access mechanisms. The project will also establish a flexible, demand-driven framework which allows test facilities to join during the course of its lifetime by defining a set of entry requirements for new facilities to join and to comply with the federation. FIRE Experimental Facilities generate an ever increasing amount of research data that provides the foundation for new knowledge and insight into the behaviour of FI systems. Fed4FIRE+ will participate in the Pilot on Open Research Data in Horizon 2020 to offer open access to its scientific results, to the relevant scientific data and to data generated throughout the project's lifetime. Fed4FIRE+ will finally build on the existing community of experimenters, testbeds and tool developers and bring them together regularly (two times a year) in engineering conferences to have maximal interaction between the different stakeholders involved.

8.5. International Initiatives

8.5.1. Inria Associate Teams Involved in an Inria International Lab

8.5.1.1. DrIVE

Title: DrIVE: Distributed Intelligent Vehicular Environment - Enabling ITS through programmable networks

Inria International Lab: **Inria@SiliconValley**

International Partners (Institution - Laboratory - Researcher):

UniCamp (Brazil) - Department of Computer Engineering and Industrial Automation - Mateus Augusto Silva Santos

UNICAMP (Brazil) - Department of Computer Engineering and Industrial Automation - Christian Esteve Rothenberg

UC Santa Cruz (USA) - Department of Computer Science and Engineering- Katia Obraczka

Start year: 2018

See also: https://team.inria.fr/diana/drive-associated-team/

Transportation systems are part of our society's critical infrastructure and are expected to experience transformative changes as the Internet revolution unfolds. The automotive industry is a notable example: it has been undergoing disruptive transformations as vehicles transition from traditional unassisted driving to fully automated driving, and eventually to the self-driving model. Communication technology advancements such as support for vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication have been one of the key enablers of next generation transportation services, also known as Intelligent Transport Systems (ITS). However, ITS services and applications pose significant challenges to the underlying communication and network infrastructure due to their stringent low latency, reliability, scalability, and geographic decentralization requirements. The DrIVE associated team proposal aims at addressing such challenges by: (1) developing a programmable network control plane that will dynamically adjust to current environment conditions and network characteristics to support ITS' scalability, quality of service (QoS), and decentralization requirements, and (2) applying the proposed distributed network control plane framework to ITS applications, such as road hazard warning, autonomous- and self-driving vehicles, and passenger-centric services (e.g., infotainment and video streaming).

8.6. International Research Visitors

8.6.1. Visits of International Scientists

Mark Crovella, Professor at Boston University, visited us in March 2019 and gave a talk at Forum Numerica of Université Côte d'Azur. Mark is currently collaborating with Chadi Barakat on network-wide anomaly detection within the IPL BetterNet.

8.6.2. Internships

Houssam Elbouanani

Date: from March 2019 to August 2019

Institution: Ubinet Master 2 program at Université Côte D'Azur

Supervisors: Chadi Barakat and Guillaume Urvoy-Keller

Subject: Measurement as a Service in modern Data Centers

Anas Errahali

Date: from March 2019 to August 2019

Institution: Ubinet Master 2 program at Université Côte D'Azur

Supervisosr: Walid Dabbous and Thierry Turletti

Subject: Enhancing geolocation accuracy in LoRa Low Power Wide Area Networks

Youssef Rachid

Date: from March 2019 to August 2019

Institution: Ubinet Master 2 program at Université Côte D'Azur

Supervisor: Arnaud Legout

Subject: Exploring bias in the YouTube recommendation system.

Tareq Si Salem

Date: from March 2019 to August 2019

Institution: Ubinet Master 2 program at Université Côte D'Azur

Supervisor: Arnaud Legout

Subject: Identifying exposure profiles of Electrosmart users.

8.6.3. Visits to International Teams

Mohamed Naoufal Mahfoudi spent six months (october 2018, March 2019) PhD internship in University of California at San Diego in Professor Xinyu Zhang team. During this period he worked on a new passive localization system based on deep learning.

Tingting Yuan spent a 3-week visit at UNICAMP, Brazil, in the context of the DrIVE associated team (Oct 21 – Nov 8, 2019).

9. Dissemination

9.1. Promoting Scientific Activities

Chadi Barakat is on the editorial board of the Computer Networks journal, and was/is on the Technical Program Committee for the Network Traffic Measurement and Analysis Conference (2019 and 2020), the IEEE Symposium on Measurements and Networking M&N (2019), the International Conference on Network and Service Management (CNSM 2019) and the NetLearn Workshop (2020). He is currently in charge of international affairs at Inria Sophia Antipolis and is member of the COST-GTRI of Inria.

Walid Dabbous is member of the scientific committee of the DS4H Graduate school. He is also member of the Ubinet International Master program steering committee. He served as a Technical Program Committee member of the Artefact Evaluation Committee for the CoNext 2019 conference. He was member of the selection committee for the 2019 ACM SIGOPS France and GDR RSD thesis prize.

Arnaud Legout is the president of the Commission of the users of IT resources of Sophia Antipolis Inria research center.

Damien Saucez has co-chaired the ACM SIGCOMM *Artefact Evaluation Committee* whose role is to assess the reproducibility level of papers accepted to ACM SIGCOMM sponsored conferences and journals. He was TPC co-chair of the 2019 ACM Workshop on ns-3. He is regular reviewer for IEEE, ACM, Elsevier, and Springer journals.

Thierry Turletti, Senior ACM and IEEE member, served in 2019 in the program committees of the following international workshops and conferences: 2nd Workshop on Emerging Trends in Softwarized Networks (ETSN'19), Paris, France, June 28, 2019; 10th Workshop on ns-3, Mangalore, India, University of Florence, Italy, June 19-20 2019; 21st Algotel Conference, Narbonne, France, June 3-7, 2019; and VTC2019-Spring workshop, Kuala Lumpur, Malaysia, 28 April – 1 May 2019. Thierry Turletti is president of the Committee for Technological Development (CDT) and member of the committee NICE that studies postdoc and visiting researcher applications at Inria Sophia Antipolis. Thierry Turletti is member of the Editorial Boards of the Journal of Mobile Communication, Computation and Information (WINET) published by Springer Science and of the Advances in Multimedia Journal published by Hindawi Publishing Corporation.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master 2 Ubinet: Chadi Barakat and Walid Dabbous, Evolving Internet, 31.5 hours, M2, University of Nice-Sophia Antipolis, France.

Master Ubinet: Chadi Barakat and Walid Dabbous, Internet Measurements and New Architectures, 31.5 hours, M2, University of Nice-Sophia Antipolis, France.

Master 1 in Computer Science: Chadi Barakat, Computer Networks, 15 hours, M1, University of Nice Sophia Antipolis, France.

Master 1 in Computer Science: Chadi Barakat, Internet of the Future, 15 hours, M1, University of Nice Sophia Antipolis, France

Master Estel: Chadi Barakat, Voice over IP, 9 hours, University of Nice-Sophia Antipolis, France.

Master Ubinet: Arnaud Legout, From BitTorrent to Privacy, 36 hours, M2, University of Nice-Sophia Antipolis, France.

Master 1 in Computer Science: Arnaud Legout, Oral and written communications, 18 hours, M1, University of Nice-Sophia Antipolis, France.

Master IUP GMI: Damien Saucez, Security and privacy in networks, 38h, M2, University of Avignon, France.

E-learning

Python: Arnaud Legout and Thierry Parmentelat are co-authors of the MOOC Python 3 : "Python 3 : des fondamentaux aux concepts avancés du langage" that lasts 9 weeks on FUN (https://www.france-universite-numerique-mooc.fr/), UCA. For the second session there were 12748 registered persons. In total, this MOOC all on its editions has been followed by 57938 persons.

9.2.2. Supervision

PhD in progress: Othmane Belmoukadam works on “QoE aware content management in the Internet caching and transport”. He is supervised by Chadi Barakat and funded by the doctoral school EDSTIC of Université Côte d’Azur (UCA).

PhD in progress: Yanis Boussad works on “Large scale characterization of the exposition to microwaves”. He is co-supervised with Leonardo Lizzi, LEAT.

PhD in progress: Giuseppe Di Lena works on “Building a resilience methodology for NFV/SDN” in Apr 2018. His PhD is co-supervised by Thierry Turletti, Damien Saucez and Frédéric Giroire from the Coati project-team .

PhD started: Mamoutou Diarra started his PhD on “Multi-access Edge Computing” in november 2019. He is co-supervised by Thierry Turletti, Walid Dabbous and Amine Ismail from Ekinops.

PhD stopped: Thibaut Ehlinger stopped his PhD on “Mapping Quality of Service metrics to user Quality of Experience in the Internet” in April 2019. He was co-supervised by Chadi Barakat and Vassilis Christophides (EPI MiMove, Inria Paris).

PhD started: Houssam Elbouanani started his PhD on “Experiment control for reproducible research” in december 2019. He is co-supervised by Walid Dabbous, Chadi Barakat and Thierry Turletti.

PhD in progress: Iman Fouad started her PhD on on Web tracking technologies and privacy protection in november 2017. Her thesis is co-supervised by Arnaud Legout and Nataliia Bielova (Indes).

PhD: Karyna Gogunska defended her PhD thesis [11] entitled “Empowering Virtualized Networks with Measurement As a Service (MaaS)” in december 2019. Her thesis was co-supervised by Chadi Barakat and Guillaume Urvoy-Keller (I3S) and was funded by the Labex UCN@SOPHIA.

PhD: Muhammad Jawad Khokhar defended his PhD thesis [12] entitled “From Network Level Measurements to Expected Quality of User Experience” in october 2019. His PhD was supervised by Chadi Barakat and was funded by the ANR BottleNet project.

PhD: Mohamed Naoufal Mahfoudi defended his PhD thesis entitled [13] ”Unlocking Wireless Sensing Potential in Wi-Fi and IoT Networks” in ocotber 2019. His thesis was co-supervised by Walid Dabbous and Robert Staraj (LEAT) and was funded by the Labex UCN@SOPHIA.

PhD: Ghada Moualla defended her PhD thesis [14] entitled “Resilient Virtualized Network Functions for Data Centers and Decentralized Environments” in september 2019. Her thesis is co-supervised by Thierry Turletti and Damien Saucez and was funded by the ANR Reflexion project.

PhD in progress: Imane Taibi works on “Big data analysis for network monitoring and troubleshooting”. She is co-supervised by Gerardo Rubino, Yassine Hadjadj-Aoul from the Dionysos project-team and Chadi Barakat.

PhD in progress: Mathieu Thiery works on “Data protection of connected objects and smartphones” in April 2017. He is co-supervised by Vincent Roca from the Privatics project-team and Arnaud Legout.

PhD in progress: Thibaud Trolliet works on “Exploring trust on Twitter”. He is now fully supervised by Frederic Giroire and member of the Coati project team.

9.2.3. Juries

Chadi Barakat served as reviewer of Jingxiu SU PhD thesis, "Recherches sur la mesure de l’analyse du tracking sur le Web", defended in December 2019 at the University Grenoble Alpes and the Chinese Academy of Sciences.

Chadi Barakat served as examiner of Lakhdar Meftah PhD thesis, “Towards Privacy-sensitive Mobile Crowdsourcing”, defended in December 2019 at the University of Lille, France.

Chadi Barakat served as reviewer of Mariem Ben Yahia PhD thesis, “Low Latency Video Streaming Solutions based on HTTP/2”, defended in May 2019 at IMT-Atlantique, France.

Chadi Barakat served as reviewer of Hamza Ben Ammar PhD thesis, “On Models for Performance Evaluationand Cache Resources Placement in Multi-Cache Networks”, defended in May 2019 at the University of Rennes 1, France.

Chadi Barakat served as jury member for the mid-term review of the PhD thesis of Antoine Saverimoutou (Orange Labs) for his thesis entitled "Métrologie de l’Internet du futur: Nouvelles métriques et méthodes de mesure de la qualité de navigation Web" in March 2019.

Walid Dabbous wrote an examiner report on the thesis of Fangzhou Jiang entitled “Towards Characterizing and Exploiting Fine-grained User Behaviors in Mobile System” at the Univeristy of New South Wales.

Walid Dabbous served as reviewer of the PhD thesis of Kim-Hung LE “Mécanismes d’interopérabilité pour les applications industrielles de l’Internet des Objets et la Ville Intelligente”, defended on April 1, 2019 at Eurecom, France.

Walid Dabbous served as reviewer of the PhD thesis of Yoann Desmouceaux “Network-Layer Protocols for Data Center Scalability”, defended on April 10, 2019 at École Polytechnique, France.

Walid Dabbous served as a member of the recruitment committee for a Professor position at Sorbonne University in April 2019.

Thierry Turletti served as reviewer of Romuald Corbel PhD thesis “Évolution des protocoles de transport du point de vue de l’équité”, defended on December 4, 2019 at Université de Rennes 1, France.

Thierry Turletti served as reviewer of Géraldine Texier HDR “Vers un Internet programmable offrant des garanties de qualité de service”, defended on December 3, 2019 at Université de Rennes 1, France.

Thierry Turletti served as reviewer of Jean-Michel Sanner PhD thesis “Architecture du plan de contrôle SDN et placement des services réseaux dans les infrastructures des opérateurs”, defended on July 23, 2019 at Université de Rennes 1, France.

Thierry Turletti served as examiner of Andrea Tomassilli PhD thesis “Vers un Internet programmable offrant des garanties de qualité de service”, defended on June 24, 2019, at UCA, Sophia Antipolis, France.

9.3. Popularization

9.3.1. Internal or external Inria responsibilities

Damien Saucez is part of the MASTIC (https://project.inria.fr/mastic) group at Inria. MASTIC groups all the activities for scientific dissemination for Inria Sophia Antipolis.

9.3.2. Articles and contents

Walid Dabbous wrote an Interstices article [37] on the occasion of the 50^{th} anniversary of the Internet. The article recalls the story of the first France-ARPAnet connection that was established by Christian Huitema’s team in July 1988.

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Project-Team ECUADOR

Program transformations for scientific computing

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Numerical schemes and simulations

Table of contents

Project-Team ECUADOR

Creation of the Project-Team: 2014 January 01

Keywords:

Computer Science and Digital Science:

A2.1.1. - Semantics of programming languages
A2.2.1. - Static analysis
A2.5. - Software engineering
A6.1.1. - Continuous Modeling (PDE, ODE)
A6.2.6. - Optimization
A6.2.7. - High performance computing
A6.3.1. - Inverse problems
A6.3.2. - Data assimilation

Other Research Topics and Application Domains:

B1.1.2. - Molecular and cellular biology
B3.2. - Climate and meteorology
B3.3.2. - Water: sea & ocean, lake & river
B3.3.4. - Atmosphere
B5.2.3. - Aviation
B5.2.4. - Aerospace
B9.6.3. - Economy, Finance

1. Team, Visitors, External Collaborators

Research Scientists

Laurent Hascoët [Team leader, Inria, Senior Researcher, HDR]
Alain Dervieux [Inria, Emeritus, HDR]
Valérie Pascual [Inria, Researcher]

External Collaborator

Bruno Koobus [Univ Montpellier II (sciences et techniques du Languedoc)]

Administrative Assistant

Christine Claux [Inria, Administrative Assistant]

2. Overall Objectives

2.1. Overall Objectives

Team Ecuador studies Algorithmic Differentiation (AD) of computer programs, blending :

- **AD theory:** We study software engineering techniques, to analyze and transform programs mechanically. Algorithmic Differentiation (AD) transforms a program `P` that computes a function F, into a program `P'` that computes analytical derivatives of F. We put emphasis on the *adjoint mode* of AD, a sophisticated transformation that yields gradients for optimization at a remarkably low cost.
- **AD application to Scientific Computing:** We adapt the strategies of Scientific Computing to take full advantage of AD. We validate our work on real-size applications.

We aim to produce AD code that can compete with hand-written sensitivity and adjoint programs used in the industry. We implement our algorithms into the tool Tapenade, one of the most popular AD tools at present.

Our research directions :

- Efficient adjoint AD of frequent dialects e.g. Fixed-Point loops.
- Development of the adjoint AD model towards Dynamic Memory Management.
- Evolution of the adjoint AD model to keep in pace with with modern programming languages constructs.
- Optimal shape design and optimal control for steady and unsteady simulations. Higher-order derivatives for uncertainty quantification.
- Adjoint-driven mesh adaptation.

3. Research Program

3.1. Algorithmic Differentiation

Participants: Laurent Hascoët, Valérie Pascual.

algorithmic differentiation (AD, aka Automatic Differentiation) Transformation of a program, that returns a new program that computes derivatives of the initial program, i.e. some combination of the partial derivatives of the program's outputs with respect to its inputs.

adjoint Mathematical manipulation of the Partial Differential Equations that define a problem, obtaining new differential equations that define the gradient of the original problem's solution.

checkpointing General trade-off technique, used in adjoint AD, that trades duplicate execution of a part of the program to save some memory space that was used to save intermediate results.

Algorithmic Differentiation (AD) differentiates *programs*. The input of AD is a source program P that, given some $X \in \mathbb{R}^n$, returns some $Y = F(X) \in \mathbb{R}^m$, for a differentiable F. AD generates a new source program P' that, given X, computes some derivatives of F [4].

Any execution of P amounts to a sequence of instructions, which is identified with a composition of vector functions. Thus, if

$$\begin{array}{ccc} P & \text{runs} & \{I_1; I_2; \cdots I_p;\}, \\ F & \text{then is} & f_p \circ f_{p-1} \circ \cdots \circ f_1, \end{array} \tag{2}$$

where each f_k is the elementary function implemented by instruction I_k. AD applies the chain rule to obtain derivatives of F. Calling X_k the values of all variables after instruction I_k, i.e. $X_0 = X$ and $X_k = f_k(X_{k-1})$, the Jacobian of F is

$$F'(X) = f'_p(X_{p-1}) \,.\, f'_{p-1}(X_{p-2}) \,.\, \cdots \,.\, f'_1(X_0) \tag{3}$$

which can be mechanically written as a sequence of instructions I'_k. This can be generalized to higher level derivatives, Taylor series, etc. Combining the I'_k with the control of P yields P', and therefore this differentiation is piecewise.

The above computation of $F'(X)$, albeit simple and mechanical, can be prohibitively expensive on large codes. In practice, many applications only need cheaper projections of $F'(X)$ such as:

- **Sensitivities**, defined for a given direction $\dot{X}$ in the input space as:

$$F'(X).\dot{X} = f'_p(X_{p-1}) \,.\, f'_{p-1}(X_{p-2}) \,.\, \cdots \,.\, f'_1(X_0) \,.\, \dot{X} \quad . \tag{4}$$

This expression is easily computed from right to left, interleaved with the original program instructions. This is the *tangent mode* of AD.

- **Adjoints**, defined after transposition (F'^*), for a given weighting $\overline{Y}$ of the outputs as:

$$F'^*(X).\overline{Y} = f_1'^*(X_0).f_2'^*(X_1).\;\cdots\;.f_{p-1}'^*(X_{p-2}).f_p'^*(X_{p-1}).\overline{Y} \quad . \tag{5}$$

This expression is most efficiently computed from right to left, because matrix×vector products are cheaper than matrix×matrix products. This is the *adjoint mode* of AD, most effective for optimization, data assimilation [31], adjoint problems [25], or inverse problems.

Adjoint AD builds a very efficient program [27], which computes the gradient in a time independent from the number of parameters n. In contrast, computing the same gradient with the *tangent mode* would require running the tangent differentiated program n times.

However, the X_k are required in the *inverse* of their computation order. If the original program *overwrites* a part of X_k, the differentiated program must restore X_k before it is used by $f_{k+1}'^*(X_k)$. Therefore, the central research problem of adjoint AD is to make the X_k available in reverse order at the cheapest cost, using strategies that combine storage, repeated forward computation from available previous values, or even inverted computation from available later values.

Another research issue is to make the AD model cope with the constant evolution of modern language constructs. From the old days of Fortran77, novelties include pointers and dynamic allocation, modularity, structured data types, objects, vectorial notation and parallel programming. We keep developing our models and tools to handle these new constructs.

3.2. Static Analysis and Transformation of programs

Participants: Laurent Hascoët, Valérie Pascual.

abstract syntax tree Tree representation of a computer program, that keeps only the semantically significant information and abstracts away syntactic sugar such as indentation, parentheses, or separators.

control flow graph Representation of a procedure body as a directed graph, whose nodes, known as basic blocks, each contain a sequence of instructions and whose arrows represent all possible control jumps that can occur at run-time.

abstract interpretation Model that describes program static analysis as a special sort of execution, in which all branches of control switches are taken concurrently, and where computed values are replaced by abstract values from a given *semantic domain*. Each particular analysis gives birth to a specific semantic domain.

data flow analysis Program analysis that studies how a given property of variables evolves with execution of the program. Data Flow analysis is static, therefore studying all possible run-time behaviors and making conservative approximations. A typical data-flow analysis is to detect, at any location in the source program, whether a variable is initialized or not.

The most obvious example of a program transformation tool is certainly a compiler. Other examples are program translators, that go from one language or formalism to another, or optimizers, that transform a program to make it run better. AD is just one such transformation. These tools share the technological basis that lets them implement the sophisticated analyses [14] required. In particular there are common mathematical models to specify these analyses and analyze their properties.

An important principle is *abstraction*: the core of a compiler should not bother about syntactic details of the compiled program. The optimization and code generation phases must be independent from the particular input programming language. This is generally achieved using language-specific *front-ends*, language-independent *middle-ends*, and target-specific *back-ends*. In the middle-end, analysis can concentrate on the semantics of a reduced set of constructs. This analysis operates on an abstract representation of programs made of one *call graph*, whose nodes are themselves *flow graphs* whose nodes (*basic blocks*) contain abstract *syntax trees* for the individual atomic instructions. To each level are attached symbol tables, nested to capture scoping.

Static program analysis can be defined on this internal representation, which is largely language independent. The simplest analyses on trees can be specified with inference rules [18], [28], [15]. But many *data-flow analyses* are more complex, and better defined on graphs than on trees. Since both call graphs and flow graphs may be cyclic, these global analyses will be solved iteratively. *Abstract Interpretation* [19] is a theoretical framework to study complexity and termination of these analyses.

Data flow analyses must be carefully designed to avoid or control combinatorial explosion. At the call graph level, they can run bottom-up or top-down, and they yield more accurate results when they take into account the different call sites of each procedure, which is called *context sensitivity*. At the flow graph level, they can run forwards or backwards, and yield more accurate results when they take into account only the possible execution flows resulting from possible control, which is called *flow sensitivity*.

Even then, data flow analyses are limited, because they are static and thus have very little knowledge of actual run-time values. Far before reaching the very theoretical limit of *undecidability*, one reaches practical limitations to how much information one can infer from programs that use arrays [34], [20] or pointers. Therefore, conservative *over-approximations* must be made, leading to derivative code less efficient than ideal.

3.3. Algorithmic Differentiation and Scientific Computing

Participants: Alain Dervieux, Laurent Hascoët, Bruno Koobus, Eléonore Gauci, Emmanuelle Itam, Olivier Allain, Stephen Wornom.

linearization In Scientific Computing, the mathematical model often consists of Partial Differential Equations, that are discretized and then solved by a computer program. Linearization of these equations, or alternatively linearization of the computer program, predict the behavior of the model when small perturbations are applied. This is useful when the perturbations are effectively small, as in acoustics, or when one wants the sensitivity of the system with respect to one parameter, as in optimization.

adjoint state Consider a system of Partial Differential Equations that define some characteristics of a system with respect to some parameters. Consider one particular scalar characteristic. Its sensitivity (or gradient) with respect to the parameters can be defined by means of *adjoint* equations, deduced from the original equations through linearization and transposition. The solution of the adjoint equations is known as the adjoint state.

Scientific Computing provides reliable simulations of complex systems. For example it is possible to *simulate* the steady or unsteady 3D air flow around a plane that captures the physical phenomena of shocks and turbulence. Next comes *optimization*, one degree higher in complexity because it repeatedly simulates and applies gradient-based optimization steps until an optimum is reached. The next sophistication is *robustness*, that detects undesirable solutions which, although maybe optimal, are very sensitive to uncertainty on design parameters or on manufacturing tolerances. This makes second derivatives come into play. Similarly *Uncertainty Quantification* can use second derivatives to evaluate how uncertainty on the simulation inputs imply uncertainty on its outputs.

To obtain this gradient and possibly higher derivatives, we advocate adjoint AD (*cf*3.1) of the program that discretizes and solves the direct system. This gives the exact gradient of the discrete function computed by the program, which is quicker and more sound than differentiating the original mathematical equations [25]. Theoretical results [24] guarantee convergence of these derivatives when the direct program converges. This approach is highly mechanizable. However, it requires careful study and special developments of the AD model [29], [32] to master possibly heavy memory usage. Among these additional developments, we promote in particular specialized AD models for Fixed-Point iterations [26], [17], efficient adjoints for linear algebra operators such as solvers, or exploitation of parallel properties of the adjoint code.

4. Application Domains

4.1. Algorithmic Differentiation

Algorithmic Differentiation of programs gives sensitivities or gradients, useful for instance for :

- optimum shape design under constraints, multidisciplinary optimization, and more generally any algorithm based on local linearization,
- inverse problems, such as parameter estimation and in particular 4Dvar data assimilation in climate sciences (meteorology, oceanography),
- first-order linearization of complex systems, or higher-order simulations, yielding reduced models for simulation of complex systems around a given state,
- adaption of parameters for classification tools such as Machine Learning systems, in which Adjoint Differentiation is also known as *backpropagation*.
- mesh adaptation and mesh optimization with gradients or adjoints,
- equation solving with the Newton method,
- sensitivity analysis, propagation of truncation errors.

4.2. Multidisciplinary optimization

A CFD program computes the flow around a shape, starting from a number of inputs that define the shape and other parameters. On this flow one can define optimization criteria e.g. the lift of an aircraft. To optimize a criterion by a gradient descent, one needs the gradient of the criterion with respect to all inputs, and possibly additional gradients when there are constraints. Adjoint AD is the most efficient way to compute these gradients.

4.3. Inverse problems and Data Assimilation

Inverse problems aim at estimating the value of hidden parameters from other measurable values, that depend on the hidden parameters through a system of equations. For example, the hidden parameter might be the shape of the ocean floor, and the measurable values of the altitude and velocities of the surface. Figure 1 shows an example of an inverse problem using the glaciology code ALIF (a pure C version of ISSM [30]) and its AD-adjoint produced by Tapenade.

One particular case of inverse problems is *data assimilation* [31] in weather forecasting or in oceanography. The quality of the initial state of the simulation conditions the quality of the prediction. But this initial state is not well known. Only some measurements at arbitrary places and times are available. A good initial state is found by solving a least squares problem between the measurements and a guessed initial state which itself must verify the equations of meteorology. This boils down to solving an adjoint problem, which can be done though AD [33]. The special case of *4Dvar* data assimilation is particularly challenging. The 4^{th} dimension in “4D” is time, as available measurements are distributed over a given assimilation period. Therefore the least squares mechanism must be applied to a simulation over time that follows the time evolution model. This process gives a much better estimation of the initial state, because both position and time of measurements are taken into account. On the other hand, the adjoint problem involved is more complex, because it must run (backwards) over many time steps. This demanding application of AD justifies our efforts in reducing the runtime and memory costs of AD adjoint codes.

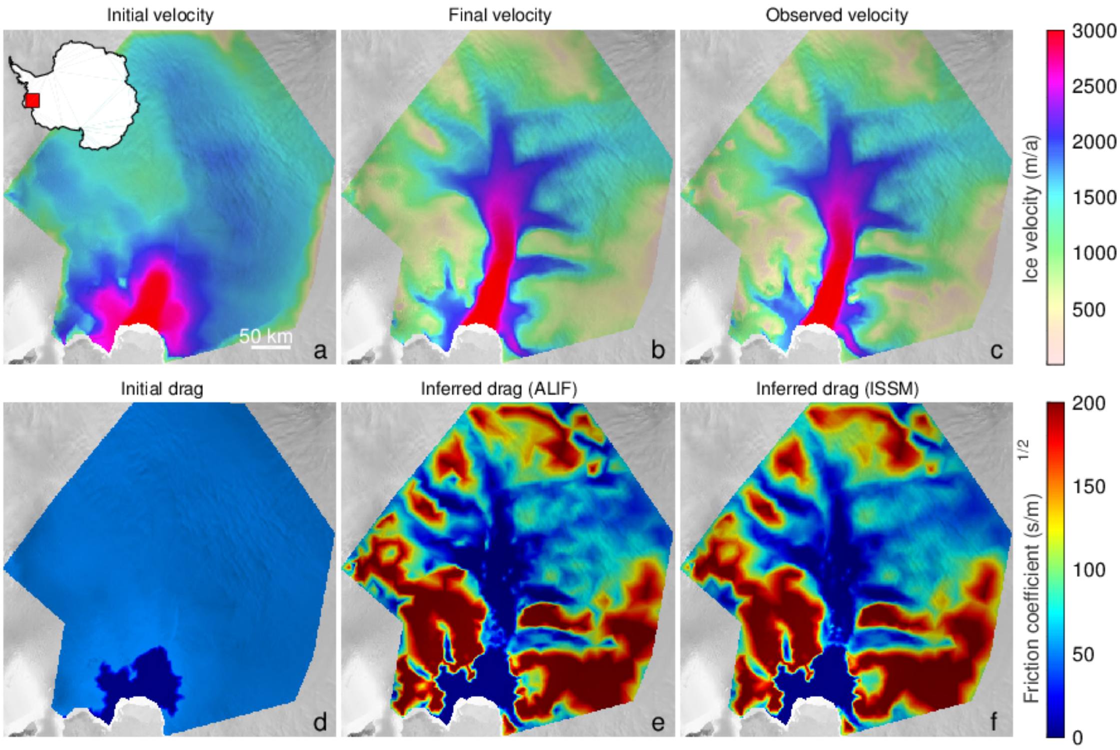

Figure 1. Assimilation of the basal friction under Pine Island glacier, West Antarctica. The final simulated surface velocity (b) is made to match the observed surface velocity (c), by estimation of the basal friction (e). A reference basal friction (f) is obtained by another data assimilation using the hand=written adjoint of ISSM

4.4. Linearization

Simulating a complex system often requires solving a system of Partial Differential Equations. This can be too expensive, in particular for real-time simulations. When one wants to simulate the reaction of this complex system to small perturbations around a fixed set of parameters, there is an efficient approximation: just suppose that the system is linear in a small neighborhood of the current set of parameters. The reaction of the system is thus approximated by a simple product of the variation of the parameters with the Jacobian matrix of the system. This Jacobian matrix can be obtained by AD. This is especially cheap when the Jacobian matrix is sparse. The simulation can be improved further by introducing higher-order derivatives, such as Taylor expansions, which can also be computed through AD. The result is often called a *reduced model*.

4.5. Mesh adaptation

Some approximation errors can be expressed by an adjoint state. Mesh adaptation can benefit from this. The classical optimization step can give an optimization direction not only for the control parameters, but also for the approximation parameters, and in particular the mesh geometry. The ultimate goal is to obtain optimal control parameters up to a precision prescribed in advance.

5. New Software and Platforms

5.1. AIRONUM

KEYWORDS: Computational Fluid Dynamics - Turbulence

FUNCTIONAL DESCRIPTION: Aironum is an experimental software that solves the unsteady compressible Navier-Stokes equations with k-epsilon, LES-VMS and hybrid turbulence modelling on parallel platforms, using MPI. The mesh model is unstructured tetrahedrization, with possible mesh motion.

- Participant: Alain Dervieux
- Contact: Alain Dervieux
- URL: http://www-sop.inria.fr/tropics/aironum

5.2. TAPENADE

KEYWORDS: Static analysis - Optimization - Compilation - Gradients

SCIENTIFIC DESCRIPTION: Tapenade implements the results of our research about models and static analyses for AD. Tapenade can be downloaded and installed on most architectures. Alternatively, it can be used as a web server. Higher-order derivatives can be obtained through repeated application.

Tapenade performs sophisticated data-flow analysis, flow-sensitive and context-sensitive, on the complete source program to produce an efficient differentiated code. Analyses include Type-Checking, Read-Write analysis, and Pointer analysis. AD-specific analyses include the so-called Activity analysis, Adjoint Liveness analysis, and TBR analysis.

FUNCTIONAL DESCRIPTION: Tapenade is an Algorithmic Differentiation tool that transforms an original program into a new program that computes derivatives of the original program. Algorithmic Differentiation produces analytical derivatives, that are exact up to machine precision. Adjoint-mode AD can compute gradients at a cost which is independent from the number of input variables. Tapenade accepts source programs written in Fortran77, Fortran90, or C. It provides differentiation in the following modes: tangent, vector tangent, adjoint, and vector adjoint.

NEWS OF THE YEAR: - Continued development of multi-language capacity: AD of codes mixing Fortran and C - Continued front-end for C++ (using Clang-LLVM) - Preliminary work, including refactoring, in view of future Open-Source distribution

- Participants: Laurent Hascoët and Valérie Pascual
- Contact: Laurent Hascoët
- URL: http://www-sop.inria.fr/tropics/tapenade.html

6. New Results

6.1. Towards Algorithmic Differentiation of C++

Participants: Laurent Hascoët, Valérie Pascual, Frederic Cazals [ABS team, Inria Sophia-Antipolis].

Our goal is to extend Tapenade for C++. We further developed our external parser for C++, built on top of Clang-LLVM https://clang.llvm.org/. This parser is now connected to the input formalism "IL" of Tapenade. Tapenade now manages enough constructs of Object languages to be able to build its own Internal Representation (IR) and to regenerate back from the IR a non-transformed C++ source.

In the present development stage, this back-and-forth chain works on several small C++ codes. Still, many issues remain on the large example provided by the ABS team. We are working to solve those progressively. The lack of serious development documentation on the Clang internals obviously doesn't help.

The next development stage will be to adapt the analysis and differentiation components of Tapenade to the new Object constructs of the IR. This development has not started yet. Upstream this development, we need to devise an extended AD model correspondingly. This research part is in progress.

6.2. AD of mixed-language codes

Participants: Valérie Pascual, Laurent Hascoët.

We extend Tapenade to differentiate codes that mix different languages, for both tangent and adjoint modes of AD. Our motivating application is Calculix, a 3-D Structural Finite Element code that mixes Fortran and C. This year we improved the memory representation of Tapenade's IR to handle the C-Fortran memory correspondence (commons, structs...) defined by the Fortran standard.

C files (aka "translation units") and Fortran modules are two instances of the more general notion of "package" for which we have developed a unified representation in Tapenade, that also handles C++ namespaces.

6.3. Application to large industrial codes

Participants: Valérie Pascual, Laurent Hascoët, Bruno Maugars [ONERA], Sébastien Bourasseau [ONERA], Cédric Content [ONERA], Jose I. Cardesa [IMFT], Christophe Airiau [IMFT].

We support industrial users with their first experiments of Algorithmic Differentiation of large in-house codes. This concerned two industrial codes this year.

One application is with ONERA on their ElsA CFD platform (Fortran 90). This is the continuation of a collaboration started in 2018. Both tangent and adjoint models of the kernel of ElsA were built successfully with Tapenade. This year's work was mostly about improving efficiency. It is worth noticing that this application was performed inside ONERA by ONERA engineers (Bruno Maugars, Sébastien Bourasseau, Cédric Content) with no need for installation of ElsA inside Inria. We take this as a sign of maturity of Tapenade. Our contribution is driven by development meetings, in which we point out some strategies and tool options to improve efficiency of the adjoint code. As a result from these discussions, we developed improved strategies and AD model, that will be useful to other tools. These improvements deal mostly with the adjoint of vectorized code. We prepared together an aticle that describes the architecture of a modular and AD-friendly ElsA, together with the corresponding extensions of the AD model of Tapenade. This article has been submitted to "Computers and Fluids".

The other application ultimately targets AD of the “Jaguar” code, developed jointly by ONERA, CERFACS, and IMFT in Toulouse. This is a collaboration with Jose I. Cardesa and Christophe Airiau, both at IMFT. After a relatively easy tangent differentiation, most of the effort was devoted to obtaining a running and efficient adjoint code. Not too surprisingly, the main source of trouble was the Message-Passing parallel aspect on the application code. This underlined a lack of debugging support for adjoint-differentiated code. Given the run-time of the simulation that we consider (from hours to a few days on a 4110 processors platform), efficiency is crucial. We used the optimal binomial checkpointing scheme at the time-stepping level. However, performance of the adjoint code can probably be improved further with a better checkpointing scheme on the call tree. This calls in particular for AD-specific performance profiling tools, that we are planning to develop. We prepared together an article that describes this succesful experiment, which is now submitted to “Journal of Computational Science”.

Two collaborations are in preparation for next year, one with Jan Hueckelheim at Argonne National Lab. about SIMD parallel codes, and one with Stefano Carli at KU Leuven about adjoint AD of the plasma code SOLPS-ITER.

6.4. Control of approximation errors

Participants: Alain Dervieux, Loic Frazza [Gamma3 team, Inria-Saclay], Adrien Loseille [Gamma3 team, Inria-Saclay], Frédéric Alauzet [Gamma3 team, Inria-Saclay], Anca Belme [university of Paris 6], Alexandre Carabias [Lemma].

Reducing approximation errors as much as possible is a particular kind of optimal control problem. We formulate it exactly this way when we look for the optimal metric of the mesh, which minimizes a user-specified functional (goal-oriented mesh adaptation). In that case, the usual methods of optimal control apply, using adjoint states that can be produced by Algorithmic Differentiation.

This year, we published the final revised versions of two conference papers [23], [21], we published in a journal the final version of the adjoint-based mesh adaptation for Navier-Stokes flows [16]), and we published in “Numerical Methods in Fluids” a work on nonlinear correctors extending [22]. Let us also mention the final publication of the book “Uncertainty Management for Robust Industrial Design in Aeronautics”, edited by C. Hirsch et al. in the Springer series Notes on Numerical Fluid Mechanics and Multidisciplinary Design (2019) in which we have contributed chapters 20, 21, 45, and 48.

The monography on mesh adaptation currently being written by Alauzet, Loseille, Koobus and Dervieux now involves all its chapters (14 chapters) and is being finalized.

6.5. Turbulence models

Participants: Alain Dervieux, Bruno Koobus, Stephen Wornom.

Modeling turbulence is an essential aspect of CFD. The purpose of our work in hybrid RANS/LES (Reynolds Averaged Navier-Stokes / Large Eddy Simulation) is to develop new approaches for industrial applications of LES-based analyses. In the applications targetted (aeronautics, hydraulics), the Reynolds number can be as high as several tens of millions, far too high for pure LES models. However, certain regions in the flow can be predicted better with LES than with usual statistical RANS models. These are mainly vortical separated regions as assumed in one of the most popular hybrid models, the hybrid Detached Eddy Simulation (DES) model. Here, “hybrid” means that a blending is applied between LES and RANS. An important difference between a real life flow and a wind tunnel or basin is that the turbulence of the flow upstream of each body is not well known.

The development of hybrid models, in particular DES in the litterature, has raised the question of the domain of validity of these models. According to theory, these models should not be applied to flow involving laminar boundary layers (BL). But industrial flows are complex flows and often present regions of laminar BL, regions of fully developed turbulent BL and regions of non-equilibrium vortical BL. It is then mandatory for industrial use that the new hybrid models give a reasonable prediction for all these types of flow. We concentrated on evaluating the behavior of hybrid models for laminar BL and for vortical wakes. While less predictive than pure LES on laminar BL, some hybrid models still give reasonable predictions for rather low Reynolds numbers.

We have developed a new model relying on the hybridation of a DES model based on a k-ϵ closure with our dynamic VMS model [13] [11]. Our purpose is to propose a model rather predictive in condition where the engineer has not much information concerning the turbulence in the flow under study. This year, we continued to improve this model and to test it for a large set of configurations with Reynolds numbers ranging from low (laminar flows) to very large.

6.6. High order approximations

Participants: Alain Dervieux, Bruno Koobus, Stephen Wornom, Tanya Kozubskaya [Keldysh Institute of Russian Academy].

High order approximations for compressible flows on unstructured meshes are facing many constraints that increase their complexity i.e. their computational cost. This is clear for the largest class of approximation, the class of k-exact schemes, which rely on a local polynomial representation of degree k. We are investigating schemes which would solve as efficiently as possible the dilemma of choosing between an approximation with a representation inside macro-elements which finally constrains the mesh, and a representation around each individual cell, as in vertex formulations. This is a cooperation with the Keldysh Institute of Russian Academy which whom we have already developed several families of superconvergent schemes.

6.7. Aeroacoustics

Participants: Alain Dervieux, Bruno Koobus, Stephen Wornom, Tanya Kozubskaya [Keldysh Institute of Russian Academy].

The progress in highly accurate schemes for compressible flows on unstructured meshes (together with advances in massive parallelization of these schemes) allows us to solve problems previously out of reach. The three teams of Montpellier university (coordinator), Inria-Sophia and Keldysh Institute of Moscow have written a proposal for cooperation on the subject of the extension of these methods to simulate the noise emission of rotating machines (helicopters, future aerial vehicles, unmanned aerial vehicles, wind turbines...). The proposal has been selected by ANR and RSF (Russian Science Foundation) for support for a program duration of 4 years.

7. Dissemination

7.1. Promoting Scientific Activities

7.1.1. Scientific Events: Organisation

7.1.1.1. Member of the organizing committees

- Laurent Hascoët is on the organizing commitee of the EuroAD Workshops on Algorithmic Differentiation (http://www.autodiff.org).
- Laurent Hascoët was on the organizing and program committees of the workshop "Program Transformations for Machine Learning" at NeurIPS2019, Vancouver Canada, December 14th.

7.1.2. Invited Talks

Laurent Hascoët was invited to give a talk on AD for the "GdR Calcul", at "Institut de Physique du Globe", Paris, January 24th.

7.1.3. Scientific Expertise

Alain Dervieux is Scientific Director for the LEMMA company.

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Project-Team EPIONE

E-Patient: Images, Data & MOdels for e-MediciNE

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Computational Neuroscience and Medicine

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Project-Team EPIONE

Creation of the Team: 2018 January 01, updated into Project-Team: 2018 May 01

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A5.2. - Data visualization
A5.3. - Image processing and analysis
A5.4. - Computer vision
A5.6. - Virtual reality, augmented reality
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Other Research Topics and Application Domains:

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B2.6.1. - Brain imaging
B2.6.2. - Cardiac imaging
B2.6.3. - Biological Imaging

1. Team, Visitors, External Collaborators

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2. Overall Objectives

2.1. Description

Our long-term goal is to contribute to the development of what we call the e-patient (digital patient) for e-medicine (digital medicine).

- the e-patient (or digital patient) is a set of computational models of the human body able to describe and simulate the anatomy and the physiology of the patient's organs and tissues, at various scales, for an individual or a population. The e-patient can be seen as a framework to integrate and analyze in a coherent manner the heterogeneous information measured on the patient from disparate sources: imaging, biological, clinical, sensors, ...
- e-medicine (or digital medicine) is defined as the computational tools applied to the e-patient to assist the physician and the surgeon in their medical practice, to assess the diagnosis/prognosis, and to plan, control and evaluate the therapy.

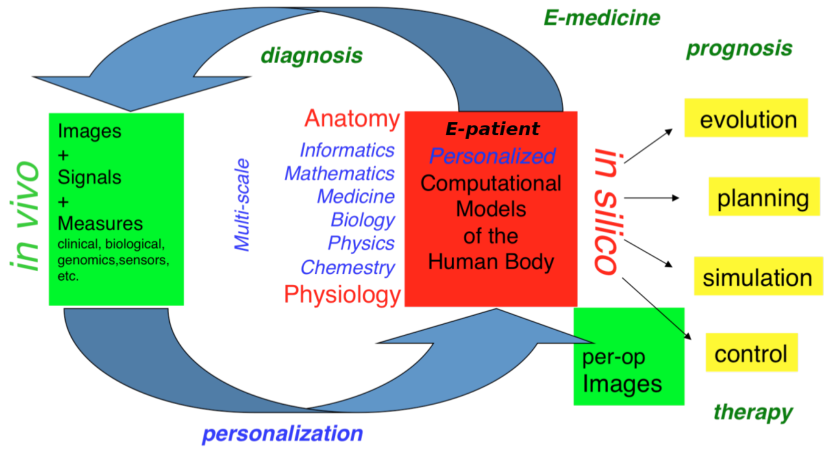

Figure 1. The e-patient for e-medicine

The models that govern the algorithms designed for e-patients and e-medicine come from various disciplines: computer science, mathematics, medicine, statistics, physics, biology, chemistry, etc. The parameters of those models must be adjusted to an individual or a population based on the available images, signals and data. This adjustment is called personalization and usually requires solving difficult inverse problems. The overall picture of the construction of the personalized e-patient for e-medicine was presented at the College de France through an inaugural lecture and a series of courses and seminars (fr), concluded by an international workshop.

2.1.1. Organisation

The research organization in our field is often built on a virtuous triangle. On one vertex, academic research requires multidisciplinary collaborations associating informatics and mathematics to other disciplines: medicine, biology, physics, chemistry ... On a second vertex, a clinical partnership is required to help defining pertinent questions, to get access to clinical data, and to clinically evaluate any proposed solution. On the third vertex, an industrial partnership can be introduced for the research activity itself, and also to transform any proposed solution into a validated product that can ultimately be transferred to the clinical sites for an effective use on the patients.

Keeping this triangle in mind, we choose our research directions within a virtuous circle: we look at difficult problems raised by our clinical or industrial partners, and then try to identify some classes of generic fundamental/theoretical problems associated to their resolution. We also study some fundamental/theoretical problems per se in order to produce fundamental scientific advances that can help in turn to promote new applications.

3. Research Program

3.1. Introduction

Our research objectives are organized along 5 scientific axes:

1. Biomedical Image Analysis & Machine Learning
2. Imaging & Phenomics, Biostatistics
3. Computational Anatomy, Geometric Statistics
4. Computational Physiology & Image-Guided Therapy
5. Computational Cardiology & Image-Based Cardiac Interventions

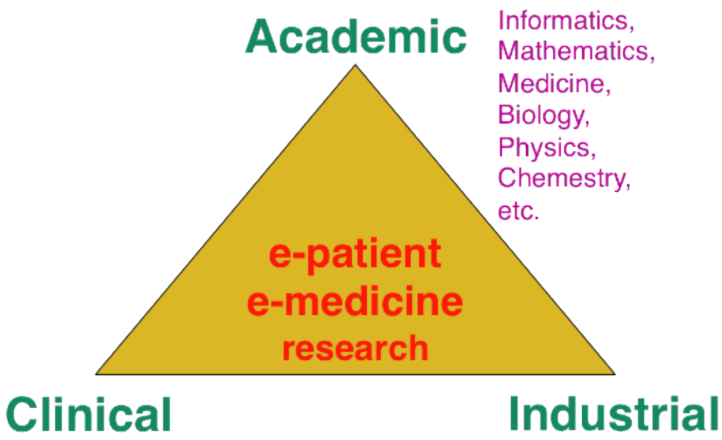

Figure 2. A pluridisciplinary research triangle

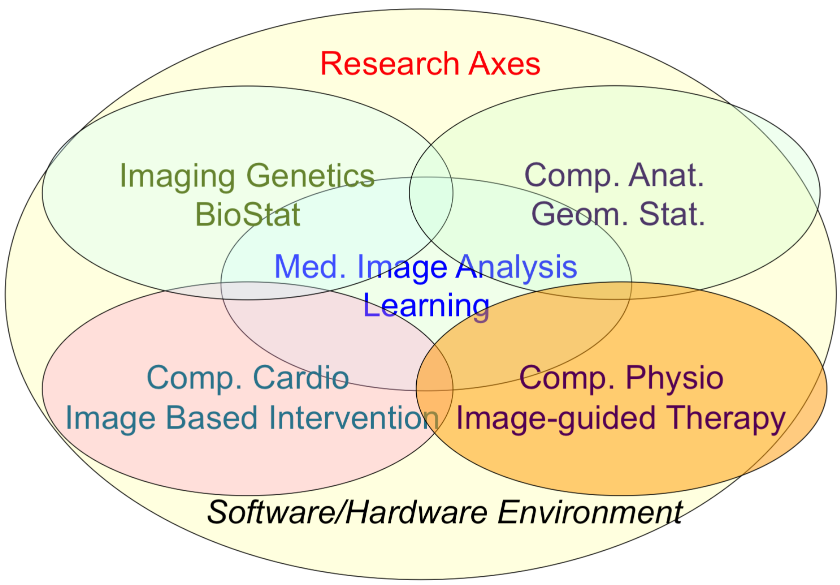

Figure 3. Epione's five main research axes

For each scientific axis, we introduce the context and the long term vision of our research.

3.2. Biomedical Image Analysis & Machine Learning

The long-term objective of biomedical image analysis is to extract, from biomedical images, pertinent information for the construction of the e-patient and for the development of e-medicine. This relates to the development of advanced segmentation and registration of images, the extraction of image biomarkers of pathologies, the detection and classification of image abnormalities, the construction of temporal models of motion or evolution from time-series of images, etc.

A good illustration of the current state of the art and of the remaining challenges can be found in these recent publications which address for instance the extraction of quantitative biomarkers on static or time varying images, as well as image registration and deformation analysis problems. This also applies to the analysis of microscopic and multi-scale images.

In addition, the growing availability of very large databases of biomedical images, the growing power of computers and the progress of machine learning (ML) approaches have opened up new opportunities for biomedical image analysis.

This is the reason why we decided to revisit a number of biomedical image analysis problems with ML approaches, including segmentation and registration problems, automatic detection of abnormalities, prediction of a missing imaging modality, etc. Not only those ML approaches often outperform the previous state-of-the-art solutions in terms of performances (accuracy of the results, computing times), but they also tend to offer a higher flexibility like the possibility to be transferred from one problem to another one with a similar framework. However, even when successful, ML approaches tend to suffer from a lack of explanatory power, which is particularly annoying for medical applications. We also plan to work on methods that can interpret the results of the ML algorithms that we develop.

- **Revisiting Segmentation problems with Machine Learning:** Through a partnership with Microsoft Research in Cambridge (UK), we are studying new segmentation methods based on deep learning with *weakly annotated* data. In effect, a complete segmentation ground truth is costly to collect in medical image analysis, as it requires the tedious task of contouring regions of interest and their validation by an expert. On the other hand, the label "presence" or "absence" of a lesion for instance (weak annotation) can be obtained at a much lower cost.

  We also plan to explore the application of deep learning methods to the fast segmentation of static or deformable organs. For instance we plan to use deep learning methods for the 3D consistent segmentation of the myocardium tissue of the 2 cardiac ventricles, an important preliminary step to mesh the cardiac muscle for computational anatomy, physiology and cardiology projects.
- **Revisiting Registration problems with Machine Learning:** We are studying, through a partnership with Siemens (Princeton), the possibility to apply robust non-rigid registration through agent-based action learning. We propose a decision process where the objective simplifies to iteratively finding the strategically next best step. An artificial agent is driven to solve the task of non-rigid registration through exploring the parametric space of a statistical deformation model built from training data. Since it is difficult to extract trustworthy ground-truth deformation fields we propose a training scheme with synthetically deformed cases and few real inter-subject cases.
- **Prediction of an imaging modality from other imaging modalities with machine learning:** Through a partnership with the Brain and Stem Institute in Paris, we plan to develop deep learning approaches to quantify some brain alterations currently measured by an invasive nuclear medicine imaging modality (PET imaging with specific tracers), directly from a multi-sequence acquisition of a non-invasive imaging modality (MRI). This requires innovative approaches taking into account the relatively small size of the ground truth database (patients having undergone both PET and MR Image acquisitions) and exploiting the a priori knowledge on the brain anatomy. We believe that this approach could apply to other image prediction problems in the longer term.

- **Prediction of cardiac pathologies with machine learning and image simulation:** Following the important work on cardiac image simulation done during the ERC project MedYMA, we are currently able to simulate time-series of images of various cardiac pathologies for which we can vary the parameters of a generative electro-mechanical model. We plan to develop new deep learning methods exploiting both the *shape* and *motion* phenotypes present in the time-series of images to detect and characterize a number of cardiac pathologies, including subtle assynchronies, local ischemia or infarcts.
- **Measuring Brain, Cognition, Behaviour:** We developed a collaborative project MNC3 which is supported by the excellence initiative Idex UCA^{Jedi}. This project gathers partners from Inria, Nice Hospitals (physicians), Nice University, and IPMC (biologists). The goal is to provide a joint analysis of heterogenous data collected on patients with neurological and psychiatric diseases. Those data include medical imaging (mainly MRI), activity (measured by connected wrists or video or microphones), biology/genomics, and clinical information. We want to show the increase in the statistical power of a joint analysis of the data to classify a pathology and to quantify its evolution.

In addition to these mid-term goals, we have applied to two important projects with local clinicians. A project on "Lung cancer", headed by anatomopathologist P. Hofman, to better exploit the joint information coming from imaging and circulating tumoral cells (in collaboration with Median Tech company); and a project "Cluster headache", headed by neurosurgeon D. Fontaine, to better integrate and exploit information coming from imaging, genetics and clinic (in collaboration with Inria Team Athena).

3.3. Imaging & Phenomics, Biostatistics

The human phenotype is associated with a multitude of heterogeneous biomarkers quantified by imaging, clinical and biological measurements, reflecting the biological and patho-physiological processes governing the human body, and essentially linked to the underlying individual genotype.In order to deepen our understanding of these complex relationships and better identify pathological traits in individuals and clinical groups, a long-term objective of e-medicine is therefore to develop the tools for the joint analysis of this heterogeneous information, termed *Phenomics*, within the unified modeling setting of the e-patient.

Ongoing research efforts aim at investigating optimal approaches at the crossroad between biomedical imaging and bioinformatics to exploit this diverse information. This is an exciting and promising research avenue, fostered by the recent availability of large amounts of data from joint imaging and biological studies (such as the UK biobank [0], ENIGMA [0], ADNI [0],...). However, we currently face important methodological challenges, which limit the ability in detecting and understanding meaningful associations between phenotype and biological information.

To date the most common approach to the analysis of the joint variation between the structure and function of organs represented in medical images, and the classical -omics modalities from biology, such as genomics or lipidomics, is essentially based on the massive univariate statistical testing of single candidate features out of the many available. This is for example the case of genome-wide association studies (GWAS) aimed at identifying statistically significant effects in pools consisting of up to millions of genetics variants. Such approaches have known limitations such as multiple comparison problems, leading to underpowered discoveries of significant associations, and usually explain a rather limited amount of data variance. Although more sophisticated machine learning approaches have been proposed, the reliability and generalization of multivariate methods is currently hampered by the low sample size relatively to the usually large dimension of the parameters space.

To address these issues this research axis investigates novel methods for the integration of this heterogeneous information within a parsimonious and unified multivariate modeling framework. The cornerstone of the project consists in achieving an optimal trade-off between modeling flexibility and ability to generalize

[0]http://www.ukbiobank.ac.uk/
[0]http://enigma.ini.usc.edu/.
[0]http://adni.loni.usc.edu/

on unseen data by developing statistical learning methods informed by prior information, either inspired by "mechanistic" biological processes, or accounting for specific signal properties (such as the structured information from spatio-temporal image time series). Finally, particular attention will be paid to the effective exploitation of the methods in the growing Big Data scenario, either in the meta-analysis context, or for the application in large datasets and biobanks.

- **Modeling associations between imaging, clinical, and biological data.** The essential aspect of this research axis concerns the study of data regularization strategies encoding prior knowledge, for the identification of meaningful associations between biological information and imaging phenotype data. This knowledge can be represented by specific biological mechanisms, such as the complex non-local correlation patterns of the -omics encoded in genes pathways, or by known spatio-temporal relationship of the data (such as time series of biological measurements or images). This axis is based on the interaction with research partners in clinics and biology, such as IPMC (CNRS, France), the Lenval Children's Hospital (France), and University College London (UK). This kind of prior information can be used for defining scalable and parsimonious probabilistic regression models. For example, it can provide relational graphs of data interactions that can be modelled by means of Bayesian priors, or can motivate dimensionality reduction techniques and sparse frameworks to limit the effective size of the parameter space. Concerning the clinical application, an important avenue of research will come from the study of the *reduced* representations of the -omics data currently available in clinics, by focusing on the modeling of the disease variants reported in previous genetic findings. The combination of this kind of data with the information routinely available to clinicians, such as medical images and memory tests, has a great potential for leading to improved diagnostic instruments. The translation of this research into clinical practice is carried out thanks to the ongoing collaboration with primary clinical partners such as the University Hospital of Nice (MNC3 partner, France), the Dementia Research Centre of UCL (UK), and the Geneva University Hospital (CH).
- **Learning from collections of biomedical databases.** The current research scenario is characterised by medium/small scale (typically from 50 to 1000 patients) heterogeneous datasets distributed across centres and countries. The straightforward extension of learning algorithms successfully applied to big data problems is therefore difficult, and specific strategies need to be envisioned in order to optimally exploit the available information. To address this problem, we focus on learning approaches to jointly model clinical data localized in different centres. This is an important issue emerging from recent large-scale multi-centric imaging-genetics studies in which partners can only share model parameters (e.g. regression coefficients between specific genes and imaging features), as represented for example by the ENIGMA imaging-genetics study, led by the collaborators at University of Southern California. This problem requires the development of statistical methods for *federated* model estimation, in order to access data hosted in different clinical institutions by simply transmitting the model parameters, that will be in turn updated by using the local available data. This approach is extended to the definition of stochastic optimization strategies in which model parameters are optimized on local datasets, and then summarized in a meta-analysis context. Finally, this project studies strategies for aggregating the information from heterogeneous datasets, accounting for missing modalities due to different study design and protocols. The developed methodology finds important applications within the context of Big Data, for the development of effective learning strategies for massive datasets in the context of medical imaging (such as with the UK biobank), and beyond.

3.4. Computational Anatomy, Geometric Statistics

Computational anatomy is an emerging discipline at the interface of geometry, statistics and image analysis which aims at developing algorithms to model and analyze the biological shape of tissues and organs. The goal is not only to establish generative models of organ anatomies across diseases, populations, species or ages but also to model the organ development across time (growth or aging) and to estimate their variability and link to other functional, genetic or structural information. Computational anatomy is a key component to support computational physiology and is evidently crucial for building the e-patient and to support e-medicine.

Pivotal applications include the spatial normalization of subjects in neuroscience (mapping all the anatomies into a common reference system) and atlas to patient registration to map generic knowledge to patient-specific data. Our objectives will be to develop new efficient algorithmic methods to address the emerging challenges described below and to generate precise specific anatomical model in particular for the brain and the heart, but also other organs and structures (e.g. auditory system, lungs, breasts, etc.).

The objects of computational anatomy are often shapes extracted from images or images of labels (segmentation). The observed organ images can also be modeled using registration as the random diffeomorphic deformation of an unknown template (i.e. an orbit).In these cases as in many other applications, invariance properties lead us to consider that these objects belong to non-linear spaces that have a geometric structure. Thus, the mathematical foundations of computational anatomy rely on statistics on non-linear spaces.

- **Geometric Statistics** aim at studying this abstracted problem at the theoretical level. Our goal is to advance the fundamental knowledge in this area, with potential applications to new areas outside of medical imaging. Several challenges which constitute shorter term objectives in this direction are described below.
- **Large databases and longitudinal evolution:** The emergence of larger databases of anatomical images (ADNI, UK biobank) and the increasing availability of temporal evolution drives the need for efficient and scalable statistical techniques. A key issue is to understand how to construct hierarchical models in a non-linear setting.
- **Non-parametric models of variability:** Despite important successes, anatomical data also tend to exhibit a larger variability than what can be modeled with a standard multivariate unimodal Gaussian model. This raises the need for new statistical models to describe the anatomical variability like Bayesian statistics or sample-based statistical model like multi-atlas and archetypal techniques. A second objective is thus to develop efficient algorithmic methods for encoding the statistical variability into models.
- **Intelligible reduced-order models:** Last but not least, these statistical models should live in low dimensional spaces with parameters that can be interpreted by clinicians. This requires of course dimension reduction and variable selection techniques. In this process, it is also fundamental to align the selected variable to a dictionary of clinically meaningful terms (an ontology), so that the statistical model can not only be used to predict but also to explain.

3.4.1. Geometric Statistics

- **Foundations of statistical estimation on geometric spaces:** Beyond the now classical Riemannian spaces, this axis will develop the foundations of statistical estimation on affine connection spaces (e.g. Lie groups), quotient and stratified metric spaces (e.g. orbifolds and tree spaces). In addition to the curvature, one of the key problem is the introduction of singularities at the boundary of the regular strata (non-smooth and non-convex analysis).
- **Parametric and non-parametric dimension reduction methods in non-linear spaces:** The goal is to extend what is currently done with the Fréchet mean (i.e. a 0-dimensional approximation space) to higher dimensional subspaces and finally to a complete hierarchy of embedded subspaces (flags) that iteratively model the data with more and more precision. The Barycentric Subspace Analysis (BSA) generalization of principal component analysis which was recently proposed in the team will of course be a tool of choice for that. In this process, a key issue is to estimate efficiently not only the model parameters (mean point, subspace, flag) but also their uncertainty. Here, we want to quantify the influence of curvature and singularities on non-asymptotic estimation theory since we always have a finite (and often too limited) number of samples. As the mean is generally not unique in curved spaces, this also leads to consider that the results of estimation procedures should be changed from points to singular distributions. A key challenge in developing such a geometrization of statistics will not only be to unify the theory for the different geometric structures, but also to provide efficient practical algorithms to implement them.

- **Learning the geometry from the data:** Data can be efficiently approximated with locally Euclidean spaces when they are very finely sampled with respect to the curvature (big data setting). In the high dimensional low sample size (small data) setting, we believe that invariance properties are essential to reasonably interpolate and approximate. New apparently antagonistic notions like approximate invariance could be the key to this interaction between geometry and learning.

  Beyond the traditional statistical survey of the anatomical shapes that is developed in computational anatomy above, we intend to explore other application fields exhibiting geometric but non-medical data. For instance, applications can be found in Brain-Computer Interfaces (BCI), tree-spaces in phylogenetics, Quantum Physics, etc.

3.5. Computational Physiology & Image-Guided Therapy

Computational Physiology aims at developing computational models of human organ *functions*, an important component of the e-patient, with applications in e-medicine and more specifically in computer-aided prevention, diagnosis, therapy planning and therapy guidance. The focus of our research is on *descriptive* (allowing to reproduce available observations), *discriminative* (allowing to separate two populations), and above all *predictive models* which can be personalized from patient data including medical images, biosignals, biological information and other available metadata. A key aspect of this scientific axis is therefore the coupling of biophysical models with patient data which implies that we are mostly considering models with relatively few and identifiable parameters. To this end, *data assimilation* methods aiming at estimating biophysical model parameters in order to reproduce available patient data are preferably developed as they potentially lead to predictive models suitable for therapy planning.

Previous research projects in computational physiology have led us to develop biomechanical models representing quasi-static small or large soft tissue deformations (e.g. liver or breast deformation after surgery), mechanical growth or atrophy models (e.g. simulating brain atrophy related to neurodegenerative diseases), heat transfer models (e.g. simulating radiofrequency ablation of tumors), and tumor growth models (e.g. brain or lung tumor growth).

To improve the data assimilation of biophysical models from patient data, a long term objective of our research will be to develop *joint imaging and biophysical generative models in a probabilistic framework* which simultaneously describe the appearance and function of an organ (or its pathologies) in medical images. Indeed, current approaches for the personalization of biophysical models often proceed in two separate steps. In a first stage, geometric, kinematic or/ functional features are first extracted from medical images. In a second stage, they are used by personalization methods to optimize model parameters in order to match the extracted features. In this process, subtle information present in the image which could be informative for biophysical models is often lost which may lead to limited personalization results. Instead, we propose to develop more integrative approaches where the extraction of image features would be performed jointly with the model parameter fitting. Those imaging and biophysical generative models should lead to a *better understanding* of the content of images, to a *better personalization* of model parameters and also *better estimates of their uncertainty*.

This improved coupling between images and model should *help solving various practical problems* driven by clinical applications. Depending on available resources, datasets, and clinical problems, we wish to develop a new expertise for the simulation of *tissue perfusion* (e.g. to capture the uptake of contrast agent or radioactive tracers), or *blood flow in medium / small vessels* (e.g. to capture the transport of drugs or radioactive materials in interventional radiology).

- **Reduced Computational Biophysical Models**. Clinical constraint and uncertainty estimation inevitably lead to the requirement of relatively fast computation of biophysical models. In addition to hardware acceleration (GPU, multithreading) we will explore various ways to accelerate the computation of models through intrusive (e.g. proper orthogonal decomposition, computation of condensed stiffness matrices in non-linear mechanics) or non intrusive methods (e.g. polynomial chaos expansion, Gaussian processes).

- **Uncertainty estimation of Biophysical Models**. We will pursue our research on this topic by developing Bayesian methods to estimate the posterior probability of model parameters, initial and boundary conditions from image features or image voxels. Such approaches rely on the definition of relevant likelihood terms relating the model state variables to the observable quantities in images. When possible joint imaging and biophysical generative models will be developed to avoid to rely on intermediate image features. Approximate inference of uncertainty will be estimated through Variational Bayes approaches whose accuracy will be evaluated through a comparison with stochastic sampling methods (e.g. MCMC). Through this uncertainty estimation, we also aim at developing a reliable framework to select the most sensitive and discriminative parameters of a given model but also to select the biophysical model best suited to solve a given problem (e.g. prediction of therapy outcome).
- **High Order Finite Element Modeling**. Soft tissue biomechanical models have until now been formulated as linear elastic or hyperelastic materials discretized as linear tetrahedra finite elements. While being very generic, those elements are known to suffer from numerical locking for nearly incompressible materials and lead to poor estimate of stress field. We will develop efficient implementation and assembly methods using high order tetrahedral (and possibly hexahedral) elements. To maintain the number of nodes relatively low while keeping a good accuracy, we intend to develop elements of adaptive degree (p-refinement) driven by local error indices. Solution for meshing surfaces or volumes with curved high order elements will be developed in collaboration with the Titane and Aromath Inria teams.
- **Clinical Applications**. We plan to develop new applications of therapy planning and therapy guidance through existing or emerging collaborations related to the following problems : breast reconstruction following insertion of breast implants (with Anatoscope), planning of cochlear electrodes implantation (with CHU Nice and Oticon Medical), lung deformation following COPD or pulmonary fibrosis (with CHU Nice), echography based elastometry (with CHU Nice).

3.6. Computational Cardiology & Image-Based Cardiac Interventions

Computational Cardiology has been an active research topic within the Computational Anatomy and Computational Physiology axes of the previous Asclepios project, leading to the development of personalized computational models of the heart designed to help characterizing the cardiac function and predict the effect of some device therapies like cardiac resynchronisation or tissue ablation. This axis of research has now gained a lot of maturity and a critical mass of involved scientists to justify an individualized research axis of the new project Epione, while maintaining many constructive interactions with the 4 other research axes of the project. This will develop all the cardiovascular aspects of the e-patient for cardiac e-medicine.

The new challenges we want to address in computational cardiology are related to the introduction of new levels of modeling and to new clinical and biological applications. They also integrate the presence of new sources of measurements and the potential access to very large multimodal databases of images and measurements at various spatial and temporal scales.

Our goal will be to combine two complementary computational approaches: *machine learning* and *biophysical modelling*. This research axis will leverage on the added value of such a combination. Also we will refine our biophysical modeling by the introduction of a pharmacokinetics/pharmacodynamics (PK/PD) component able to describe the effect of a drug on the cardiac function. This will come in complement to the current geometric, electrical, mechanical and hemodynamic components of our biophysical model of the heart. We will also carefully model the uncertainty in our modeling, and try to provide algorithms fast enough to allow future clinical translation.

- Physics of Ultrasound Images for Probe Design: we will design a digital phantom of the human torso in order to help the design of echocardiographic probes. This will be done in collaboration with GE Healthcare whose excellence centre for cardiac ultrasound probes is located in Sophia Antipolis.

- Cardiac Pharmacodynamics for Drug Personalisation: we will add to our biophysical cardiac model a pharmacodynamics model, coupled with a pharmacokinetics model and a personalisation framework in order to help the adjustment of drug therapy to a given patient. This will be done in collaboration with ExactCure, a start up company specialised on this topic.
- New Imaging Modality Coupling MRI and Electrodes: we will use our fast models in order to regularize the ill-posed inverse problem of cardiac electrocardiography in order to estimate cardiac electrical activity from body surface potentials. This will be done within the ERC Starting Grant ECSTATIC coordinated by Hubert Cochet from the IHU Liryc, Bordeaux.
- Cardiac Imaging during Exercise: a particular aspect of the cardiac function is its constant adaptation to satisfy the needs of the human body. This dynamic aspect provides important information on the cardiac function but is challenging to measure. We will set up exercise protocols with Nice University Hospital and STAPS in order to model and quantify such an adaptation of the cardiac function.
- Sudden Cardiac Death is the cause of important mortality (300 000 per year in Europe, same in US) and it is difficult to identify people at risk. Based on a large multi-centric database of images, we will learn the image features correlated with a high risk of arrhythmia, with the IHU Liryc.
- Personalising models from connected objects: with the Internet of Things and the pletora of sensors available today, the cardiac function can be monitored almost continuously. Such new data open up possibilities for novel methods and tools for diagnosis, prognosis and therapy.

4. Highlights of the Year

4.1. Highlights of the Year

4.1.1. Awards

- Nicholas Ayache, Hervé Delingette, Marco Lorenzi, Xavier Pennec, and Maxime Sermesant were awarded a chair at the institute *3IA Côte d'Azur* focused on artificial intelligence.
- Hervé Delingette was elected a Fellow of MICCAI society at MICCAI 2019 : http://www.miccai.org/about-miccai/miccai-fellows/
- Julian Krebs received the Best Presenter Award at the workshop STACOM for his presentation of the paper
- Marco Lorenzi was awarded a Contrat jeune chercheur by the National Research Agency (ANR) for his Fed-BioMed project.
- Sara Garbarino was awarded the IPMI 2019 Erbsmann Award for her paper entitled "Modeling and inference of spatio-temporal protein dynamics across brain networks".
- Nicholas Ayache was awarded the Grand Prize of the City of Nice by the Mayor of Nice, at the Villa Masséna, on May 24, 2019.
- Maxime Sermesant received the Innovator of the Year Award by CentraleSupelec on January 21st, 2019.
- Yann Thanwerdas was nominated among the 5 running papers for the best paper award at the Geometric Sciences of Information conference GSI' 2019 at ENAC in Toulouse.

4.1.2. Dissemination

- Publication of the book *Riemannian Geometric Statistics in Medical Image Analysis* [53] edited by Xavier Pennec, Stefan Sommer and Tom Fletcher, 3rd volume of "The Elsevier and MICCAI Society book series". The book contains 5 introductory chapters on the methodological foundations by Xavier Pennec, Tom Fletcher, Stefan Sommer, Stephen Marsland and Marco Lorenzi, and 11 contributed chapters on applications, including a chapter by Nina Miolane, Loic Devillier and Xavier Pennec.

- Publication of the book *Voir l'invisible - Tome 2, Comprendre, Agir* by the Collectif Amir with Maxime Sermesant as one of the scientific contributors. The second version of the book informs the public reader of the latest innovations in science and technology from different fields.
- Organization of the scientific program of the conference "The Academie des sciences in Nice and Sophia Antipolis" by N. Ayache in June 20-21, 2019.

BEST PAPERS AWARDS :

[40]
J. KREBS, T. MANSI, N. AYACHE, H. DELINGETTE.*Probabilistic Motion Modeling from Medical Image Sequences: Application to Cardiac Cine-MRI*, in "STACOM 2019 - 10th Workshop on Statistical Atlases and Computational Modelling of the Heart", Shenzhen, China, October 2019, https://arxiv.org/abs/1907.13524 - Probabilistic Motion Model, Motion Tracking, Temporal Super-Resolution, Diffeomorphic Registration, Temporal Variational Autoencoder, https://hal.inria.fr/hal-02239318

[48]
S. GARBARINO, M. LORENZI.*Modeling and Inference of Spatio-Temporal Protein Dynamics Across Brain Networks*, in "IPMI 2019 - 26th International Conference on Information Processing in Medical Imaging", Hong-Kong, China, LNCS, Springer, 2019, vol. 11492, p. 57-69, https://hal.inria.fr/hal-02165021

5. New Software and Platforms

5.1. CardiacSegmentationPropagation

KEYWORDS: 3D - Segmentation - Cardiac - MRI - Deep learning

FUNCTIONAL DESCRIPTION: Training of a deep learning model which is used for cardiac segmentation in short-axis MRI image stacks.

- Authors: Qiao Zheng, Hervé Delingette, Nicolas Duchateau and Nicholas Ayache
- Contact: Qiao Zheng
- Publication: 3D Consistent & Robust Segmentation of Cardiac Images by Deep Learning with Spatial Propagation

5.2. CardiacMotionFlow

KEYWORDS: 3D - Deep learning - Cardiac - Classification

FUNCTIONAL DESCRIPTION: Creation of a deep learning model for the motion tracking of the heart, extraction of characteristic quantities of the movement and shape of the heart to classify a sequence of cine-MRI cardiac images in terms of the types of pathologies (infarcted heart, dilated , hypertrophied, abnormality of the right ventricle).

- Contact: Qiao Zheng

5.3. MedInria

KEYWORDS: Visualization - DWI - Health - Segmentation - Medical imaging

SCIENTIFIC DESCRIPTION: MedInria aims at creating an easily extensible platform for the distribution of research algorithms developed at Inria for medical image processing. This project has been funded by the D2T (ADT MedInria-NT) in 2010, renewed in 2012. A fast-track ADT was awarded in 2017 to transition the software core to more recent dependencies and study the possibility of a consortium creation.The Empenn team leads this Inria national project and participates in the development of the common core architecture and features of the software as well as in the development of specific plugins for the team's algorithm.

FUNCTIONAL DESCRIPTION: MedInria is a free software platform dedicated to medical data visualization and processing.

- Participants: Maxime Sermesant, Olivier Commowick and Théodore Papadopoulo
- Partners: HARVARD Medical School - IHU - LIRYC - NIH
- Contact: Olivier Commowick
- URL: https://med.inria.fr

5.4. GP-ProgressionModel

GP progression model

KEYWORDS: Data modeling - Data visualization - Data integration - Machine learning - Biostatistics - Statistical modeling - Medical applications - Evolution - Brain - Uncertainly - Uncertainty quantification - Alzheimer's disease - Probability - Stochastic models - Stochastic process - Trajectory Modeling - Marker selection - Health - Statistic analysis - Statistics - Bayesian estimation

FUNCTIONAL DESCRIPTION: Disease progression modeling (DPM) of Alzheimer's disease (AD) aims at revealing long term pathological trajectories from short term clinical data. Along with the ability of providing a data-driven description of the natural evolution of the pathology, DPM has the potential of representing a valuable clinical instrument for automatic diagnosis, by explicitly describing the biomarker transition from normal to pathological stages along the disease time axis.

In this software we reformulate DPM within a probabilistic setting to quantify the diagnostic uncertainty of individual disease severity in an hypothetical clinical scenario, with respect to missing measurements, biomarkers, and follow-up information. The proposed formulation of DPM provides a statistical reference for the accurate probabilistic assessment of the pathological stage of de-novo individuals, and represents a valuable instrument for quantifying the variability and the diagnostic value of biomarkers across disease stages.

This software is based on the publication:

Probabilistic disease progression modeling to characterize diagnostic uncertainty: Application to staging and prediction in Alzheimer's disease. Marco Lorenzi, Maurizio Filippone, Daniel C. Alexander, Sebastien Ourselin Neuroimage. 2019 Apr 15,190:56-68. doi: 10.1016/j.neuroimage.2017.08.059. Epub 2017 Oct 24. HAL Id : hal-01617750 https://hal.archives-ouvertes.fr/hal-01617750/

RELEASE FUNCTIONAL DESCRIPTION: - New interface and output - Completely based on pytorch

- Participant: Marco Lorenzi
- Contact: Marco Lorenzi
- Publication: Probabilistic disease progression modeling to characterize diagnostic uncertainty: application to staging and prediction in Alzheimer's disease
- URL: http://gpprogressionmodel.inria.fr

5.5. Music

Multi-modality Platform for Specific Imaging in Cardiology

KEYWORDS: Medical imaging - Cardiac Electrophysiology - Computer-assisted surgery - Cardiac - Health

FUNCTIONAL DESCRIPTION: MUSIC is a software developed by the Asclepios research project in close collaboration with the IHU LIRYC in order to propose functionalities dedicated to cardiac interventional planning and guidance. This includes specific tools (algorithms of segmentation, registration, etc.) as well as pipelines. The software is based on the MedInria platform.

- Participants: Florent Collot, Mathilde Merle and Maxime Sermesant
- Partner: IHU- Bordeau
- Contact: Maxime Sermesant
- URL: https://team.inria.fr/asclepios/software/music/

5.6. SOFA

Simulation Open Framework Architecture

KEYWORDS: Real time - Multi-physics simulation - Medical applications

FUNCTIONAL DESCRIPTION: SOFA is an Open Source framework primarily targeted at real-time simulation, with an emphasis on medical simulation. It is mostly intended for the research community to help develop new algorithms, but can also be used as an efficient prototyping tool. Based on an advanced software architecture, it allows : the creation of complex and evolving simulations by combining new algorithms with algorithms already included in SOFA, the modification of most parameters of the simulation (deformable behavior, surface representation, solver, constraints, collision algorithm, etc.) by simply editing an XML file, the building of complex models from simpler ones using a scene-graph description, the efficient simulation of the dynamics of interacting objects using abstract equation solvers, the reuse and easy comparison of a variety of available methods.

- Participants: Christian Duriez, François Faure, Hervé Delingette and Stéphane Cotin
- Partner: IGG
- Contact: Hugo Talbot
- URL: http://www.sofa-framework.org

5.7. geomstats

Computations and statistics on manifolds with geometric structures

KEYWORD: Geometry

FUNCTIONAL DESCRIPTION: Geomstats is a python package that performs computations on manifolds such as hyperspheres, hyperbolic spaces, spaces of symmetric positive definite matrices and Lie groups of transformations. It provides efficient and extensively unit-tested implementations of these manifolds, together with useful Riemannian metrics and associated Exponential and Logarithm maps. The corresponding geodesic distances provide a range of intuitive choices of Machine Learning loss functions. We also give the corresponding Riemannian gradients. The operations implemented in geomstats are available with different computing backends such as numpy, tensorflow and keras. Geomstats manifold computations have are integrated into keras deep learning framework thanks to GPU-enabled implementations.

- Partner: Stanford Department of Statistics
- Contact: Nina Miolane
- URL: https://github.com/geomstats/

5.8. MC-VAE

Multi Channel Variational Autoencoder

KEYWORDS: Machine learning - Artificial intelligence - Medical applications - Dimensionality reduction - High Dimensional Data - Unsupervised learning - Heterogeneity

SCIENTIFIC DESCRIPTION: Interpretable modeling of heterogeneous data channels is essential in medical applications, for example when jointly analyzing clinical scores and medical images. Variational Autoencoders (VAE) are powerful generative models that learn representations of complex data. The flexibility of VAE may come at the expense of lack of interpretability in describing the joint relationship between heterogeneous data. To tackle this problem, in this work we extend the variational framework of VAE to bring parsimony and interpretability when jointly account for latent relationships across multiple channels. In the latent space, this is achieved by constraining the variational distribution of each channel to a common target prior. Parsimonious latent representations are enforced by variational dropout. Experiments on synthetic data show that our model correctly identifies the prescribed latent dimensions and data relationships across multiple testing scenarios. When applied to imaging and clinical data, our method allows to identify the joint effect of age and pathology in describing clinical condition in a large scale clinical cohort.

FUNCTIONAL DESCRIPTION: This software implements the work published in the paper "Sparse Multi-Channel Variational Autoencoder for the Joint Analysis of Heterogeneous Data" presented at the conference ICML 2019 (Long Beach, California, USA).

The software extends classical variational autoencoders by identifying a joint latent code associated to heterogeneous data represented in different channels. The software is implemented in python and is based on pytorch. It can be applied to any kind of data arrays, and provides functions for optimisation, visualisation and writing of the modelling results.

RELEASE FUNCTIONAL DESCRIPTION: First release

NEWS OF THE YEAR: Method presented in the International Conference on Machine Learning (ICML 2019).

- Participants: Luigi Antelmi, Marco Lorenzi and Nicholas Ayache
- Partner: CoBteK
- Contact: Luigi Antelmi
- URL: https://gitlab.inria.fr/epione_ML/mcvae

5.9. SOFA-CardiacReduction

KEYWORDS: Simulation - 3D modeling - Model Order Reduction - Cardiac

SCIENTIFIC DESCRIPTION: Modification of a finite element deformation model : meshless approach and frame-based description, reduction in the number of affine degrees of freedom and integration points.

FUNCTIONAL DESCRIPTION: This SOFA plugin is intented to build a reduced model for deformable solids (especially cardiac simulations).

- Participants: Gaetan Desrues, Hervé Delingette and Maxime Sermesant
- Contact: Gaetan Desrues

6. New Results

6.1. Medical Image Analysis

6.1.1. Learning a Probabilistic Model for Diffeomorphic Registration and Motion Modeling

Participants: Julian Krebs [Correspondant], Hervé Delingette, Tommaso Mansi [Siemens Healthineers, Princeton, NJ, USA], Nicholas Ayache.

This work is funded by Siemens Healthineers, Princeton, NJ, USA

deformable registration, probabilistic motion modeling, artificial intelligence, latent variable model, deformation transport

We developed a probabilistic approach for multi-scale deformable image registration in 3-D using conditional variational autoencoder [16], [58] and extended it to a motion model by using cardiac MRI image sequences [40]. This includes:

- A probabilistic formulation of the registration problem through unsupervised learning of an encoded deformation model.
- A generative motion model using explicit time-dependent temporal convolutional networks (Fig. 4).
- Demonstration on cardiac cine-MRI for cardiac motion tracking, simulation, transport and temporal super-resolution.

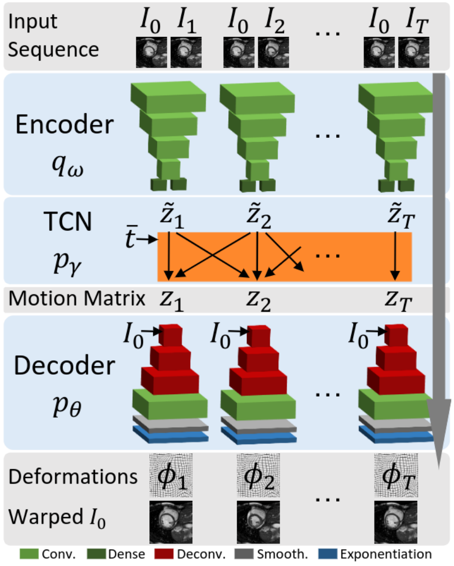

Figure 4. Probabilistic motion model: the encoder q_ω projects the image pair (I_0, I_t) to a probabilistic low-dimensional deformation encoding $\tilde{z}_t$ from which the temporal convolutional network p_γ constructs the motion matrix $z \in \mathbb{R}^{d \times T}$. The decoder p_θ maps the motion matrix to the deformations ϕ_t.

6.1.2. Predicting PET-derived demyelination from multimodal MRI using sketcher-refiner adversarial training for multiple sclerosis

Participants: Wen Wei [Correspondent], Nicholas Ayache, Olivier Colliot [ARAMIS].

This work is done in collaboration with the Aramis-Project team of Inria in Paris and the researchers at the Brain and Spinal Cord Institute (ICM) located in Paris.

Multiple Sclerosis, MRI, PET, GANs

By using multiparametric MRI, we proposed to use a 3D FCNN to predict FLAIR MRI which is used clinically for the detection of WM lesions [26]. In addition, we proposed Sketcher-Refiner GANs to predict PET-derived demyelination from multiparametric MRI [25] with the following contributions:

- Learning the complex relationship between myelin content and multimodal MRI data;
- Comparing quantitatively our approach to other state-of-the-art techniques;
- Proposing visual attention saliency maps to better interpret the neural networks;
- Comparing different combinations of MRI modalities and features to assess which is the optimal input;

6.1.3. Patch Based Bayesian Mesh Registration

Participants: Paul Blanc-Durand [Correspondant], Hervé Delingette.

A 1 year grant from APHP

Bayesian Modeling, Mesh deformation, Mechanical model

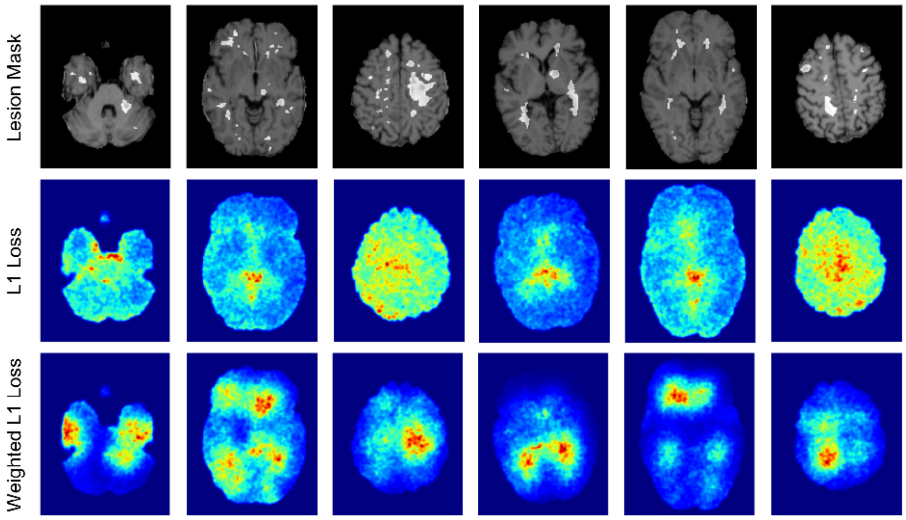

Figure 5. The proposed visual attention saliency map. The white regions shown in first row are MS lesion masks. The second row shows some examples of the attention of neural networks when L1 loss is used as the traditional constraint in the loss function, without the specific weighting scheme that we proposed. The third row shows the corresponding attention of neural networks when our proposed weighted L1 loss is applied. It is clear that our designed loss function is able to effectively shift the attention of neural networks towards MS lesions.

The objective of this work is to co-register two lung CT scans of the same patient acquired at different breathing cycle based on an elastic and Bayesian model of lung deformation. Its originality stems from the joint estimation of a displacement fields and its derivatives (gradient matrix) defined from a tetrahedral mesh. Inference is performed in two alternating steps including the optimization of local affine transforms and the global optimiztion of the displacement.

6.2. Imaging & Phenomics, Biostatistics

6.2.1. Statistical learning on large databases of heterogeneous imaging, cognitive and behavioral data

Participants: Luigi Antelmi [Correspondent], Nicholas Ayache, Philippe Robert, Marco Lorenzi.

Supported by the French government, through the UCA^{JEDI} Investments in the Future project managed by the National Research Agency (ANR) ref. num. ANR-15-IDEX-01, our research is within the MNC3 initiative (Médecine Numérique: Cerveau, Cognition, Comportement), in collaboration with the Institut Claude Pompidou (CHU of Nice). Computational facilities are funded by the grant AAP Santé 06 2017-260 DGA-DSH, and by the Inria Sophia Antipolis - Méditerranée, "NEF" computation cluster.

statistical learning, joint analysis, neuroimaging

The aim of our work is to build scalable learning models for the joint analysis of heterogeneous biomedical data, to be applied to the investigation of neurological and neuropsychiatric disorders from collections of brain imaging, body sensors, biological and clinical data available in current large-scale databases such as ADNI[0] and local clinical cohorts.

[0] http://adni.loni.usc.edu/

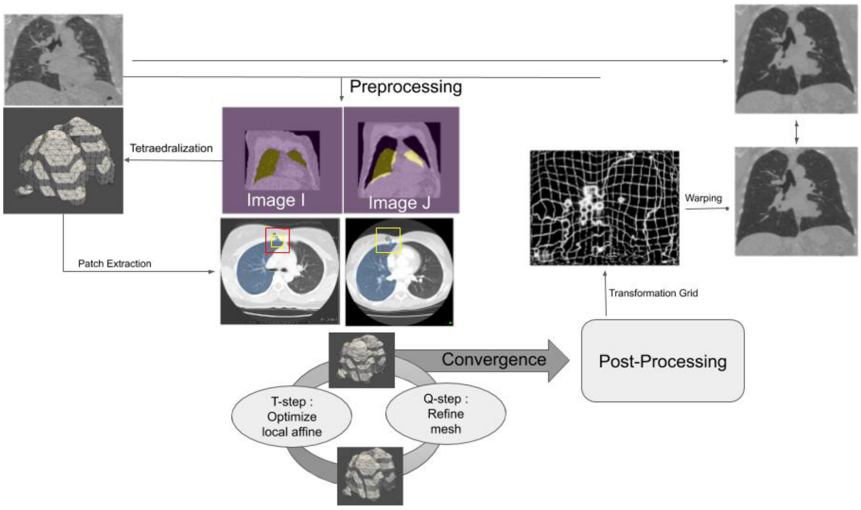

Figure 6. Patches are extracted around vertices of mesh. During T-step, we aim to optimize an affine transform centered on a vertice of image I (the moving image) to image J (the fixed image). The affine transform is regularized under a probabilistic model taking into account the deformation of the mesh. During Q-step, we developed an elastical model of lung which homogenize predictions. After few epochs, convergence is achieved.

We developed a probabilistic latent variable model able to account for heterogeneous data modalities jointly [6]. In the latent space, this is achieved by constraining the variational distribution of each modality to a common target prior. Moreover, we added *ad hoc* prior distribution and parameterization for the latent space to induce sparsity (Fig. 7a). This approach is capable to highlight meaningful relationships among biomarkers in the context of Alzheimer's disease (Fig. 7b) that can be used to develop optimal strategies for disease quantification and prediction.

6.2.2. Joint Biological & Imaging markers for the Diagnosis of severe lung diseases

Participants: Benoit Audelan [Correspondant], Hervé Delingette, Nicholas Ayache.

Lung cancer, Early detection, Biomarkers, Segmentation quality control

Lung cancer is among the most common cancer and is considered to be one of the most important public health problem. In recent years, immunotherapy has revolutionized cancer treatments but its efficiency is varying among patients. To prevent possible negative side effects there is a critical need in reliable biomarkers capable of predicting the response to immunotherapy treatments. We analyzed the performance of different biomarkers and studied their combination through logistic regression and decision tree models, as part of a joint project with the IRCAN laboratory (Pr P. Hofman, Dr S. Heeke) at Nice hospital [13].

Furthermore, we investigated the issue of automated quality control assessment of image segmentations, which are a key point of medical image processing pipelines. We propose a novel unsupervised quality control approach based on simple intensity and smoothness assumptions [30]. We introduce a novel spatial prior which allows an automatic estimation of all parameters through Bayesian learning. The approach was tested on various medical imaging datasets (Fig. 8).

6.2.3. Modelling and inference of protein dynamics in neurodegenerative diseases across brain networks

Participants: Sara Garbarino [Correspondant], Marco Lorenzi.

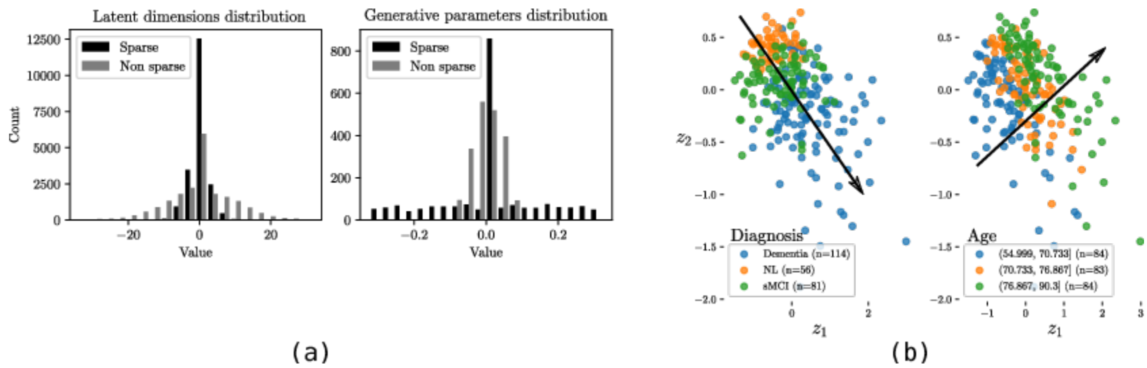

Figure 7. (a) Effect of variational dropout on a synthetic experiment modeled with the Multi-Channel VAE. As expected, the minimum amount of non-zero components of the latent variables (left) and generative parameters (right) is obtained with the sparse model. (b) Stratification of the ADNI subjects (test data) in the sparse latent space. In the same space it is possible to stratify subjects in the test-set by disease status (left) and by age (right) in almost orthogonal directions.

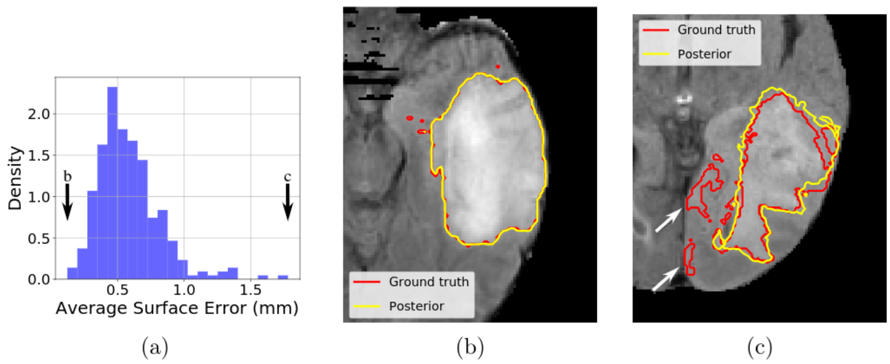

Figure 8. Unsupervised quality control of the BRATS 2017 challenge training set. Distribution of the Average Surface Error (a). Example of a segmentation explained by the model (b). Example of a segmentation not explained by the model (c).

Sara Garbarino acknowledges financial support from the French government managed by L'Agence Nationale de la Recherche under Investissements d'Avenir UCA JEDI (ANR-15-IDEX-01) through the project "AtroPro-Dem: A data-driven model of mechanistic brain Atrophy Propagation in Dementia".

Gaussian Processes, Bayesian non–parametric modelling, neuroimaging data, protein dynamics, brain network

In this project we propose the first unified framework for the joint estimation of long term neurodegenerative disease progression and kinetic parameters describing pathological protein dynamics across brain networks [48]. The model is expressed within a constrained Gaussian Process regression setting. We use stochastic variational inference for scalable inference and uncertainty quantification. Experiments on simulated data and on AV45-PET brain imaging data measuring topographic amyloid deposition in Alzheimer's disease show that our model accurately recovers prescribed rates along graph dynamics and precisely reconstructs the underlying progression.

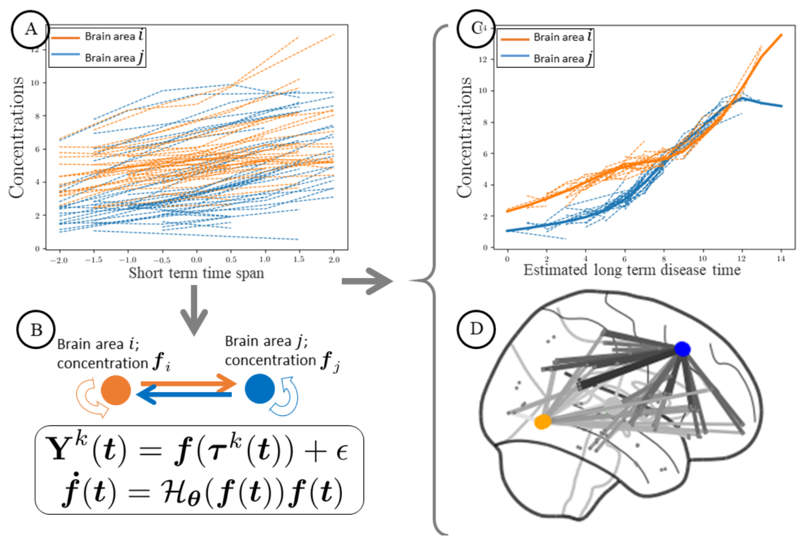

Figure 9. Schematic representation of the proposed framework. Regional protein concentrations are collected for a number of subjects over a short term time span (A). The dynamics of such concentrations are described in terms of a dynamical system for the vector of concentrations (B). The proposed framework estimates such parameters encoding the strength of propagation (D) and the long term protein concentrations with respect to the estimated long term time axis (C).

6.3. Computational Anatomy & Geometric Statistics

6.3.1. Riemannian Geometric Statistics in Medical Image Analysis

Participants: Xavier Pennec [Correspondant], Stefan Sommer [CPH Univ, DK], Tom Fletcher [University of Virginia at Charlottesville, USA].

This work is partially funded by the ERC-Adv G-Statistics

Geometric statistics, Riemannian geometry, medical image analysis, computational anatomy

There has been a growing need in the medical image computing community for principled methods to process nonlinear geometric data. Riemannian geometry has emerged as one of the most powerful mathematical and computational frameworks for analyzing such data. In the book *Riemannian Geometric Statistics in Medical Image Analysis* [53], we provided an introduction to the core methodology for performing statistics on Riemannian manifolds and more general nonlinear spaces followed by a presentation of state-of-the-art methods in medical image analysis.

We provided more specifically an introduction chapter on differential and Riemannian geometry [56] (with S. Sommer and T. Fletcher), a comprehensive chapter on symmetric positive definite matrices (SPD) and manifold value image processing [55], and reference chapter on the affine connection setting for transformation groups including the stationary velocity fields parametrisation of diffeomorphisms and its use in medical image registration for longitudinal modeling of Alzheimer's disease [54] (with M. Lorenzi) and a chapter on the statistical bias on the estimation in quotient space [52] (with N. Miolane and L Devillier).

6.3.2. Effect of curvature on the Empirical Fréchet mean estimation in manifolds

Participant: Xavier Pennec [Correspondant].

This work is funded by the ERC-Adv G-Statistics

Geometric statistics, empirical Fréchet mean

Statistical inference in manifolds most often rely on the Fréchet mean in the Riemannian case, or on exponential barycenters in affine connection spaces. The uncertainty of the empirical mean estimation with a fixed number of samples is a key question. In sufficient concentration conditions, a central limit theorem was established in Riemannian manifolds by Bhattacharya and Patrangenaru in 2005. We propose in [62] an asymptotic development valid in Riemannian and affine cases which better explain the role of the curvature in the modulation of the speed of convergence of the empirical mean. We also establish a non-asymptotic development in high concentration which shows a statistical bias on the empirical mean in the direction of the average gradient of the curvature. These curvature effects become important with large curvature and can drastically modify the estimation of the mean. They could partly explain the phenomenon of sticky means recently put into evidence in stratified spaces, notably in the case of negative curvature.

6.3.3. Shape Analysis with diffeomorphisms

Participants: Nicolas Guigui [Correspondant], Shuman Jia, Maxime Sermesant, Xavier Pennec.

This work is partially funded by the ERC-Adv G-Statistics

Shape Analysis, parallel transport, LDDMM, symmetry

The statistical analysis of temporal deformations and inter-subject variability relies on shape registration and parallel transport of deformations (Figure 10). However, the numerical integration and optimization required lead to important numerical errors. This work aims at improving the numerical consistency and reproducibility of the Pole Ladder scheme to perform parallel transport. We propose a modification of this scheme using registration errors [39] and define different types of errors to evaluate the accuracy: the involutivity and transvectivity. We test our method on 138 cardiac shapes and demonstrate improved numerical consistency for both types of errors.

6.3.4. Classification of Riemannian metrics on the manifold of symmetric positive definite matrices

Participants: Yann Thanwerdas [Correspondant], Xavier Pennec.

This work is partially funded by the ERC-Adv G-Statistics and by the IDEX UCA-JEDI ANR-15-IDEX-01 through an excellence OPhD fellowship.

Symmetric Positive Definite matrices, Riemannian metrics, dually flat manifolds

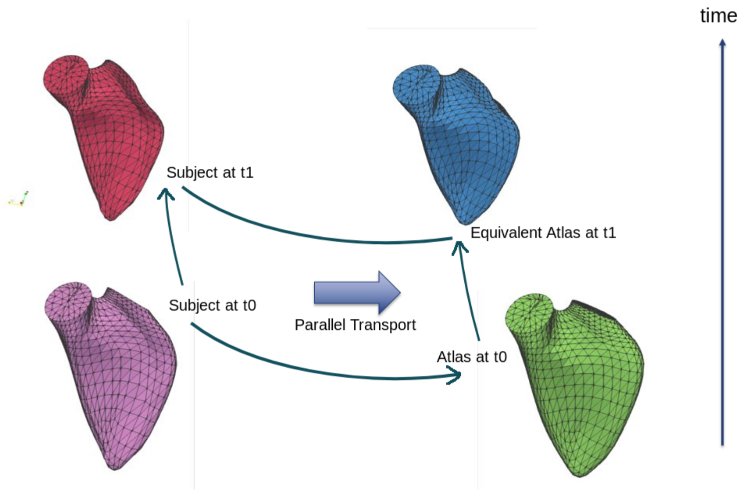

Figure 10. Illustration of our framework using parallel transport to normalize individual temporal deformations to an atlas.

Symmetric Positive Definite matrices have been used in many fields of medical data analysis. Many Riemannian metrics have been defined on this manifold but the choice of the Riemannian structure lacks a set of principles that could lead one to choose properly the metric. We introduced several families of Riemannian metrics supported by a deformation principle and a principle of balanced metrics:

1. Power-Affine and Deformed-Affine metrics [43], that highlight relations between the affine-invariant, the polar-affine and the log-Euclidean metrics ;
2. Mixed-Power-Euclidean and Mixed-Power-Affine metrics [42], that highlight relations between many Riemannian metrics, as shown on Figure 11.

6.3.5. Statistical shape analysis of faces for computer aided dermatology and plastic surgery

Participants: Florent Jousse [Correspondant], Xavier Pennec, Hervé Delingette, Matilde Gonzalez.

Supported by the company Quantificare through a CIFRE funding.

Gaussian Processes, non rigid registration

The objective of this work is to model complex face deformations related to natural aging, facial expressions, surgical interventions or posture motions to improve the 3D reconstruction of faces and to normalize their analysis. It includes the development of non-rigid registration methods of textured meshes and their statistical modeling through Gaussian processes.

6.3.6. Brain Morphometry in the MAPT clinical trial

Participants: Raphaël Sivera [Correspondant], Hervé Delingette, Marco Lorenzi, Xavier Pennec, Nicholas Ayache.

This work is partially funded by the ERC-Adv G-Statistics

Longitudinal deformation modeling, multivariate statistics, brain morphology, Alzheimer's disease, clinical trial.

- We proposed a complete framework for statistical hypothesis testing on mass-multivariate data. This framework builds on the recent works on multivariate statistics in neuroimaging to propose a generic approach adapted to the study of longitudinal deformations [3].

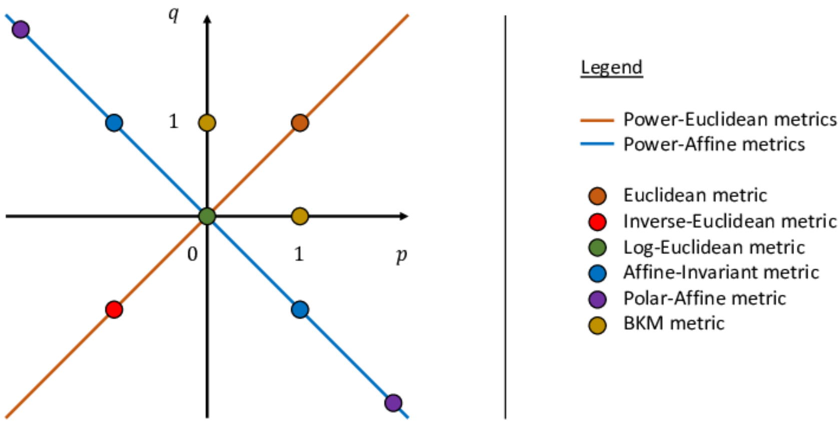

Figure 11. The family of Mixed-Power-Euclidean metrics

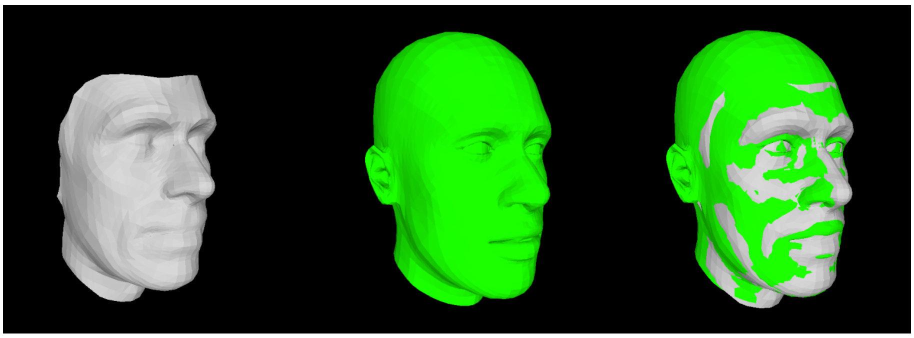

Figure 12. Example of facial template fitting. The white mesh (target) has been acquired by stereoscopy while the green one is a template mesh that has been deformed to fit the target.

- This framework is used in the context of the MAPT study to highlight a significant effect of the multidomain intervention on the brain morphological changes (see Figure 13) [22].

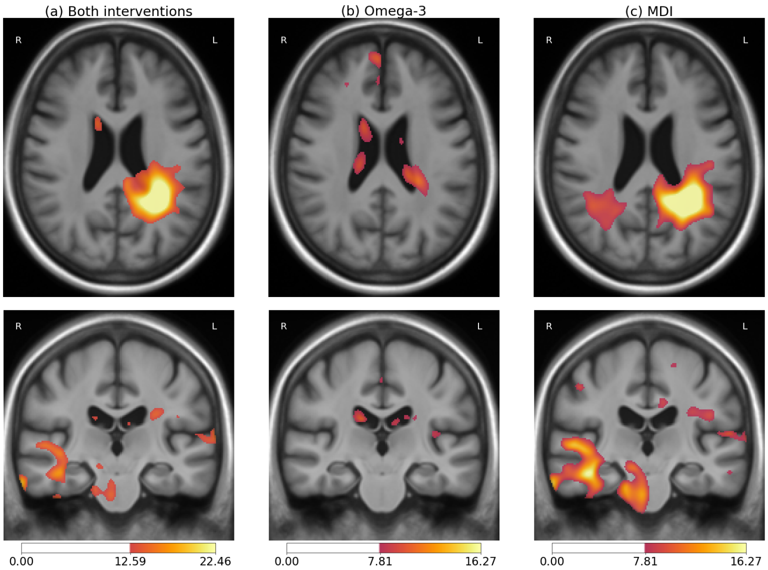

Figure 13. Localization of the MAPT treatments effect on the longitudinal morphological changes for: (a) both categorical variables associated with the omega-3 supplementation and the multidomain intervention, (b) omega-3 only, (c) multidomain intervention only. Color bars indicate the magnitude of the z-values for the likelihood-ratio test. High values indicate a difference in the morphological changes that is associated with the treatment status.

6.3.7. Statistical Learning of Heterogeneous Data in Large-Scale Clinical Databases

Participants: Clement Abi Nader [Correspondant], Nicholas Ayache, Philippe Robert, Marco Lorenzi.

Gaussian Process, Alzheimer's Disease, Disease Progression Modelling

The aim of this thesis is to develop a spatio-temporal model of Alzheimer's Disease (AD) progession based on multi-modal brain data. We assume that the brain progression is characterized by independent spatio-temporal sources that we want to separate. We estimate brain structures involved in the disease progression at different resolutions thus dealing with the non-stationarity of medical images, while assigning to each of them a monotonic temporal progression using Gaussian processes (Figure 14). We also compute an individual time-shift parameter to assess the disease stage of each subject. This work has been accepted for publication in the journal NeuroImage [5]

6.4. Computational Physiology

6.4.1. Deep Learning based Metal Artifacts Reduction in post-operative Cochlear Implant CT Imaging

Participants: Zihao Wang [Correspondant], Clair Vandersteen, Thomas Demarcy, Dan Gnansia, Charles Raffaelli, Nicolas Guevara, Hervé Delingette.

This work is funded by the Provence-Alpes-Côte-d'Azur region, the Université Côte d'Azur and Oticon Medical through CIMPLE https://team.inria.fr/epione/en/research/cimple/ research project.

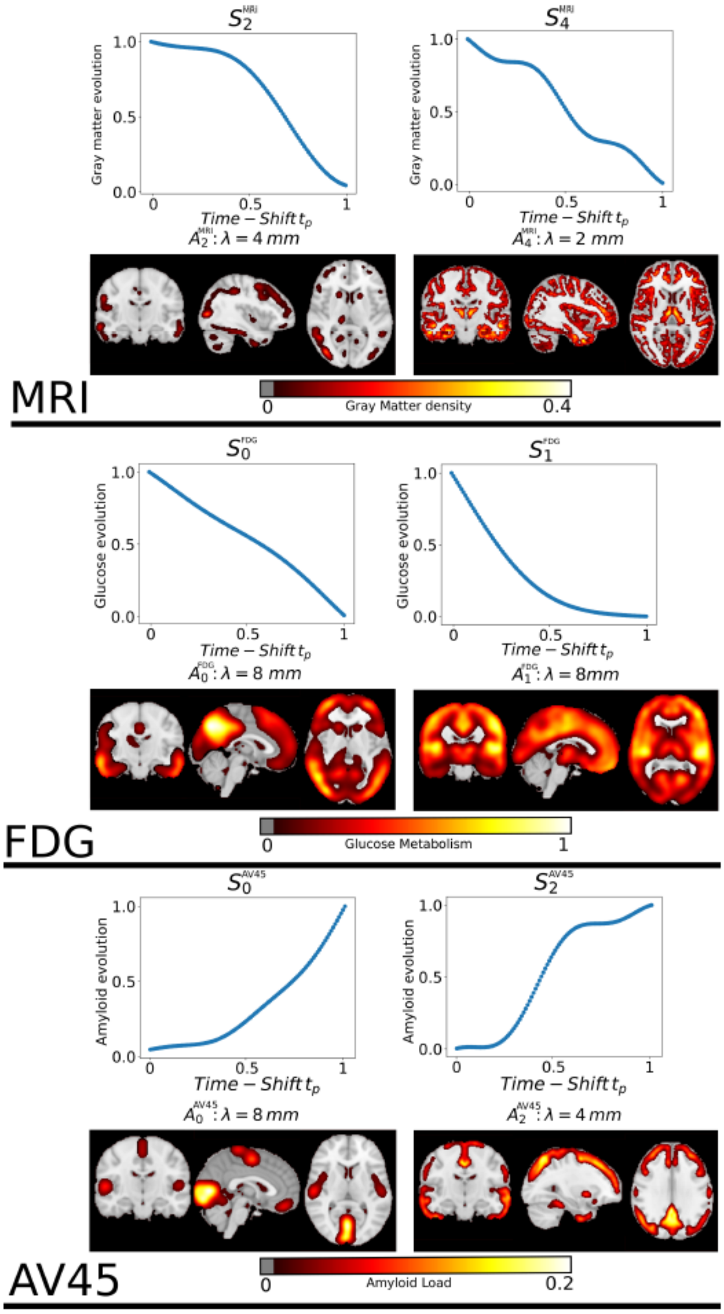

Figure 14. Estimated spatio-temporal processes affecting the brain during Alzheimer's Disease for three different imaging markers.

Generative Adversarial Network, Metal Artifacts Reduction, Cochlea Implantation

We propose a 3D metal artifact reduction method using convolutional neural networks for post-operative cochlear implant imaging.[44]

- Learn metal artifacts reduction by using pre-operative images and metal artifacts simulation to create image pairs for training GANs.
- Metal artifacts simulation starts from a cochlea implantation fusion image and ends with the simulated post-operative image.(Fig. 15)
- A 3D generative adversarial network (MARGANs) to create an image with a reduction of metal artifacts.
- Evaluations on ten patients show the effectiveness of artefact reduction compared to two classical methods.

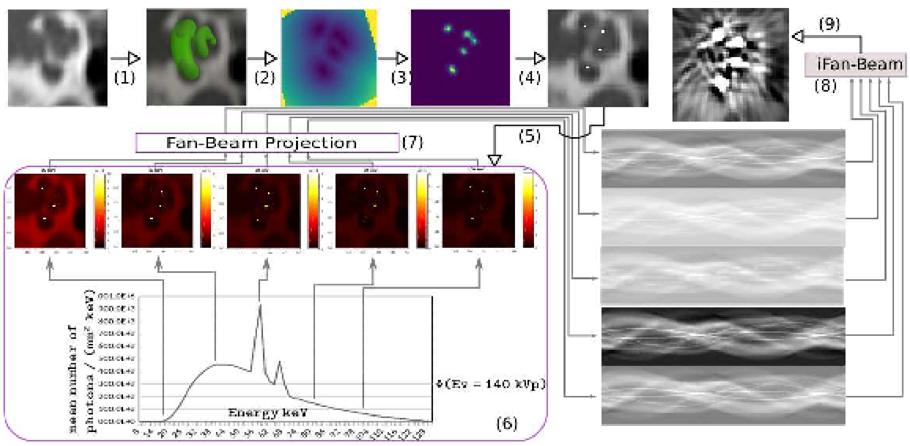

Figure 15. CI metal artifacts simulation workflow starting from a pre-operative image and ending with the simulated post-operative image after 9 processing steps.

6.4.2. Kinematic Spiral Shape Recognition in the Human Cochlea

Participants: Wilhelm Wimmer [Correspondant], Clair Vandersteen, Nicolas Guevara, Marco Caversaccio, Hervé Delingette.

Supported by the Swiss National Science Foundation (no. P400P2_180822) and the French government (UCA JEDI - ANR-15-IDEX-01).

Approximate maximum likelihood, kinematic surface recognition, natural growth

To improve therapies for hearing loss and deafness, e.g., with auditory neuroprostheses, we developed a reliable detection algorithm for the cochlear modiolar axis in CT images (Fig. 16). The algorithm was tested in an experimental study with 4 experts in 23 human cochlea CT data sets [45] [27]. Our experiments showed that the algorithm reduces the alignment error providing more reliable modiolar axis detection for clinical and research applications.

6.5. Computational Cardiology & Image-Based Cardiac Interventions

6.5.1. Cardial Electrophysiological Model Learning and Personalisation

Participants: Nicolas Cedilnik [Correspondant], Ibrahim Ayed [Sorbonne, LIP6, Paris], Hubert Cochet [IHU Liryc, Bordeaux], Patrick Gallinari [Sorbonne, LIP6, Paris], Maxime Sermesant.

This work is funded by the IHU Liryc, Bordeaux.

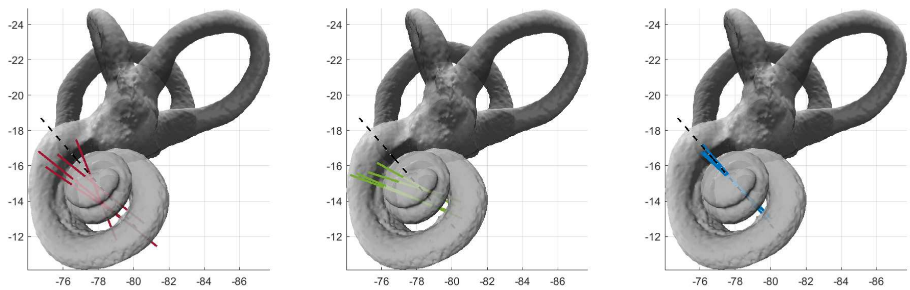

Figure 16. Visualization of the bony labyrinth with reference modiolar axis (dashed line). Modiolar axes after manual landmark-based (left), PCA-based (middle), and robust kinematic detection (right) in CT data are shown for comparison.

modelling, electrophysiology, ventricular tachycardia, ischemic cardiomyopathy

This project aims at making electrophysiological model personalisation enter clinical practice in interventional cardiology. During this year:

- we evaluated a fully automated computed tomography-based model personalisation framework in the context of post-ischemic ventricular tachycardia [35],
- we developped a model personalisation methodology based on invasive data in our participation in the STACOM2019 modelling challenge [37],
- we proposed a deep learning based approach to replace numerical integration of partial differential equations used in cardiac modelling [32], see Figure 17.

6.5.2. Deep Learning Formulation of ECGI for Data-driven Integration of Spatiotemporal Correlations and Imaging Information

Participants: Tania Marina Bacoyannis [Correspondant], Hubert Cochet [IHU Liryc, Bordeaux], Maxime Sermesant.

This work is funded within the ERC Project ECSTATIC with the IHU Liryc, in Bordeaux.

Deep Learning, Electrocardiographic Imaging, Inverse problem of ECG, Electrical simulation, Generative Model.

Electrocardiographic imaging (ECGI) aims at reconstructing the electrical activity of the heart using body surface potentials.To achieve this one has to solve the ill-posed inverse problem of the torso propagation. We propose in [33] a novel Deep Learning method based on Conditional Variational Autoencoder able to solve ECGI inverse problem in 2D. This generative probabilistic model learns geometrical and spatio-temporal information and enables to generate the corresponding activation map of the specific heart.

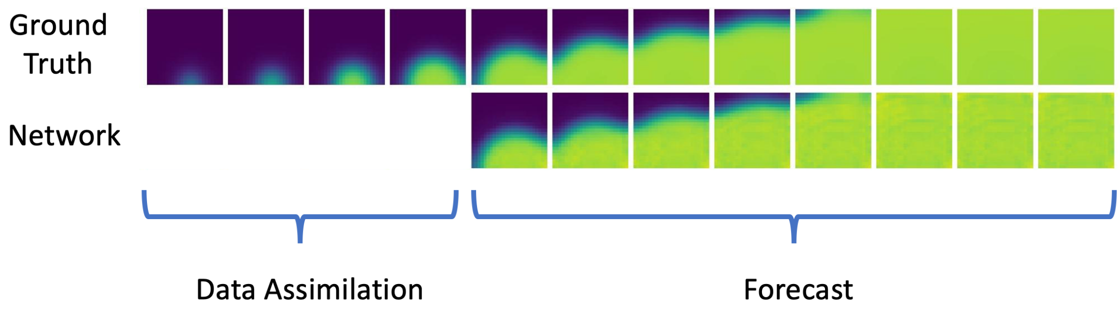

Figure 17. Transmembrane potential obtained with a reaction diffusion model (top) and forecasted by EP-Net (bottom) for one slice of a tissue slab

120 activation maps and the corresponding Body Surface Potentials (BSP) were generated using the dipole formulation. 80% of the simulated data was used for training and 20% for testing.We generate 10 propbable solutions for each given input using our model. The Mean Squarre Error (MSE) metric over all the tests was 0.095. As results we were able to observe that the reconstruction performs well. Next, we will extend the model in 3D and test it on real data provided by the IHU Liryc.

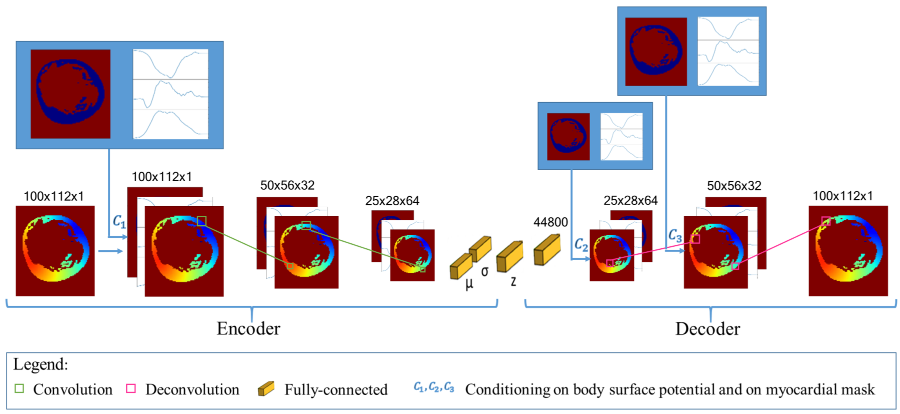

Figure 18. Architecture of our conditioned generative model (encoder) and our conditioned variational approximation (decoder)

6.5.3. Discovering the link between cardiovascular pathologies and neurodegeneration through biophysical and statistical models of cardiac and brain images

Participants: Jaume Banus Cobo [Correspondant], Marco Lorenzi, Maxime Sermesant.

Université Côte d'Azur (UCA)

Lumped models - Biophysical simulation - Statistical learning

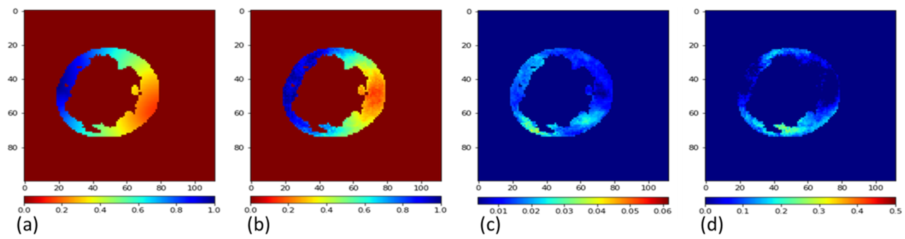

Figure 19. (a) Simulated and (b) predicted mean activation maps for proposed deep learning based ECGI, (c) Standard deviation map calculated over 10 predictions, (d) error map, difference between predicted and simulated activation maps.

The project aims at developing a computational model of the relationship between cardiac function and brain damage from large-scale clinical databases of multi-modal and multi-organ medical images. The model is based on advanced statistical learning tools for discovering relevant imaging features related to cardiac dysfunction and brain damage; these features are combined within a unified mechanistic framework to providing a novel understanding of the relationship between cardiac function, vascular pathology and brain damage. [34]

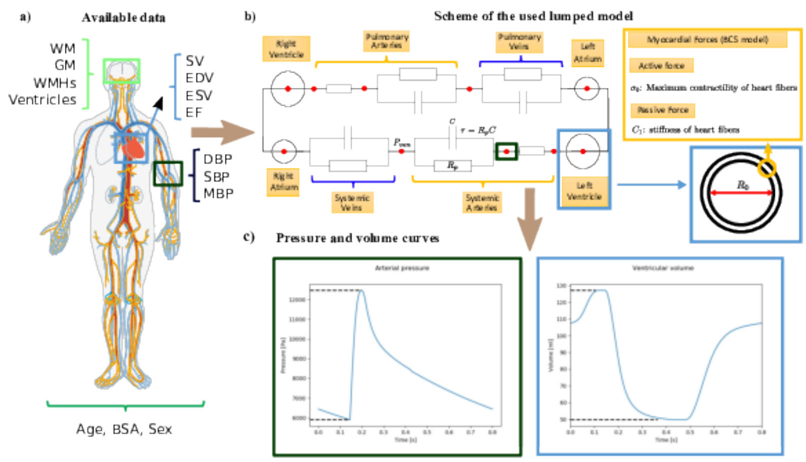

Figure 20. a) Summary of the available data for each subject, including cardiac data, socio-demographic information, blood pressure measurements and brain volumetric indicators. b) Simplified representation of the lumped model showing the parameters used in the personalisation. τ characterizes the contractility of the main systemic arteries, R_p the peripheral resistance, P_{ven} the venous pressure right after the capillaries, R_0 the radius of the left ventricle, σ_0 the contractility of the cardiac fibers and C_1 their stiffness. A more detailed representation of the myocardial forces is omitted for the sake of clarification. c) Example of the pressure and volume curves that can be obtained from the model, from these curves we extract scalar indicators to match the available clinical data.

6.5.4. Parallel transport of surface deformations from pole ladder to symmetrical extension

Participants: Shuman Jia [Correspondant], Nicolas Guigui, Nicolas Duchateau, Pamela Moceri, Maxime Sermesant, Xavier Pennec.

The authors acknowledge the partial funding by the Agence Nationale de la Recherche (ANR)/ERA CoSysMedSysAFib and ANR MIGAT projects.

We proposed a general scheme to perform statistical modeling of the temporal deformation of the heart, directly based on meshes. We encoded the motion and the intersubject shape variations, with diffeomorphisms parameterized either by stationary SVFs or by time-varying velocity fields in the LDDMM framework.

Experiments on a 4D right-ventricular endocardial meshes database demonstrated the stability of our transport algorithm, of importance for the assessment of pathological changes. The method is adaptable to other anatomies with temporal or longitudinal data.

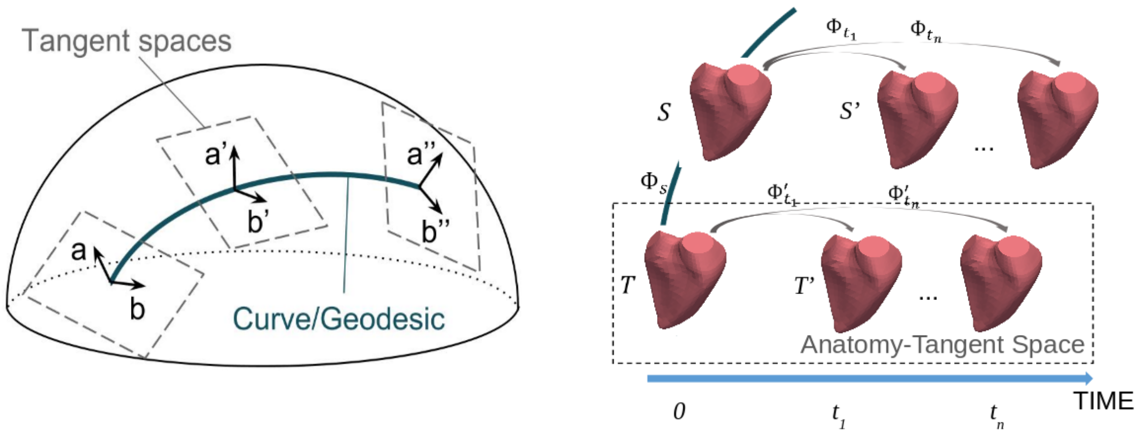

Figure 21. Illustration of parallel transport of vectors a and b along a curve (left) and its application to cardiac imaging (right) with a focus on surfaces.

6.5.5. Machine Learning and Pulmonary hypertension

Participants: Yingyu Yang [Correspondant], Stephane Gillon, Jaume Banus Cobo, Pamela Moceri, Maxime Sermesant.

cardiac modelling, machine learning

Right heart catheterisation is considered as the gold standard for the assessment of patients with suspected pulmonary hyper-tension. It provides clinicians with meaningful data, such as pulmonary capillary wedge pressure and pulmonary vascular resistance, however its usage is limited due to its invasive nature. Non-invasive alternatives, like Doppler echocardiography could present insightful measurements of right heart but lack detailed information related to pulmonary vasculature. In order to explore non-invasive means, we studied a dataset of 95 pulmonary hypertension patients, which includes measurements from echocardiography and from right-heart catheterisation. We used data extracted from echocardiography to conduct cardiac circulation model personalisation and tested its prediction power of catheter data. Standard machine learning methods were also investigated for pulmonary artery pressure prediction. Our preliminary results demonstrated the potential prediction power of both data-driven and model-based approaches. It was published as "Non-Invasive Pressure Estimation in Patients with Pulmonary Arterial Hypertension: Data-driven or Model-based?" accepted at 10th Workshop on Statistical Atlases and Computational Modelling of the Heart, Oct 2019, Shenzhen, China [46]

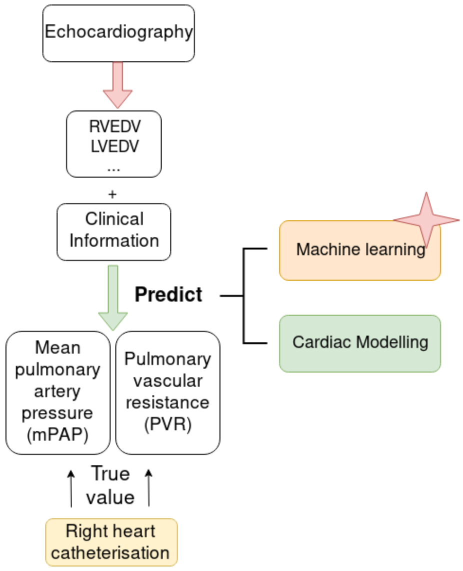

Figure 22. The main idea and logic of this work

6.5.6. Style Data Augmentation for Robust Segmentation of Multi-Modality Cardiac MRI

Participants: Buntheng Ly [Correspondent], Hubert Cochet [IHU Liryc, Bordeaux], Maxime Sermesant.

Image Segmentation. Multi-modality, Cardiac Magnetic Resonance Imaging, Late Gadolinium Enhanced, Deep Learning

We propose a data augmentation method to improve the segmentation accuracy of the convolutional neural network on multi-modality cardiac magnetic resonance dataset [41].

The strategy aims to reduce over-fitting of the network toward any specific intensity or contrast of the training images by introducing diversity in these two aspects, as shown in figure 23.

6.5.7. Towards Hyper-Reduction of Cardiac Models using Poly-Affine Deformation

Participants: Gaëtan Desrues [Correspondant], Hervé Delingette, Maxime Sermesant.

Model Order Reduction, Finite Elements Method, Affine Transformation, Meshless

Patient-specific 3D models can help in improving therapy selection, treatment optimization and interventional training. However, these simulations generally have an important computational cost. The aim of this project is to optimize a 3D electromechanical model of the heart for faster simulations [38]. The cardiac deformation is approached by a reduced number of degrees of freedom represented by affine transformations (frames in Figure 24b) located at the center of the AHA regions (Figure 24a). The displacement of the material points are computed using region-based shape functions (Figure 24c).

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. Microsoft Research

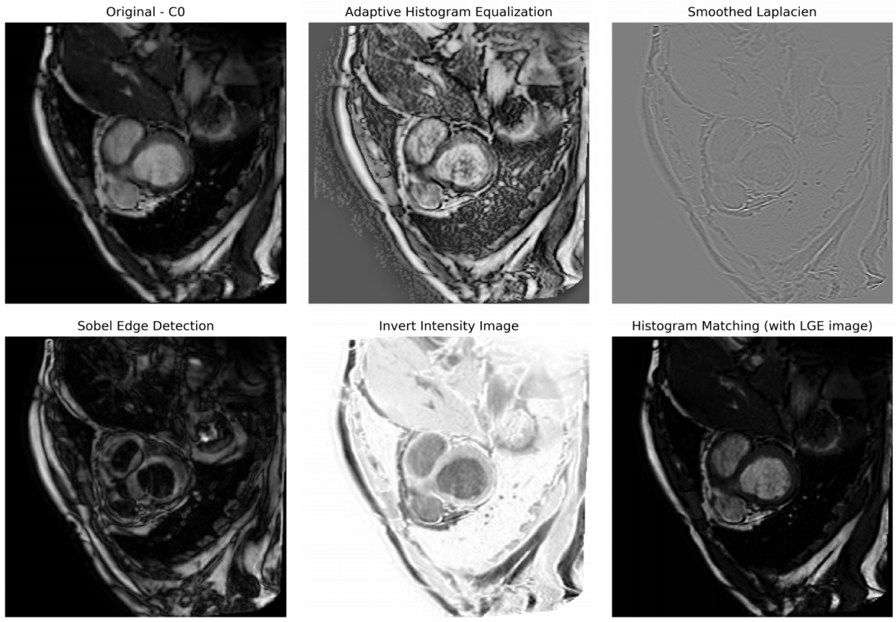

Figure 23. Different variation of input images and the image processing methods used. C0 denotes the steady-state free precessing CMR modality image.

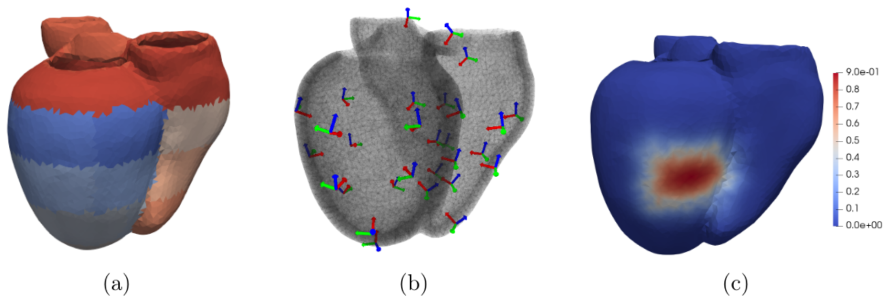

Figure 24. Framework on a cardiac topology. AHA regions (a). Affine degrees of freedom (b). Shape function in one region (c).

Microsoft Research is funding through the Inria-Microsoft joint lab the projects "4D Cardiac MR Images"[0] and "Medilearn"[0] which aim at analyzing large databases of cardiac images to help the diagnosis of cardiac diseases and planning of therapy. This project involves A. Crimisi from MSR and partially funds the PhDs of Pawel Mlynarski.

7.1.2. Spin-off company inHEART

inHEART[0] is a spin-off of the Epione team and IHU Liryc founded in 2017. inHEART provides a service to generate detailed anatomical and structural meshes from medical images, that can be used during ablation interventions. inHEART received 2 awards, one from Aquitaine region and one i-LAB from the BPI. It currently employs 10 people.

7.1.3. Live Anatomy

A 3 month InriaTech contract was performed with the Live Anatomy start-up between January and March 2019 in order to develop a remote viewer and to optimise image segmentation.

7.1.4. Siemens HealthCare

Siemens Healthcare, Medical Imaging Technologies, Princeton, NJ (U.S.A). is funding the PhD work of Julian Krebs which aims at developing robust medical image registration methods

7.1.5. Quantificare

The company Quantificare is funding the PhD of Florent Jousse through a CIFRE grant, on the statistical analysis of shapes, deformations and appearance of anatomical surfaces for computer-aided dermatology and plastic surgery. The primary purpose is to model complex face deformations such as natural aging, facial expressions, surgical interventions and posture motions.

7.1.6. Oticon Medical

Oticon Medical, Vallauris, France, is co-funding the PhD work of Zihao Wang which aims at developing robust medical image algorithms for cochlea image segmentation.

8. Partnerships and Cooperations

8.1. Regional Initiatives

- Marco Lorenzi is principal investigator of the project Big Data for Brain Research, funded during 2017-20 by the Départment des Alpes Maritimes.
- Marco Lorenzi is principal investigator of the project MetaImaGen, funded by Idex Jedi UCA (2018-2020, 37k€).
- Maxime Sermesant is principal investigator of the project "The Digital Heart" and the innovation action "Digital Heart Phantom" with General Electrics, funded by Idex UCA Jedi. These projects gather the local cardiac research in academia, clinics and industry.
- Hervé Delingette is the principal investigator of the LungMark project funded by Idex Jedi UCA (2018-2021).
- Hervé Delingette is the principal investigator of the CIMPLE project, funded by Idex Jedi UCA (2018-2021), the region PACA and Oticon Medical. The region PACA and Oticon Medical are co-funding the Phd of Zihao Wang.

[0] http://www.msr-inria.fr/projects/4d-cardiac-mr-images
[0] http://www.msr-inria.fr/projects/medilearn
[0] https://www.inheart.fr/

- N. Ayache and P. Robert are principal investigators of the project MNC3 (Médecine Numérique, Cerveau, Cognition, Comportement) funded by Idex Jedi UCA (2017-2021, 450k€). M. Lorenzi (Inria) actively participates to the supervision of this project with the help of V. Manera (ICP).

8.2. National Initiatives

8.2.1. Consulting for Industry

- Marco Lorenzi is a scientific consultant for the company MyDataModels (Sophia Antipolis), and for the company Flexper (Sophia Antipolis.)
- Maxime Sermesant is a scientific consultant for the company inHEART (Bordeaux)
- Nicholas Ayache is a scientific consultant for the company Mauna Kea Technologies (Paris).

8.2.2. Institute 3IA Côte d'Azur

The 3IA Côte d'Azurhttp://univ-cotedazur.fr/institutes/3IA/home is one of the four "Interdisciplinary Institutes of Artificial Intelligence" that were created in France in 2019. Its ambition is to create an innovative ecosystem that is influential at the local, national and international levels, and a focal point of excellence for research, education and the world of AI.

Epione is heavily involved in this institute since its 5 permanents researchers (N. Ayache, H. Delingette, M. Lorenzi, M. Sermesant and X.Pennec) are chair holders in this institute, and N. Ayache is its scientific director.

8.2.3. Collaboration with national hospitals

The Epione-project team collaborates with the following 3 French IHU (University Hospital Institute): the IHU-Strasbourg (Pr J. Marescaux and L. Soler) on image-guided surgery, the IHU-Bordeaux (Pr M. Haïssaguere and Pr P. Jaïs) on cardiac imaging and modeling and the IHU-Pitié Salpétrière (Dr. O. Colliot and S. Durrleman) on neuroimaging.

We also have long term collaborations with the CHU Nice and Centre Antoine Lacassagne in Nice.

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

8.3.1.1. ERC ECSTATIC

Title: Electrostructural Tomography – Towards Multiparametric Imaging of Cardiac Electrical Disorders

Programm: H2020

Type: ERC

Duration: 2017 - 2022

Coordinator: U. Bordeaux

Inria contact: Maxime Sermesant

Cardiac electrical diseases are directly responsible for sudden cardiac death, heart failure and stroke. They result from a complex interplay between myocardial electrical activation and structural heterogeneity. Current diagnostic strategy based on separate electrocardiographic and imaging assessment is unable to grasp both these aspects. Improvements in personalized diagnostics are urgently needed as existing curative or preventive therapies (catheter ablation, multisite pacing, and implantable defibrillators) cannot be offered until patients are correctly recognized.

ECSTATIC aims at achieving a major advance in the way cardiac electrical diseases are characterized and thus diagnosed and treated, through the development of a novel non-invasive modality (Electrostructural Tomography), combining magnetic resonance imaging (MRI) and non-invasive cardiac mapping (NIM) technologies.

The approach will consist of: (1) hybridising NIM and MRI technologies to enable the joint acquisition of magnetic resonance images of the heart and torso and of a large array of body surface potentials within a single environment; (2) personalising the inverse problem of electrocardiography based on MRI characteristics within the heart and torso, to enable accurate reconstruction of cardiac electrophysiological maps from body surface potentials within the 3D cardiac tissue; and (3) developing a novel disease characterisation framework based on registered non-invasive imaging and electrophysiological data, and propose novel diagnostic and prognostic markers.

This project will dramatically impact the tailored management of cardiac electrical disorders, with applications for diagnosis, risk stratification/patient selection and guidance of pacing and catheter ablation therapies. It will bridge two medical fields (cardiac electrophysiology and imaging), thereby creating a new research area and a novel semiology with the potential to modify the existing classification of cardiac electrical diseases.

8.3.1.2. ERC G-statistics

Title: Biophysical Modeling and Analysis of Dynamic Medical Images

Programme: FP7

Type: ERC

Period: 2018-2023

Coordinator: Inria

PI: Xavier Pennec

G-Statistics aims at exploring the foundations of statistics on non-linear spaces with applications in the Life Siences. Invariance under gauge transformation groups provides the natural structure explaining the laws of physics. In life sciences, new mathematical tools are needed to estimate approximate invariance and establish general but approximate laws. Rephrasing Poincaré: a geometry cannot be more true than another, it may just be more convenient, and statisticians must find the most convenient one for their data. At the crossing of geometry and statistics, G-Statistics aims at grounding the mathematical foundations of geometric statistics and to exemplify their impact on selected applications in the life sciences.

So far, mainly Riemannian manifolds and negatively curved metric spaces have been studied. Other geometric structures like quotient spaces, stratified spaces or affine connection spaces naturally arise in applications. G-Statistics will explore ways to unify statistical estimation theories, explaining how the statistical estimations diverges from the Euclidean case in the presence of curvature, singularities, stratification. Beyond classical manifolds, particular emphasis will be put on flags of subspaces in manifolds as they appear to be natural mathematical object to encode hierarchically embedded approximation spaces.

In order to establish geometric statistics as an effective discipline, G-Statistics will propose new mathematical structures and characterizations of their properties. It will also implement novel generic algorithms and illustrate the impact of some of their efficient specializations on selected applications in life sciences. Surveying the manifolds of anatomical shapes and forecasting their evolution from databases of medical images is a key problem in computational anatomy requiring dimension reduction in non-linear spaces and Lie groups. By inventing radically new principled estimations methods, we aim at illustrating the power of the methodology and strengthening the “unreasonable effectiveness of mathematics” for life sciences.

8.3.2. Collaborations in European Programs, Except FP7 & H2020

Program: ERA CoSysMed

Project acronym: SysAFib

Project title: Systems medicine for diagnosis and stratification of atrial fibrillation

Duration: Mai 2016 - Mai 2019

Coordinator: Simula, Norway

Inria contact: Maxime Sermesant

Other partners: Inria, Helmholtz Zentrum München, Oslo University Hospital, Maastricht University, CardioCentro Ticino/CCMC

Abstract: Atrial fibrillation (AF) sharply increases the risk of stroke and is associated with a number of other severe complications, including heart failure. The SysAFib project aims to combine advanced data analysis and computer simulations with classical clinical approaches to create a decision support tool for treating AF. Diverse data sources, such as the individual patient's medical history, clinical measurements and genetic data will be combined into a single tool for optimizing and personalizing AF therapy. SysAFib's ultimate goal is to deliver the right treatment to the right patient at the right time, stopping AF in its tracks and ending the need for repeat invasive procedures.

8.4. International Initiatives

8.4.1. Inria International Labs

Inria@SiliconValley

Associate Team involved in the International Lab:

8.4.1.1. GeomStats

Title: Geometric Statistics in Computational Anatomy: Non-linear Subspace Learning Beyond the Riemannian Structure

International Partner (Institution - Laboratory - Researcher):

Stanford (United States) - Department of Statistics - Susan Holmes

Start year: 2018

See also: http://www-sop.inria.fr/asclepios/projects/GeomStats/

The scientific goal of the associated team is to develop the field of geometric statistics with key applications in computational anatomy. Computational anatomy is an emerging discipline at the interface of geometry, statistics, image analysis and medicine that aims at analysing and modelling the biological variability of the organs shapes at the population level. An important application in neuroimaging is the spatial normalization of subjects that is necessary to compare anatomies and functions through images in populations with different clinical conditions. Following the developments of the last 3 years of the associated team GeomStat, the new research directions have been broken into three axes. The first axis aims at continuing the progresses in theoretical and applied Geometric statistics, with a first theme studying the impact of curvature on the estimation with a finite sample, and a second axis extending the current work on Barycentric Subspace Analysis (BSA), notably with algorithms. The second axis aims at developing a hierarchical atlas of the brain anatomy based on the stratification of the space of image orbits under diffeomorphisms. The third axis explores three important applications of low-dimensional subspace learning in manifolds using BSA in neuroscience: the approximation of EEG signals for brain-computer interfaces (BCI); the acceleration and robustification of Tensor Distribution Functions (TDF) estimation in diffusion images; and the efficient inference in spaces of rank-deficient symmetric matrices for imaging-genetics from multi-centric databases.

8.4.2. Inria Associate Teams Not Involved in an Inria International Labs

8.4.2.1. PERSOCARDIOLEARN

Title: Personalization of Cardiac Models using Experimental Data and Machine Learning

International Partner (Institution - Laboratory - Researcher):

University of Toronto (Canada) - Sunnybrook Research Institute - Mihaela Pop

Start year: 2017

See also: https://team.inria.fr/asclepios/research/associated-team-persocardiolearn/

Multi-scale computer modelling is a powerful tool that could be used to simulate in silico cardiac electrical activity and biomechanical function of individual heart. Imaging and 3D heart models built from images can help us understand the basis of structurally-diseased hearts at organ level and to predict in silico the changes in electro-mechanical function as a consequence of muscle remodelling in pathologic state (e.g. chronic infarction, a major cause of death). We hypothesize that MRI-based predictive models can help us identify new opportunities to intervene or to predict the outcome of ablation therapy, which currently has low clinical success. However, these predictive models need to be validated and thoroughly tested in preclinical experiments prior to their integration into the clinical stage. Hence, the next logical step for our joint Inria-SB efforts is to expand our experimental-theoretical framework and to personalize fast 3D heart models from in vivo MR-EP data. This translational step involves numerous challenging tasks from the modelling perspective since the in vivo imaging and physiological signals are rather noisy and obtained at a poor spatial resolution, potentially leading to erroneous customization of mathematical model parameters. However, this collaboration employs a rare combination of experiments and modelling specialists. Moreover, the originality of the proposed approach is to build upon machine-learning techniques rather than on data assimilation methods that are more explored in the literature but have inherent limitations (robustness to noise, local minima…).

8.4.3. Inria International Partners

8.4.3.1. Informal International Partners

8.4.3.1.1. University College London (UCL), London, UK

Marco Lorenzi is collaborator of the Translational Imaging Group of UCL, and with the UCL Institute od Ophtalmology. His collaboration is around the topic of spatio-temporal analysis of medical images, with special focus on brain imaging analysis and biomarker development. He is also collaborating with the "Progression Over Neurodegenerative Disorders" (POND) group (Prof. Daniel Alexander) for developing new computational models and techniques for learning characteristic patterns of disease progression using large longitudinal clinical data sets, with special focus on dementias.

8.4.3.1.2. Imaging Genetics Center (IGC), University of Southern California (USC), CA, USA

Marco Lorenzi is currently collaborator of IGC for the investigation of the complex relationship between brain atrophy and genetics in Alzheimer's disease, in particular for demonstrating the effectiveness of multivariate statistical models in providing a meaningful description of the relationship between genotype and brain phenotype.

8.4.3.1.3. St Thomas' Hospital, King's College London, United Kingdom

Maxime Sermesant is a visiting lecturer in the Division of Imaging Sciences and Biomedical Engineering, St Thomas' Hospital, King's College London lead by Pr Reza Razavi. The XMR facility within this hospital is a unique opportunity to validate and exploit the cardiovascular modelling work.

8.4.3.1.4. Other International Hospitals

Collaborations with several other European hospitals have been established through the European projects VP2HF, MD PAEDIGREE, SysAFib and with BarcelonaBeta research centre for Alzheimer.

8.5. International Research Visitors

8.5.1. Visits of International Scientists

- Dr. Gabriel Ziegler (German Center for Neurodegenerative Disorder, DE) visited the group from Oct 14th to Oct 18t.
- Guillaume Lajoinie (Physics of Fluid laboratory, University of Twente, NL) visited the team from April until October 2019.

- Wilhelm Wimmer (Center ARTORG, University of Bern, CH) visited the team from Nov. 2018 until Oct. 2019.
- Pr. Dmitri Alekseevky (The Institute for Information Transmission Problems, Moscow) visited the Geometric Statistics group from february 6 to 13 2019.

8.5.1.1. Internships

- Buntheng LY, Master student at the University Claude Bernard Lyon 1, visited the Epione team from March to September 2019 to work with Maxime Sermesant on Machine Learning methods for the prediction of Sudden Cardiac Death.
- YingYu Yang, Master student at Ecole Polytechnique, visited the Epione team from April to September 2019 to work with Maxime Sermesant on Machine Learning and Pulmonary hypertension.
- Gaetan Desrues, Master student at University of Bordeaux, visited the Epione team from March to September 2019 to work with Maxime Sermesant on hyper-reduction of cardiac models using poly-affine deformation.
- Paul Blanc Durand, Master student at University Paris-Est Créteuil, visited the Epione team from April to October 2019 to work with Hervé Delingette on Mesh-based Registration of lung CT scans between inhale and exhale phases.
- Bastien Manach-Perennou, Master student at Ecole Central Supélec, visited the Epione team from September to January 2019 to work with Xavier Pennec on Registration synchronisation.
- Julien Moreira, Master student from University Côte d'Azur, visited the Epione team from April to June 2019 to work with Marco Lorenzi on the analysis of apathy and depression in the UK Biobank. The internship is within a collaboration with Centre de la Memoire de Nice.
- Yann Fraboni visited the Epione team from December 2019 to work with Marco Lorenzi on the analysis of bias of federated learning methods in distributed application. The internship is within a collaboration with Accenture Labs of Sophia Antipolis.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. General Chair, Scientific Chair

- X. Pennec organized the Geometric Statistics workshop in Toulouse from August 30 to September 5 2019, in the framwork of the Associated team GeomStats with Stanford, the ERC G-Statistics and the thematic semester "Statistics with Geometry and Topology" of the CIMI Labex of Toulouse. The workshop featured 6 hours courses by Susan Holmes and Xavier Pennec and talks by Nina Miolane and Yann Thanwerdas.
- N. Ayache organized the scientific program of the conference "The Académie des Sciences in Nice and Sophia Antipolis" in June 20-21 2019.

9.1.2. Member of the Organizing Committees

- X. Pennec was a co-chair of the MICCAI 2019 Workshop on Mathematical Foundations of Computational Anatomy (MFCA 2019), which was held in Shenzen in October 2019 [57].
- M. Sermesant was a co-chair of the MICCAI 2019 Workshop Statistical Atlases and Computational Models of the Heart (STACOM 2019), which was held in Shenzhen, October 2019.
- H. Delingette co-organized the meeting on "Digital Sciences & Technologies" on April 3rd as well as the meeting on "Digital Sobriety" on Dec. 2nd as part of the scientific animation of the UCA Academy of Excellence on Digital Sciences. He was also member of the organizing committee of the 2019 SophIA summit in Sophia Antipolis that was held in Sophia Antipolis from Nov. 20-22nd.

9.1.3. Scientific Events Selection

9.1.3.1. Member of the Conference Program Committees

- X. Pennec was a program committee member and session chair of the Geometric Sciences of Information conference GSI' 2019 at ENAC in Toulouse.

9.1.3.2. Reviewer

- M. Lorenzi was a reviewer for the conferences Neural Information Processing Systems (NeurIPS 2019), International Conference on Machine Learning (ICML 2019), Medical Image Computing and Computer Aided Intervention (MICCAI 2019), International Conference on Learning Representations (ICLR 2020), Information Processing in Medical Imaging (IPMI 2019).
- M. Sermesant was a reviewer for Medical Image Computing and Computer Aided Intervention (MICCAI 2019), the MICCAI workshop STACOM and the Computing in Cardiology conference.
- X. Pennec was a reviewer for Medical Image Computing and Computer Aided Intervention (MICCAI 2019) and for Information Processing in Medical Images (IPMI 2019), the 35th Annual Symposium on Computational Geometry (CG Week 2019).
- H. Delingette was a reviewer for the International Symposium on Biomedical Imaging (ISBI'19), the international conference on computer-aided interventions (IPCAI'19), the International Conference on Computer Vision and Pattern Recognition (CVPR 2019).

9.1.4. Journal

9.1.4.1. Member of the Editorial Boards

- H. Delingette is a member of the editorial board of the journal Medical Image Analysis (Elsevier).
- M. Lorenzi is a member of the editorial board of the journal Scientific Reports (Nature Publishing Group); he is also member of the Board of Statisticians of the Journal of Alzheimer's Disease (IOS Press).
- X. Pennec is a member of the editorial board of the journal Medical Image Analysis (MedIA, Elsevier), of the International Journal of Computer Vision (IJCV, Springer), and of the Journal of Mathematical Imaging and Vision (JMIV, Springer).
- N. Ayache is the co-founder and the Co-Editor in Chief with J. Duncan (Professor at Yale) of Medical Image Analysis journal. This scientific journal was created in 1996 and is published by Elsevier.
- N. Ayache is a member of the editorial board of the following journals: Medical Image Technology (Japanese journal) and Journal of Computer Assisted Surgery (Wiley).
- I. Strobant is editorial coordinator for Medical Image Analysis, Elsevier (since october 2001).

9.1.4.2. Reviewer - Reviewing Activities

- M. Lorenzi was a reviewer for the following journals: Neurobiology of Aging, Alzheimer's and Dementia, Journal of Alzheimer's Disease, Medical Image Analysis, IEEE Transactions on Medical Imaging, NeuroImage, International Journal of Computer Vision, Journal of Mathematical Image and Vision, Scientific Reports.
- X. Pennec was a reviewer for the Journal of Computational Dynamics, Annals of Statistics, Communications in Statistics - Simulation and Computation, Linear Algebra and its Applications, Information geometry, Medical Image Analysis, IEEE Transactions on Medical Imaging.
- M. Sermesant was a reviewer for the following journals: Journal of Machine Learning Research, Journal of the American College of Cardiology, IEEE Transactions on Medical Imaging, IEEE Transactions on Biomedical Engineering, Medical Image Analysis and Computers in Biology and Medecine.
- H. Delingette was a reviewer for the following journals: Medical Image Analysis (Elsevier), IEEE Transactions in Medical Imaging, Pattern Recognition, and Computer Vision and Image Understanding.

9.1.5. Invited Talks

- **M. Lorenzi** was invited to give a lecture to: Nice Genomic Winter School, Dec 18th; Imaging-Genetics Winter School, University of Verona, Nov 25th-29th; SophIA Summit of Sophia Antipolis, Nov 19th; International Tau Workshop, Geneva University Hospital, Nov 11th; International Meeting "The future of Medicine Starts Now", Menarini Foundation, Genoa, Italy, Sep 27th; European Glaucoma Society Meeting, Bordeaux, Aug 30th; Big@UCA Summer School, Nice, Jun 26th; Lacassagne Hospital, Jun 20th; VUmc Hospital, Amsterdam, May 23rd; Collége de France, Paris, Apr 23rd; UCA Maison de la Simulation, Apr 18th; International Conference ISBI 2019, Venice, Apr 9th; UPF University, Barcelona, Feb 7th;
- **H. Delingette** was a keynote speaker at the University of Twente (NL) seminar on Nov 6th, at the regional Otology meeting "ORL PACA" on June 15th 2019, and at the Machine Learning Meets Medical Imaging workshop in Shenzhen, China, on Oct 13th.
- **X. Pennec** gave the following plenary invited talks:
  - IPAM program on Geometry and Learning from Data in 3D and Beyond (Los Angeles, USA, 02/04).
  - CARS 2019 conference in Rennes (19/06).
  - the Academie des Sciences en région in Nice and Sophia Antipolis (21/06).

  He also gave invited lectures and seminars at: Copenhagen University (DK 18/03); the Institut Mathematique de Toulouse (27/05); the ENUMATH 2019 conference held in Egmond aan Zee (NL, 04/10); LJK-Deterministic Models and Algorithms: EDP-AIRSEA-CVGI Seminar, Univ Grenoble (16/12).
- **M. Sermesant** was an invited speaker at the European Heart Rhythm Association conference (18/03), eHealth Monaco (27/03), Cardiac Electromechanics workshop (15/04), EuroCMR (03/05), CVPR Medical Imaging workshop (16/05), Innovation Alzheimer summer school (26/06), Académie de Médecine working group on AI & Healthcare (10/09), Inria/SIMULA workshop (26/09), SOPH.I.A Summit (20/11) and TRM Forum (10/12).
- **N. Ayache** gave the following plenary invited talks:
  - AI for Healthcare: Hope & Challenges. Global Forum on AI for Humanity, Paris, 2019.
  - AI for Medical Imaging & Digital Twins, Keynote Lecture, Shezhen University, China 2019.
  - AI for e-medecine, 5th International Symposium on Multi-disciplinary Computational Anatomy, Fukuoka, Japan 2019.
  - Le jumeau numérique: images, modèles et IA. Académie nationale de médecine, Paris, 2019.
  - Intelligence Artificielle et médecine. Académie des Sciences, Nice, 2019.
  - La Santé à l'ère numérique, Institut de l'ENS, 2019.
  - Imaging in Cancer - Multimodal Analysis, iBV, Nice, 2019

9.1.6. Leadership within the Scientific Community

- **H. Delingette** is a member of the MICCAI Society Board of Directors.
- **H. Delingette** is elected as MICCAI Society's Fellows.

9.1.7. Scientific Expertise

- **M. Lorenzi** was reviewer of the funding agency ANR (Agence Nationale de la Recherche, France). He is providing scientific consulting for the company MyDataModels and Flexper through an Inria Tech research contract.
- **X. Pennec** was a reviewer for the funding agency Israel Science Foundation (ISF).

- **M. Sermesant** was an evaluator for the Wellcome Trust (UK), the NSF (USA) and the Netherlands research council.
- **H. Delingette** is a member of the scientific committee of the institute 3IA Côte d'Azur and was reviewer of the funding agency ANR (Agence Nationale de la Recherche, France).
- **N. Ayache** is a member of the following scientific committes:
  - 2016 -: Scientific advisory committee for Région Ile de France (20 members),
  - 2015 - 2019: Research Committee of Fondation pour la Recherche Médicale (18 members),
  - 2010 -: Scientific Advisory Boards in London (ICL,KCL,UCL), Oxford & Notthingham,
  - 2009 - 2019: Advisory Committee, Japan Initiative in Computational Anatomy, MEXT.

9.1.8. Research Administration

- **N. Ayache** is the scientific director of the 3IA Côte d'Azur since its creation in April 2019.
- **Marco Lorenzi** is a member of the local steering committee of the technological platforms (Comités Scientifiques de Pilotage des Plateformes) in charge of Cluster, Grid, Cloud, and HPC technologies. He is also member of the Scientific Board of the UCA NeuroMod Institute.
- **Xavier Pennec** is co-director of the Ecole doctorale STIC of Université Côte d'Azur. He is a member of the committee of EDSTIC, of the Doctoral follow-up Committee (CSD) at Inria Sophia Antipolis, and participated to the PhD fellowship granting committees of EDSTIC, Cofund at UCA, CORDI at Inria. He is a member of the "Comité de la Recherche Biomédicale en Santé Publique (CRBSP)" of the Nice University Hospital (CHU). At University Côte d'Azur / IDEX-JEDI, he is a member of the executive committee of the Academy 4 (Living systems Complexity and diversity), of the Scientific committee of the Academy 2 (Complex Systems), and of the Advanced Research Program Committee. He was elected member of the Evaluation Committee of Inria (Sep. 2019 to Aug. 2023) and participated to the promotion commission for CRCN, DR1, DR0.
- **M. Sermesant** is an elected member of the Inria Sophia Antipolis research centre committee.
- **Hervé Delingette** is a member of the local committee in charge of the scientific selection of visiting scientists (Comité NICE) and the local committee on the immersive platform. He is the director of the Academy of excellence on "Networks, Information and Digital Society" at the Université Côte d'Azur. He is the deputy director of the "Ecole Universitaire de recherche" entitled *Digital Systems for Humans* at Université Côte d'Azur. He is a representive of Inria at the Federation Hospitalo-Universitaire Oncoage led by the CHU Nice.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master: H. Delingette and X. Pennec, Introduction to Medical Image Analysis, 21h course (28.5 ETD), Master 2 MVA, ENS Saclay, France.

Master: H. Delingette and X. Pennec, Medical Image Processing, 30h course, M2 Data Science & AI, Univ. Côte d'Azur, France.

Master: H. Delingette, Data Visualization, 6h course, M1 Data Science & AI, Univ. Côte d'Azur, France.

Master: M. Lorenzi, Bayesian Learning, 30h course, Master Data Science, Univ. Côte d'Azur, France.

Master: M. Lorenzi, Model Selection and Resampling Methods, 30h course, Master Data Science, Univ. Côte d'Azur, France.

X. Pennec is a member of the pedagogical council of the Computational biology master QCSBD, Univ. Côte d'Azur, France.

9.2.2. Theses Defended

- Qiao Zheng, Deep learning for cardiac image analysis, Université Côte d'Azur. Started in January 2016. Co-directed by N. Ayache and H. Delingette. Defended on March the 27th, 2019.
- Pawel Mlynarski, Tumor segmentation based on Random Forests and Convolutional Neural Networks trained on partially annotaded data, Université Côte d'Azur. Started in December 2015. Co-directed by N. Ayache and H. Delingette. Defended on November the 15th, 2019.
- Raphaël Sivera, Analyse statistique de l'évolution de structures morphologiques partir de séquences temporelles d'IRM, Université Côte d'Azur. Started in October 2015. Co-directed by N. Ayache and H. Delingette and co-supervised by M. Lorenzi and X. Pennec. Defended on November the 29th, 2019.
- Shuman Jia, Population-based Model of Atrial Fibrillation: from Shape Statistics to Group-wise Physiology, Université Côte d'Azur. Started in 2016. Co-directed by M. Sermesant and X. Pennec. Defended on December the 18th 2019.

9.2.3. PhD in progress

- Clément Abi-Nader, Statistical Learning of Heterogeneous Data in Large-Scale Clinical Databases, Université Côte d'Azur. Started in 2017. Co-directed by P. Robert and N. Ayache and supervised by M. Lorenzi.
- Luigi Antelmi, Statistical learning on large databases of heterogeneous imaging, cognitive and behavioural data, Université Côte d'Azur. Started in 2017. Co-directed by P. Robert and N. Ayache and supervised by M. Lorenzi.
- Benoît Audelan, Joint biological and imaging markers for the diagnosis of severe lung diseases. Started in 2018. Co-directed by H. Delingette and N. Ayache.
- Tania-Marina Bacoyannis, Cardiac Imaging and Machine Learning for Electrostructural Tomography, Université Côte d'Azur. Started in 2017. Co-directed by M. Sermesant and H. Cochet.
- Jaume Banús Cobo, Heart & Brain: discovering the link between cardiovascular pathologies and neurodegeneration through biophysical and statistical models of cardiac and brain images, Université Côte d'Azur. Started in 2017. Directed by M. Sermesant and co-supervised by Marco Lorenzi.
- Nicolas Cedilnik, Personalised Modeling for Ventricular Tachycardia Ablation Planning, Université Côte d'Azur. Started in 2017. Co-directed by M. Sermesant and H Cochet.
- Florent Jousse, Analyse statistique de forme, de déformations et d'apparences de surfaces anatomiques pour l'aide à la dermatologie et à la chirurgie plastique. Started in 2019. Cifre fellowship with Quantificare. Co-directed by X. Pennec and H. Delingette.
- Buntheng Ly, Cardiac Image Analysis for Sudden Cardiac Death Prediction, Université Côte d'Azur. Started in 2019. Co-directed by M. Sermesant and H. Cochet.
- Nicolas Guigui, Statistical estimation on Riemannian and affine symmetric spaces with applications to the statistical survey of the brain anatomy, Université Côte d'Azur. Started in 2018. Directed by X. Pennec.
- Yann Thanwerdas, Statistical Dimension Reduction in Non-Linear Manifolds for Brain Shape Analysis, Connectomics & Brain-Computer Interfaces, Université Côte d'Azur. Started in 2019. Directed by X. Pennec.
- Wen Wei, Learning Brain Alterations in Multiple Sclerosis from Multimodal Neuroimaging Data, Université Côte d'Azur. Started in 2016. Co-directed by N.Ayache and O.Colliot.
- Julian Krebs, Robust image registration based on machine learning, Université Côte d'Azur. Started in 2016. Co-directed by H. Delingette and N. Ayache.
- Zihao WANG, Cochlear Implantation Modeling, Planning & Evaluation. Started in 2018. Directed by H. Delingette.

- Hind Dadoun, AI-Based Real Time Diagnosis of Abdominal Ultrasound, Université Côte d'Azur. Started in December 2019. Co-directed by N.Ayache and H.Delingette.
- Paul Tourniaire, AI-based selection of imaging and biological markers predictive of therapy response in lung cancer, Université Côte d'Azur. Started in 2019. Co-directed by N. Ayache and H. Delingette.

9.2.4. Juries

- Marco Lorenzi was invited jury member for the PhD defense of Remi Domingues (EURECOM, Sophia Antipolis).
- Xavier Pennec was reviewer and member of the jury for the PhDs of: Line Kuhnel, Univ. Copenhagen, DK, feb. 2019; Maxime Louis, UPMC, Sorbonne Universités, Paris, sep. 2019; Emilie Buessler, Univ. Grenoble-Alpes, Dec. 2019. He was President of the PhD jury of Emmanuelle Poulain, Univ Cote d'Azur, Oct. 2019, and President of the HDR jury of Olivier Commowick, Univ. Rennes, Jun. 2019.
- Maxime Sermesant was a reviewer for the PhD of Kenny Rumindo (Lyon).
- Hervé Delingette was a reviewer and member of the jury in the PhD thesis committee of H. Bertrand (ENST), defended on Jan. 8th 2019, of H. Oliveri (ENS LYon) defended on May 28th 2019.

9.3. Popularization

9.3.1. Interventions

- Maxime Sermesant did three 45 minutes interventions on Mathematics and Healthcare at the Jules Ferry High School in Cannes.
- Tania Bacoyannis and Nicolas Cedilnik presented AI for high school teachers and interacted with them on this topic during a day.

10. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

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[2] P. Mlynarski.*Deep Learning for Segmentation of Brain Tumors and Organs at Risk in Radiotherapy Planning*, Université Côte d'Azur, November 2019, https://hal.inria.fr/tel-02358374

[3] R. Sivera.*Modeling and measuring the brain morphological evolution using structural MRI in the context of neurodegenerative diseases*, Université Cote d'Azur, November 2019, https://hal.inria.fr/tel-02389924

[4] Q. Zheng.*Deep Learning for Robust Segmentation and Explainable Analysis of 3D and Dynamic Cardiac Images*, Inria - Sophia Antipolis, March 2019, https://hal.inria.fr/tel-02083415

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Project-Team FACTAS

Functional Analysis for ConcepTion and Assessment of Systems

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Optimization and control of dynamic systems

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Project-Team FACTAS

Creation of the Project-Team: 2019 July 01

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A6.2.5. - Numerical Linear Algebra
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B6.2.3. - Satellite technology

1. Team, Visitors, External Collaborators

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Sylvain Chevillard [Inria, Researcher]
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2. Overall Objectives

2.1. Research Themes

The team develops constructive, function-theoretic approaches to inverse problems arising in modeling and design, in particular for electro-magnetic systems as well as in the analysis of certain classes of signals.

Data typically consist of measurements or desired behaviors. The general thread is to approximate them by families of solutions to the equations governing the underlying system. This leads us to consider various interpolation and approximation problems in classes of rational and meromorphic functions, harmonic gradients, or solutions to more general elliptic partial differential equations (PDE), in connection with inverse potential problems. A recurring difficulty is to control the singularities of the approximants.

The mathematical tools pertain to complex and harmonic analysis, approximation theory, potential theory, system theory, differential topology, optimization and computer algebra. Targeted applications include:

- identification and synthesis of analog microwave devices (filters, amplifiers),
- non-destructive control from field measurements in medical engineering (source recovery in magneto/electro-encephalography), and paleomagnetism (determining the magnetization of rock samples).

In each case, the endeavor is to develop algorithms resulting in dedicated software.

3. Research Program

3.1. Introduction

Within the extensive field of inverse problems, much of the research by Factas deals with reconstructing solutions of classical elliptic PDEs from their boundary behavior. Perhaps the simplest example lies with harmonic identification of a stable linear dynamical system: the transfer-function f can be evaluated at a point $i\omega$ of the imaginary axis from the response to a periodic input at frequency ω. Since f is holomorphic in the right half-plane, it satisfies there the Cauchy-Riemann equation $\overline{\partial} f = 0$, and recovering f amounts to solve a Dirichlet problem which can be done in principle using, *e.g.* the Cauchy formula.

Practice is not nearly as simple, for f is only measured pointwise in the pass-band of the system which makes the problem ill-posed [70]. Moreover, the transfer function is usually sought in specific form, displaying the necessary physical parameters for control and design. For instance if f is rational of degree n, then $\overline{\partial} f = \sum_1^n a_j \delta_{z_j}$ where the z_j are its poles and δ_{z_j} is a Dirac unit mass at z_j. Thus, to find the domain of holomorphy (*i.e.* to locate the z_j) amounts to solve a (degenerate) free-boundary inverse problem, this time on the left half-plane. To address such questions, the team has developed a two-step approach as follows.

Step 1: To determine a complete model, that is, one which is defined at every frequency, in a sufficiently versatile function class (*e.g.* Hardy spaces). This ill-posed issue requires regularization, for instance constraints on the behavior at non-measured frequencies.

Step 2: To compute a reduced order model. This typically consists of rational approximation of the complete model obtained in step 1, or phase-shift thereof to account for delays. We emphasize that deriving a complete model in step 1 is crucial to achieve stability of the reduced model in step 2.

Step 1 relates to extremal problems and analytic operator theory, see Section 3.3.1. Step 2 involves optimization, and some Schur analysis to parametrize transfer matrices of given Mc-Millan degree when dealing with systems having several inputs and outputs, see Section 3.3.2.2. It also makes contact with the topology of rational functions, in particular to count critical points and to derive bounds, see Section 3.3.2. Step 2 raises further issues in approximation theory regarding the rate of convergence and the extent to which singularities of the approximant (*i.e.* its poles) tend to singularities of the approximated function; this is where logarithmic potential theory becomes instrumental, see Section 3.3.3.

Applying a realization procedure to the result of step 2 yields an identification procedure from incomplete frequency data which was first demonstrated in [76] to tune resonant microwave filters. Harmonic identification of nonlinear systems around a stable equilibrium can also be envisaged by combining the previous steps with exact linearization techniques from [34].

A similar path can be taken to approach design problems in the frequency domain, replacing the measured behavior by some desired behavior. However, describing achievable responses in terms of the design parameters is often cumbersome, and most constructive techniques rely on specific criteria adapted to the physics of the problem. This is especially true of filters, the design of which traditionally appeals to polynomial extremal problems [72], [57]. To this area, Apics contributed the use of Zolotarev-like problems for multi-band synthesis, although we presently favor interpolation techniques in which parameters arise in a more transparent manner, as well as convex relaxation of hyperbolic approximation problems, see Sections 3.2.2 and 6.2.2.

The previous example of harmonic identification quickly suggests a generalization of itself. Indeed, on identifying $\mathbb{C}$ with $\mathbb{R}^2$, holomorphic functions become conjugate-gradients of harmonic functions, so that harmonic identification is, after all, a special case of a classical issue: to recover a harmonic function on a domain from partial knowledge of the Dirichlet-Neumann data; when the portion of boundary where data are not available is itself unknown, we meet a free boundary problem. This framework for 2-D non-destructive control was first advocated in [62] and subsequently received considerable attention. It makes clear how to state similar problems in higher dimensions and for more general operators than the Laplacian, provided solutions are essentially determined by the trace of their gradient on part of the boundary which is the case for elliptic equations [0] [32], [80]. Such questions are particular instances of the so-called inverse potential problem, where a measure μ has to be recovered from the knowledge of the gradient of its potential (*i.e.*, the field) on part of a hypersurface (a curve in 2-D) encompassing the support of μ. For Laplace's operator, potentials are logarithmic in 2-D and Newtonian in higher dimensions. For elliptic operators with non constant coefficients, the potential depends on the form of fundamental solutions and is less manageable because it is no longer of convolution type. Nevertheless it is a useful concept bringing perspective on how problems could be raised and solved, using tools from harmonic analysis.

Inverse potential problems are severely indeterminate because infinitely many measures within an open set of $\mathbb{R}^n$ produce the same field outside this set; this phenomenon is called *balayage* [69]. In the two steps approach previously described, we implicitly removed this indeterminacy by requiring in step 1 that the measure be supported on the boundary (because we seek a function holomorphic throughout the right half-space), and by requiring in step 2 that the measure be discrete in the left half-plane (in fact: a finite sum of point masses $\sum_1^N a_j\delta_{z_j}$). The discreteness assumption also prevails in 3-D inverse source problems, see Section 4.3. Conditions that ensure uniqueness of the solution to the inverse potential problem are part of the so-called regularizing assumptions which are needed in each case to derive efficient algorithms.

To recap, the gist of our approach is to approximate boundary data by (boundary traces of) fields arising from potentials of measures with specific support. This differs from standard approaches to inverse problems, where descent algorithms are applied to integration schemes of the direct problem; in such methods, it is the equation which gets approximated (in fact: discretized).

[0] There is a subtle difference here between dimension 2 and higher. Indeed, a function holomorphic on a plane domain is defined by its non-tangential limit on a boundary subset of positive linear measure, but there are non-constant harmonic functions in the 3-D ball, C^1 up to the boundary sphere, yet having vanishing gradient on a subset of positive measure of the sphere. Such a "bad" subset, however, cannot have interior points on the sphere.

Along these lines, Factas advocates the use of steps 1 and 2 above, along with some singularity analysis, to approach issues of nondestructive control in 2-D and 3-D [2], [41], [45]. The team is currently engaged in the generalization to inverse source problems for the Laplace equation in 3-D, to be described further in Section 3.2.1. There, holomorphic functions are replaced by harmonic gradients; applications are to inverse source problems in neurosciences (in particular in EEG/MEG) and inverse magnetization problems in geosciences, see Section 4.3.

The approximation-theoretic tools developed by Apics and now by Factas to handle issues mentioned so far are outlined in Section 3.3. In Section 3.2 to come, we describe in more detail which problems are considered and which applications are targeted.

Note that the Inria project-team Apics reached the end of its life cycle by the end of 2017. The proposal for our new team Factas was processed by the CEP (Comité des Équipes-Projets) of the Research Center in 2018, and approved by the head of the Institute in 2019.

3.2. Range of inverse problems

3.2.1. Elliptic partial differential equations (PDE)

Participants: Paul Asensio, Laurent Baratchart, Sylvain Chevillard, Juliette Leblond, Masimba Nemaire, Konstantinos Mavreas.

By standard properties of conjugate differentials, reconstructing Dirichlet-Neumann boundary conditions for a function harmonic in a plane domain, when these conditions are already known on a subset E of the boundary, is equivalent to recover a holomorphic function in the domain from its boundary values on E. This is the problem raised on the half-plane in step 1 of Section 3.1. It makes good sense in holomorphic Hardy spaces where functions are entirely determined by their values on boundary subsets of positive linear measure, which is the framework for Problem (P) that we set up in Section 3.3.1. Such issues naturally arise in nondestructive testing of 2-D (or 3-D cylindrical) materials from partial electrical measurements on the boundary. For instance, the ratio between the tangential and the normal currents (the so-called Robin coefficient) tells one about corrosion of the material. Thus, solving Problem (P) where ψ is chosen to be the response of some uncorroded piece with identical shape yields non destructive testing of a potentially corroded piece of material, part of which is inaccessible to measurements. This was an initial application of holomorphic extremal problems to non-destructive control [55], [58].

Another application by the team deals with non-constant conductivity over a doubly connected domain, the set E being now the outer boundary. Measuring Dirichlet-Neumann data on E, one wants to recover level lines of the solution to a conductivity equation, which is a so-called free boundary inverse problem. For this, given a closed curve inside the domain, we first quantify how constant the solution on this curve. To this effect, we state and solve an analog of Problem (P), where the constraint bears on the real part of the function on the curve (it should be close to a constant there), in a Hardy space of a conjugate Beltrami equation, of which the considered conductivity equation is the compatibility condition (just like the Laplace equation is the compatibility condition of the Cauchy-Riemann system). Subsequently, a descent algorithm on the curve leads one to improve the initial guess. For example, when the domain is regarded as separating the edge of a tokamak's vessel from the plasma (rotational symmetry makes this a 2-D situation), this method can be used to estimate the shape of a plasma subject to magnetic confinement.

This was actually carried out in collaboration with CEA (French nuclear agency) and the University of Nice (JAD Lab.), to data from *Tore Supra* in [61]. The procedure is fast because no numerical integration of the underlying PDE is needed, as an explicit basis of solutions to the conjugate Beltrami equation in terms of Bessel functions was found in this case. Generalizing this approach in a more systematic manner to free boundary problems of Bernoulli type, using descent algorithms based on shape-gradient for such approximation-theoretic criteria, is an interesting prospect to the team.

The piece of work we just mentioned requires defining and studying Hardy spaces of conjugate Beltrami equations, which is an interesting topic. For Sobolev-smooth coefficients of exponent greater than 2, they were investigated in [6], [35]. The case of the critical exponent 2 is treated in [31], which apparently provides the first example of well-posed Dirichlet problem in the non-strictly elliptic case: the conductivity may be unbounded or zero on sets of zero capacity and, accordingly, solutions need not be locally bounded. More importantly perhaps, the exponent 2 is also the key to a corresponding theory on very general (still rectifiable) domains in the plane, as coefficients of pseudo-holomorphic functions obtained by conformal transformation onto a disk are merely of L^2-class in general, even if the initial problem deals with coefficients of L^r-class for some $r > 2$. Such generalizations are now under study within the team.

Generalized Hardy classes as above are used in [32] where we address the uniqueness issue in the classical Robin inverse problem on a Lipschitz domain of $\Omega \subset \mathbb{R}^n$, $n \geq 2$, with uniformly bounded Robin coefficient, L^2 Neumann data and conductivity of Sobolev class $W^{1,r}(\Omega)$, $r > n$. We show that uniqueness of the Robin coefficient on a subset of the boundary, given Cauchy data on the complementary part, does hold in dimension $n = 2$, thanks to a unique continuation result, but needs not hold in higher dimension. In higher dimension, this raises an open issue on harmonic gradients, namely whether the positivity of the Robin coefficient is compatible with identical vanishing of the boundary gradient on a subset of positive measure.

The 3-D version of step 1 in Section 3.1 is another subject investigated by Factas: to recover a harmonic function (up to an additive constant) in a ball or a half-space from partial knowledge of its gradient. This prototypical inverse problem (*i.e.* inverse to the Cauchy problem for the Laplace equation) often recurs in electromagnetism. At present, Factas is involved with solving instances of this inverse problem arising in two fields, namely medical imaging *e.g.* for electroencephalography (EEG) or magneto-encephalography (MEG), and paleomagnetism (recovery of rocks magnetization) [2], [37], see Section 6.1. In this connection, we collaborate with two groups of partners: Athena Inria project-team and INS (Institut de Neurosciences des Systèmes, http://ins.univ-amu.fr/), hospital la Timone, Aix-Marseille Univ., on the one hand, Geosciences Lab. at MIT and Cerege CNRS Lab. on the other hand. The question is considerably more difficult than its 2-D counterpart, due mainly to the lack of multiplicative structure for harmonic gradients. Still, substantial progress has been made over the last years using methods of harmonic analysis and operator theory.

The team is further concerned with 3-D generalizations and applications to non-destructive control of step 2 in Section 3.1. A typical problem is here to localize inhomogeneities or defaults such as cracks, sources or occlusions in a planar or 3-dimensional object, knowing thermal, electrical, or magnetic measurements on the boundary. These defaults can be expressed as a lack of harmonicity of the solution to the associated Dirichlet-Neumann problem, thereby posing an inverse potential problem in order to recover them. In 2-D, finding an optimal discretization of the potential in Sobolev norm amounts to solve a best rational approximation problem, and the question arises as to how the location of the singularities of the approximant (*i.e.* its poles) reflects the location of the singularities of the potential (*i.e.* the defaults we seek). This is a fairly deep issue in approximation theory, to which Apics contributed convergence results for certain classes of fields expressed as Cauchy integrals over extremal contours for the logarithmic potential [8], [38], [52]. Initial schemes to locate cracks or sources *via* rational approximation on planar domains were obtained this way [41], [45], [55]. It is remarkable that finite inverse source problems in 3-D balls, or more general algebraic surfaces, can be approached using these 2-D techniques upon slicing the domain into planar sections [9], [42]. More precisely, each section cuts out a planar domain, the boundary of which carries data which can be proved to match an algebraic function. The singularities of this algebraic function are not located at the 3-D sources, but are related to them: the section contains a source if and only if some function of the singularities in that section meets a relative extremum. Using bisection it is thus possible to determine an extremal place along all sections parallel to a given plane direction, up to some threshold which has to be chosen small enough that one does not miss a source. This way, we reduce the original source problem in 3-D to a sequence of inverse poles and branchpoints problems in 2-D. This bottom line generates a steady research activity within Factas, and again applications are sought to medical imaging and geosciences, see Sections 4.3, 4.2 and 6.1.

Conjectures may be raised on the behavior of optimal potential discretization in 3-D, but answering them is an ambitious program still in its infancy.

3.2.2. Systems, transfer and scattering

Participants: Laurent Baratchart, Sylvain Chevillard, Adam Cooman, Martine Olivi, Fabien Seyfert.

Through contacts with CNES (French space agency), members of the team became involved in identification and tuning of microwave electromagnetic filters used in space telecommunications, see Section 4.4. The initial problem was to recover, from band-limited frequency measurements, physical parameters of the device under examination. The latter consists of interconnected dual-mode resonant cavities with negligible loss, hence its scattering matrix is modeled by a 2×2 unitary-valued matrix function on the frequency line, say the imaginary axis to fix ideas. In the bandwidth around the resonant frequency, a modal approximation of the Helmholtz equation in the cavities shows that this matrix is approximately rational, of Mc-Millan degree twice the number of cavities.

This is where system theory comes into play, through the so-called *realization* process mapping a rational transfer function in the frequency domain to a state-space representation of the underlying system of linear differential equations in the time domain. Specifically, realizing the scattering matrix allows one to construct a virtual electrical network, equivalent to the filter, the parameters of which mediate in between the frequency response and the geometric characteristics of the cavities (*i.e.* the tuning parameters).

Hardy spaces provide a framework to transform this ill-posed issue into a series of regularized analytic and meromorphic approximation problems. More precisely, the procedure sketched in Section 3.1 goes as follows:

1. infer from the pointwise boundary data in the bandwidth a stable transfer function (*i.e.* one which is holomorphic in the right half-plane), that may be infinite dimensional (numerically: of high degree). This is done by solving a problem analogous to (P) in Section 3.3.1, while taking into account prior knowledge on the decay of the response outside the bandwidth, see [13] for details.
2. A stable rational approximation of appropriate degree to the model obtained in the previous step is performed. For this, a descent method on the compact manifold of inner matrices of given size and degree is used, based on an original parametrization of stable transfer functions developed within the team [27], [13].
3. Realizations of this rational approximant are computed. To be useful, they must satisfy certain constraints imposed by the geometry of the device. These constraints typically come from the coupling topology of the equivalent electrical network used to model the filter. This network is composed of resonators, coupled according to some specific graph. This realization step can be recast, under appropriate compatibility conditions [56], as solving a zero-dimensional multivariate polynomial system. To tackle this problem in practice, we use Gröbner basis techniques and continuation methods which team up in the Dedale-HF software (see Section 3.4.2).

We recently started a collaboration with the Chinese Hong Kong University on the topic of frequency depending couplings appearing in the equivalent circuits we compute [19] continuing our work [1] on wide-band design applications.

Factas also investigates issues pertaining to design rather than identification. Given the topology of the filter, a basic problem in this connection is to find the optimal response subject to specifications that bear on rejection, transmission and group delay of the scattering parameters. Generalizing the classical approach based on Chebyshev polynomials for single band filters, we recast the problem of multi-band response synthesis as a generalization of the classical Zolotarev min-max problem for rational functions [26] [12]. Thanks to quasi-convexity, the latter can be solved efficiently using iterative methods relying on linear programming. These were implemented in the software easy-FF (see easy-FF). Currently, the team is engaged in the synthesis of more complex microwave devices like multiplexers and routers, which connect several filters through wave guides. Schur analysis plays an important role here, because scattering matrices of passive systems are of Schur type (*i.e.* contractive in the stability region). The theory originates with the work of I. Schur [75], who devised a recursive test to check for contractivity of a holomorphic function in the disk. The so-called Schur parameters of a function may be viewed as Taylor coefficients for the hyperbolic metric of the disk, and the fact that Schur functions are contractions for that metric lies at the root of Schur's test. Generalizations thereof turn out to be efficient to parametrize solutions to contractive interpolation problems [28]. Dwelling on this, Factas contributed differential parametrizations (atlases of charts) of lossless matrix functions [27], [71], [66] which are fundamental to our rational approximation software RARL2 (see Section 3.4.5). Schur analysis is also instrumental to approach de-embedding issues, and provides one with considerable insight into the so-called matching problem. The latter consists in maximizing the power a multiport can pass to a given load, and for reasons of efficiency it is all-pervasive in microwave and electric network design, *e.g.* of antennas, multiplexers, wifi cards and more. It can be viewed as a rational approximation problem in the hyperbolic metric, and the team presently deals with this hot topic using contractive interpolation with constraints on boundary peak points, within the framework of the (defense funded) ANR Cocoram, see Sections 6.2.

In recent years, our attention was driven by CNES and UPV (Bilbao) to questions about stability of high-frequency amplifiers. Contrary to previously discussed devices, these are *active* components. The response of an amplifier can be linearized around a set of primary current and voltages, and then admittances of the corresponding electrical network can be computed at various frequencies, using the so-called harmonic balance method. The initial goal is to check for stability of the linearized model, so as to ascertain existence of a well-defined working state. The network is composed of lumped electrical elements namely inductors, capacitors, negative *and* positive resistors, transmission lines, and controlled current sources. Our research so far has focused on describing the algebraic structure of admittance functions, so as to set up a function-theoretic framework where the two-steps approach outlined in Section 3.1 can be put to work. The main discovery is that the unstable part of each partial transfer function is rational and can be computed by analytic projection, see Section 6.3. We now start investigating the linearized harmonic transfer-function around a periodic cycle, to check for stability under non necessarily small inputs. This topic generates the doctoral work of S. Fueyo.

3.3. Approximation

Participants: Laurent Baratchart, Sylvain Chevillard, Juliette Leblond, Martine Olivi, Fabien Seyfert.

3.3.1. Best analytic approximation

In dimension 2, the prototypical problem to be solved in step 1 of Section 3.1 may be described as: given a domain $D \subset \mathbb{R}^2$, to recover a holomorphic function from its values on a subset K of the boundary of D. For the discussion it is convenient to normalize D, which can be done by conformal mapping. So, in the simply connected case, we fix D to be the unit disk with boundary unit circle T. We denote by H^p the Hardy space of exponent p, which is the closure of polynomials in $L^p(T)$-norm if $1 \le p < \infty$ and the space of bounded holomorphic functions in D if $p = \infty$. Functions in H^p have well-defined boundary values in $L^p(T)$, which makes it possible to speak of (traces of) analytic functions on the boundary.

To find an analytic function g in D matching some measured values f approximately on a sub-arc K of T, we formulate a constrained best approximation problem as follows.

> (P) Let $1 \le p \le \infty$, K a sub-arc of T, $f \in L^p(K)$, $\psi \in L^p(T \setminus K)$ and $M > 0$; find a function $g \in H^p$ such that $\|g - \psi\|_{L^p(T \setminus K)} \le M$ and $g - f$ is of minimal norm in $L^p(K)$ under this constraint.

Here ψ is a reference behavior capturing *a priori* assumptions on the behavior of the model off K, while M is some admissible deviation thereof. The value of p reflects the type of stability which is sought and how much one wants to smooth out the data. The choice of L^p classes is suited to handle pointwise measurements.

To fix terminology, we refer to (P) as a *bounded extremal problem*. As shown in [40], [43], [49], the solution to this convex infinite-dimensional optimization problem can be obtained when $p \neq 1$ upon iterating with respect to a Lagrange parameter the solution to spectral equations for appropriate Hankel and Toeplitz operators. These spectral equations involve the solution to the special case $K = T$ of (P), which is a standard extremal problem [64]:

> (P_0) Let $1 \le p \le \infty$ and $\varphi \in L^p(T)$; find a function $g \in H^p$ such that $g - \varphi$ is of minimal norm in $L^p(T)$.

In the case $p = 1$, partial results are known but computational issues remain open.

Various modifications of (P) can be tailored to meet specific needs. For instance when dealing with lossless transfer functions (see Section 4.4), one may want to express the constraint on $T \setminus K$ in a pointwise manner: $|g - \psi| \leq M$ a.e. on $T \setminus K$, see [44]. In this form, the problem comes close to (but still is different from) H^∞ frequency optimization used in control [67], [74]. One can also impose bounds on the real or imaginary part of $g - \psi$ on $T \setminus K$, which is useful when considering Dirichlet-Neumann problems.

The analog of Problem (P) on an annulus, K being now the outer boundary, can be seen as a means to regularize a classical inverse problem occurring in nondestructive control, namely to recover a harmonic function on the inner boundary from Dirichlet-Neumann data on the outer boundary (see Sections 3.2.1, 4.3, 6.1.3). It may serve as a tool to approach Bernoulli type problems, where we are given data on the outer boundary and we *seek the inner boundary*, knowing it is a level curve of the solution. In this case, the Lagrange parameter indicates how to deform the inner contour in order to improve data fitting. Similar topics are discussed in Section 3.2.1 for more general equations than the Laplacian, namely isotropic conductivity equations of the form $\mathrm{div}(\sigma \nabla u) = 0$ where σ is no longer constant (*i.e.*, varies in the space). Then, the Hardy spaces in Problem (P) are those of a so-called conjugate Beltrami equation: $\overline{\partial} f = \nu \overline{\partial f}$ [68], which are studied for $1 < p < \infty$ in [6], [31], [35] and [59]. Expansions of solutions needed to constructively handle such issues in the specific case of linear fractional conductivities (occurring for instance in plasma shaping) have been expounded in [61].

Though originally considered in dimension 2, Problem (P) carries over naturally to higher dimensions where analytic functions get replaced by gradients of harmonic functions. Namely, given some open set $\Omega \subset \mathbb{R}^n$ and some $\mathbb{R}^n$-valued vector field V on an open subset O of the boundary of Ω, we seek a harmonic function in Ω whose gradient is close to V on O.

When Ω is a ball or a half-space, a substitute for holomorphic Hardy spaces is provided by the Stein-Weiss Hardy spaces of harmonic gradients [78]. Conformal maps are no longer available when $n > 2$, so that Ω can no longer be normalized. More general geometries than spheres and half-spaces have not been much studied so far.

On the ball, the analog of Problem (P) is

> (P_1) Let $1 \leq p \leq \infty$ and $B \subset \mathbb{R}^n$ the unit ball. Fix O an open subset of the unit sphere $S \subset \mathbb{R}^n$. Let further $V \in L^p(O)$ and $W \in L^p(S \setminus O)$ be $\mathbb{R}^n$-valued vector fields. Given $M > 0$, find a harmonic gradient $G \in H^p(B)$ such that $\|G - W\|_{L^p(S \setminus O)} \leq M$ and $G - V$ is of minimal norm in $L^p(O)$ under this constraint.

When $p = 2$, Problem (P_1) was solved in [2] as well as its analog on a shell, when the tangent component of V is a gradient (when O is Lipschitz the general case follows easily from this). The solution extends the work in [40] to the 3-D case, using a generalization of Toeplitz operators. The case of the shell was motivated by applications to the processing of EEG data. An important ingredient is a refinement of the Hodge decomposition, that we call the *Hardy-Hodge* decomposition, allowing us to express a $\mathbb{R}^n$-valued vector field in $L^p(S)$, $1 < p < \infty$, as the sum of a vector field in $H^p(B)$, a vector field in $H^p(\mathbb{R}^n \setminus \overline{B})$, and a tangential divergence free vector field on S; the space of such divergence-free fields is denoted by $D(S)$. If $p = 1$ or $p = \infty$, L^p must be replaced by the real Hardy space or the space of functions with bounded mean oscillation. More generally this decomposition, which is valid on any sufficiently smooth surface (see Section 6.1), seems to play a fundamental role in inverse potential problems. In fact, it was first introduced formally on the plane to describe silent magnetizations supported in $\mathbb{R}^2$ (*i.e.* those generating no field in the upper half space) [37].

Just like solving problem (P) appeals to the solution of problem (P_0), our ability to solve problem (P_1) will depend on the possibility to tackle the special case where $O = S$:

> (P_2) Let $1 \leq p \leq \infty$ and $V \in L^p(S)$ be a $\mathbb{R}^n$-valued vector field. Find a harmonic gradient $G \in H^p(B)$ such that $\|G - V\|_{L^p(S)}$ is minimum.

Problem (P_2) is simple when $p = 2$ by virtue of the Hardy-Hodge decomposition together with orthogonality of $H^2(B)$ and $H^2(\mathbb{R}^n \setminus \overline{B})$, which is the reason why we were able to solve (P_1) in this case. Other values of

p cannot be treated as easily and are still under investigation, especially the case $p = \infty$ which is of particular interest and presents itself as a 3-D analog to the Nehari problem [73].

Companion to problem (P_2) is problem (P_3) below.

> (P_3) Let $1 \leq p \leq \infty$ and $V \in L^p(S)$ be a $\mathbb{R}^n$-valued vector field. Find $G \in H^p(B)$ and $D \in D(S)$ such that $\|G + D - V\|_{L^p(S)}$ is minimum.

Note that (P_2) and (P_3) are identical in 2-D, since no non-constant tangential divergence-free vector field exists on T. It is no longer so in higher dimension, where both (P_2) and (P_3) arise in connection with inverse potential problems in divergence form, like source recovery in electro/magneto encephalography and paleomagnetism, see Sections 3.2.1 and 4.3.

3.3.2. Best meromorphic and rational approximation

The techniques set forth in this section are used to solve step 2 in Section 3.2 and they are instrumental to approach inverse boundary value problems for the Poisson equation $\Delta u = \mu$, where μ is some (unknown) measure.

3.3.2.1. Scalar meromorphic and rational approximation

We put R_N for the set of rational functions with at most N poles in D. By definition, meromorphic functions in $L^p(T)$ are (traces of) functions in $H^p + R_N$.

A natural generalization of problem (P_0) is:

> (P_N) Let $1 \leq p \leq \infty$, $N \geq 0$ an integer, and $f \in L^p(T)$; find a function $g_N \in H^p + R_N$ such that $g_N - f$ is of minimal norm in $L^p(T)$.

Only for $p = \infty$ and f continuous is it known how to solve (P_N) in semi-closed form. The unique solution is given by AAK theory (named after Adamjan, Arov and Krein), which connects the spectral decomposition of Hankel operators with best approximation [73].

The case where $p = 2$ is of special importance for it reduces to rational approximation. Indeed, if we write the Hardy decomposition $f = f^+ + f^-$ where $f^+ \in H^2$ and $f^- \in H^2(\mathbb{C} \setminus \overline{D})$, then $g_N = f^+ + r_N$ where r_N is a best approximant to f^- from R_N in $L^2(T)$. Moreover, r_N has no pole outside D, hence it is a *stable* rational approximant to f^-. However, in contrast to the case where $p = \infty$, this best approximant may *not* be unique.

The Miaou project (predecessor of Apics) already designed a dedicated steepest-descent algorithm for the case $p = 2$ whose convergence to a *local minimum* is guaranteed; the algorithm ha evolved over years and still now, it seems to be the only procedure meeting this property. This gradient algorithm proceeds recursively with respect to N on a compactification of the parameter space [33]. Although it has proved to be effective in all applications carried out so far (see Sections 4.3, 4.4), it is still unknown whether the absolute minimum can always be obtained by choosing initial conditions corresponding to *critical points* of lower degree (as is done by the RARL2 software, Section 3.4.5).

In order to establish global convergence results, Apics has undertaken a deeper study of the number and nature of critical points (local minima, saddle points, ...), in which tools from differential topology and operator theory team up with classical interpolation theory [46], [48]. Based on this work, uniqueness or asymptotic uniqueness of the approximant was proved for certain classes of functions like transfer functions of relaxation systems (*i.e.* Markov functions) [50] and more generally Cauchy integrals over hyperbolic geodesic arcs [53]. These are the only results of this kind. Research by Apics on this topic remained dormant for a while by reasons of opportunity, but revisiting the work [29] in higher dimension is a worthy and timely endeavor today. Meanwhile, an analog to AAK theory was carried out for $2 \leq p < \infty$ in [49]. Although not as effective computationally, it was recently used to derive lower bounds [5]. When $1 \leq p < 2$, problem (P_N) is still quite open.

A common feature to the above-mentioned problems is that critical point equations yield non-Hermitian orthogonality relations for the denominator of the approximant. This stresses connections with interpolation, which is a standard way to build approximants, and in many respects best or near-best rational approximation may be regarded as a clever manner to pick interpolation points. This was exploited in [54], [51], and is used in an essential manner to assess the behavior of poles of best approximants to functions with branched singularities, which is of particular interest for inverse source problems (*cf.* Sections 3.4.3 and 6.1).

In higher dimensions, the analog of Problem (P_N) is best approximation of a vector field by gradients of discrete potentials generated by N point masses. This basic issue is by no means fully understood, and it is an exciting field of research. It is connected with certain generalizations of Toeplitz or Hankel operators, and with constructive approaches to so-called weak factorizations for real Hardy functions [60].

Besides, certain constrained rational approximation problems, of special interest in identification and design of passive systems, arise when putting additional requirements on the approximant, for instance that it should be smaller than 1 in modulus (*i.e.* a Schur function). In particular, Schur interpolation lately received renewed attention from the team, in connection with matching problems. There, interpolation data are subject to a well-known compatibility condition (positive definiteness of the so-called Pick matrix), and the main difficulty is to put interpolation points on the boundary of D while controlling both the degree and the extremal points (peak points for the modulus) of the interpolant. Results obtained by Apics in this direction generalize a variant of contractive interpolation with degree constraint as studied in [65]. We mention that contractive interpolation with nodes approaching the boundary has been a subsidiary research topic by the team in the past, which plays an interesting role in the spectral representation of certain non-stationary stochastic processes [36], [39].

3.3.2.2. Matrix-valued rational approximation

Matrix-valued approximation is necessary to handle systems with several inputs and outputs but it generates additional difficulties as compared to scalar-valued approximation, both theoretically and algorithmically. In the matrix case, the McMillan degree (*i.e.* the degree of a minimal realization in the System-Theoretic sense) generalizes the usual notion of degree for rational functions. For instance when poles are simple, the McMillan degree is the sum of the ranks of the residues.

The basic problem that we consider now goes as follows: *let* $\mathcal{F} \in (H^2)^{m\times l}$ *and* n *an integer; find a rational matrix of size* $m \times l$ *without poles in the unit disk and of McMillan degree at most* n *which is nearest possible to* $\mathcal{F}$ *in* $(H^2)^{m\times l}$. Here the L^2 norm of a matrix is the square root of the sum of the squares of the norms of its entries.

The scalar approximation algorithm derived in [33] and mentioned in Section 3.3.2.1 generalizes to the matrix-valued situation [63]. The first difficulty here is to parametrize inner matrices (*i.e.* matrix-valued functions analytic in the unit disk and unitary on the unit circle) of given McMillan degree degree n. Indeed, inner matrices play the role of denominators in fractional representations of transfer matrices (using the so-called Douglas-Shapiro-Shields factorization). The set of inner matrices of given degree is a smooth manifold that allows one to use differential tools as in the scalar case. In practice, one has to produce an atlas of charts (local parametrizations) and to handle changes of charts in the course of the algorithm. Such parametrization can be obtained using interpolation theory and Schur-type algorithms, the parameters of which are vectors or matrices ([27], [66], [71]). Some of these parametrizations are also interesting to compute realizations and achieve filter synthesis ([66], [71]). The rational approximation software "RARL2" developed by the team is described in Section 3.4.5.

Difficulties relative to multiple local minima of course arise in the matrix-valued case as well, and deriving criteria that guarantee uniqueness is even more difficult than in the scalar case. The case of rational functions of degree n or small perturbations thereof (the consistency problem) was solved in [47]. Matrix-valued Markov functions are the only known example beyond this one [30].

Let us stress that RARL2 seems the only algorithm handling rational approximation in the matrix case that demonstrably converges to a local minimum while meeting stability constraints on the approximant. It is still a working pin of many developments by Factas on frequency optimization and design.

3.3.3. Behavior of poles of meromorphic approximants

Participant: Laurent Baratchart.

We refer here to the behavior of poles of best meromorphic approximants, in the L^p-sense on a closed curve, to functions f defined as Cauchy integrals of complex measures whose support lies inside the curve. Normalizing the contour to be the unit circle T, we are back to Problem (P_N) in Section 3.3.2.1; invariance of the latter under conformal mapping was established in [45]. Research so far has focused on functions whose singular set inside the contour is polar, meaning that the function can be continued analytically (possibly in a multiple-valued manner) except over a set of logarithmic capacity zero.

Generally speaking in approximation theory, assessing the behavior of poles of rational approximants is essential to obtain error rates as the degree goes large, and to tackle constructive issues like uniqueness. However, as explained in Section 3.2.1, the original twist by Apics, now Factas, is to consider this issue also as a means to extract information on singularities of the solution to a Dirichlet-Neumann problem. The general theme is thus: *how do the singularities of the approximant reflect those of the approximated function?* This approach to inverse problem for the 2-D Laplacian turns out to be attractive when singularities are zero- or one-dimensional (see Section 4.3). It can be used as a computationally cheap initial condition for more precise but much heavier numerical optimizations which often do not even converge unless properly initialized. As regards crack detection or source recovery, this approach boils down to analyzing the behavior of best meromorphic approximants of given pole cardinality to a function with branch points, which is the prototype of a polar singular set. For piecewise analytic cracks, or in the case of sources, we were able to prove ([8], [45], [38]), that the poles of the approximants accumulate, when the degree goes large, to some extremal cut of minimum weighted logarithmic capacity connecting the singular points of the crack, or the sources [41]. Moreover, the asymptotic density of the poles turns out to be the Green equilibrium distribution on this cut in D, therefore it charges the singular points if one is able to approximate in sufficiently high degree (this is where the method could fail, because high-order approximation requires rather precise data).

The case of two-dimensional singularities is still an outstanding open problem.

It is remarkable that inverse source problems inside a sphere or an ellipsoid in 3-D can be approached with such 2-D techniques, as applied to planar sections, see Section 6.1. The technique is implemented in the software FindSources3D, see Section 3.4.3.

3.4. Software tools of the team

In addition to the above-mentioned research activities, Factas develops and maintains a number of long-term software tools that either implement and illustrate effectiveness of the algorithms theoretically developed by the team or serve as tools to help further research by team members. We present briefly the most important of them.

3.4.1. Pisa

KEYWORDS: Electrical circuit - Stability

FUNCTIONAL DESCRIPTION: To minimise prototyping costs, the design of analog circuits is performed using computer-aided design tools which simulate the circuit's response as accurately as possible.

Some commonly used simulation tools do not impose stability, which can result in costly errors when the prototype turns out to be unstable. A thorough stability analysis is therefore a very important step in circuit design. This is where pisa is used.

pisa is a Matlab toolbox that allows designers of analog electronic circuits to determine the stability of their circuits in the simulator. It analyses the impedance presented by a circuit to determine the circuit's stability. When an instability is detected, pisa can estimate location of the unstable poles to help designers fix their stability issue.

RELEASE FUNCTIONAL DESCRIPTION: First version

- Authors: Adam Cooman, David Martinez Martinez, Fabien Seyfert and Martine Olivi
- Contact: Fabien Seyfert
- Publications: Model-Free Closed-Loop Stability Analysis: A Linear Functional Approach - On Transfer Functions Realizable with Active Electronic Components
- URL: https://project.inria.fr/pisa

3.4.2. DEDALE-HF

SCIENTIFIC DESCRIPTION

Dedale-HF consists in two parts: a database of coupling topologies as well as a dedicated predictor-corrector code. Roughly speaking each reference file of the database contains, for a given coupling topology, the complete solution to the coupling matrix synthesis problem (C.M. problem for short) associated to particular filtering characteristics. The latter is then used as a starting point for a predictor-corrector integration method that computes the solution to the C.M. corresponding to the user-specified filter characteristics. The reference files are computed off-line using Gröbner basis techniques or numerical techniques based on the exploration of a monodromy group. The use of such continuation techniques, combined with an efficient implementation of the integrator, drastically reduces the computational time.

Dedale-HF has been licensed to, and is currently used by TAS-Espana
FUNCTIONAL DESCRIPTION

Dedale-HF is a software dedicated to solve exhaustively the coupling matrix synthesis problem in reasonable time for the filtering community. Given a coupling topology, the coupling matrix synthesis problem consists in finding all possible electromagnetic coupling values between resonators that yield a realization of given filter characteristics. Solving the latter is crucial during the design step of a filter in order to derive its physical dimensions, as well as during the tuning process where coupling values need to be extracted from frequency measurements.

- Participant: Fabien Seyfert
- Contact: Fabien Seyfert
- URL: http://www-sop.inria.fr/apics/Dedale/

3.4.3. FindSources3D

KEYWORDS: Health - Neuroimaging - Visualization - Compilers - Medical - Image - Processing
FindSources3D is a software program dedicated to the resolution of inverse source problems in electroencephalography (EEG). From pointwise measurements of the electrical potential taken by electrodes on the scalp, FindSources3D estimates pointwise dipolar current sources within the brain in a spherical model.

After a first data transmission “cortical mapping” step, it makes use of best rational approximation on 2-D planar cross-sections and of the software RARL2 in order to locate singularities. From those planar singularities, the 3-D sources are estimated in a last step, see [9].

The present version of FindSources3D (called FindSources3D-bolis) provides a modular, ergonomic, accessible and interactive platform, with a convenient graphical interface for EEG medical imaging. Modularity is now granted (using the tools dtk, Qt, with compiled Matlab libraries). It offers a detailed and nice visualization of data and tuning parameters, processing steps, and of the computed results (using VTK).

A new version is being developed that will incorporate a first Singular Value Decomposition (SVD) step in order to be able to handle time dependent data and to find the corresponding principal static components.

- Participants: Juliette Leblond, Maureen Clerc (team Athena, Inria Sophia), Jean-Paul Marmorat, Théodore Papadopoulo (team Athena).
- Contact: Juliette Leblond
- URL: http://www-sop.inria.fr/apics/FindSources3D/en/index.html

3.4.4. PRESTO-HF

SCIENTIFIC DESCRIPTION

For the matrix-valued rational approximation step, Presto-HF relies on RARL2. Constrained realizations are computed using the Dedale-HF software. As a toolbox, Presto-HF has a modular structure, which allows one for example to include some building blocks in an already existing software.

The delay compensation algorithm is based on the following assumption: far off the pass-band, one can reasonably expect a good approximation of the rational components of S11 and S22 by the first few terms of their Taylor expansion at infinity, a small degree polynomial in 1/s. Using this idea, a sequence of quadratic convex optimization problems are solved, in order to obtain appropriate compensations. In order to check the previous assumption, one has to measure the filter on a larger band, typically three times the pass band.

This toolbox has been licensed to (and is currently used by) Thales Alenia Space in Toulouse and Madrid, Thales airborne systems and Flextronics (two licenses). Xlim (University of Limoges) is a heavy user of Presto-HF among the academic filtering community and some free license agreements have been granted to the microwave department of the University of Erlangen (Germany) and the Royal Military College (Kingston, Canada).

FUNCTIONAL DESCRIPTION

Presto-HF is a toolbox dedicated to low-pass parameter identification for microwave filters. In order to allow the industrial transfer of our methods, a Matlab-based toolbox has been developed, dedicated to the problem of identification of low-pass microwave filter parameters. It allows one to run the following algorithmic steps, either individually or in a single stroke:

• Determination of delay components caused by the access devices (automatic reference plane adjustment),

• Automatic determination of an analytic completion, bounded in modulus for each channel,

• Rational approximation of fixed McMillan degree,

• Determination of a constrained realization.

- Participants: Fabien Seyfert, Jean-Paul Marmorat and Martine Olivi
- Contact: Fabien Seyfert
- URL: https://project.inria.fr/presto-hf/

3.4.5. RARL2

Réalisation interne et Approximation Rationnelle L2

SCIENTIFIC DESCRIPTION

The method is a steepest-descent algorithm. A parametrization of MIMO systems is used, which ensures that the stability constraint on the approximant is met. The implementation, in Matlab, is based on state-space representations.

RARL2 performs the rational approximation step in the software tools PRESTO-HF and FindSources3D. It is distributed under a particular license, allowing unlimited usage for academic research purposes. It was released to the universities of Delft and Maastricht (the Netherlands), Cork (Ireland), Brussels (Belgium), Macao (China) and BITS-Pilani Hyderabad Campus (India).

FUNCTIONAL DESCRIPTION

RARL2 is a software for rational approximation. It computes a stable rational L2-approximation of specified order to a given L2-stable (L2 on the unit circle, analytic in the complement of the unit disk) matrix-valued function. This can be the transfer function of a multivariable discrete-time stable system. RARL2 takes as input either:

• its internal realization,

• its first N Fourier coefficients,

• discretized (uniformly distributed) values on the circle. In this case, a least-square criterion is used instead of the L2 norm.

It thus performs model reduction in the first or the second case, and leans on frequency data identification in the third. For band-limited frequency data, it could be necessary to infer the behavior of the system outside the bandwidth before performing rational approximation.

An appropriate Möbius transformation allows to use the software for continuous-time systems as well.

- Participants: Jean-Paul Marmorat and Martine Olivi
- Contact: Martine Olivi
- URL: http://www-sop.inria.fr/apics/RARL2/rarl2.html

3.4.6. Sollya

KEYWORDS: Numerical algorithm - Supremum norm - Curve plotting - Remez algorithm - Code generator - Proof synthesis

FUNCTIONAL DESCRIPTION

Sollya is an interactive tool where the developers of mathematical floating-point libraries (libm) can experiment before actually developing code. The environment is safe with respect to floating-point errors, i.e. the user precisely knows when rounding errors or approximation errors happen, and rigorous bounds are always provided for these errors.

Among other features, it offers a fast Remez algorithm for computing polynomial approximations of real functions and also an algorithm for finding good polynomial approximants with floating-point coefficients to any real function. As well, it provides algorithms for the certification of numerical codes, such as Taylor Models, interval arithmetic or certified supremum norms.

It is available as a free software under the CeCILL-C license.

- Participants: Sylvain Chevillard, Christoph Lauter, Mioara Joldes and Nicolas Jourdan
- Partners: CNRS - ENS Lyon - UCBL Lyon 1
- Contact: Sylvain Chevillard
- URL: http://sollya.gforge.inria.fr/

4. Application Domains

4.1. Introduction

Application domains are naturally linked to the problems described in Sections 3.2.1 and 3.2.2. By and large, they split into a systems-and-circuits part and an inverse-source-and-boundary-problems part, united under a common umbrella of function-theoretic techniques as described in Section 3.3.

4.2. Inverse magnetization problems

Participants: Laurent Baratchart, Sylvain Chevillard, Juliette Leblond, Konstantinos Mavreas.

Generally speaking, inverse potential problems, similar to the one appearing in Section 4.3, occur naturally in connection with systems governed by Maxwell's equation in the quasi-static approximation regime. In particular, they arise in magnetic reconstruction issues. A specific application is to geophysics, which led us to form the Inria Associate Team IMPINGE (Inverse Magnetization Problems IN GEosciences) together with MIT and Vanderbilt University. Though this Associate Team reached the end of its term in 2018, the collaborations it has generated are still active. A joint work with Cerege (CNRS, Aix-en-Provence), in the framework of the ANR-project MagLune, completes this picture, see Sections 6.1.2, 8.2.1.

To set up the context, recall that the Earth's geomagnetic field is generated by convection of the liquid metallic core (geodynamo) and that rocks become magnetized by the ambient field as they are formed or after subsequent alteration. Their remanent magnetization provides records of past variations of the geodynamo, which is used to study important processes in Earth sciences like motion of tectonic plates and geomagnetic reversals. Rocks from Mars, the Moon, and asteroids also contain remanent magnetization which indicates the past presence of core dynamos. Magnetization in meteorites may even record fields produced by the young sun and the protoplanetary disk which may have played a key role in solar system formation.

For a long time, paleomagnetic techniques were only capable of analyzing bulk samples and compute their net magnetic moment. The development of SQUID microscopes has recently extended the spatial resolution to sub-millimeter scales, raising new physical and algorithmic challenges. The associate team IMPINGE aims at tackling them, experimenting with the SQUID microscope set up in the Paleomagnetism Laboratory of the department of Earth, Atmospheric and Planetary Sciences at MIT. Typically, pieces of rock are sanded down to a thin slab, and the magnetization has to be recovered from the field measured on a planar region at small distance from the slab.

Mathematically speaking, both inverse source problems for EEG from Section 4.3 and inverse magnetization problems described presently amount to recover the (3-D valued) quantity m (primary current density in case of the brain or magnetization in case of a thin slab of rock) from measurements of the potential:

$$V(x) = \int_{\Omega} \frac{\operatorname{div} m(x')\, dx'}{|x-x'|}\,, \tag{6}$$

outside the volume Ω of the object. Depending on the geometry of models, the magnetization distribution m may lie in a volume or spread out on a surface. This results in quite different identifiability properties, see [37] and Section 6.1.1, but the two situations share a substantial mathematical common core.

Another timely instance of inverse magnetization problems lies with geomagnetism. Satellites orbiting around the Earth measure the magnetic field at many points, and nowadays it is a challenge to extract global information from those measurements. In collaboration with C. Gerhards (Geomathematics and Geoinformatics Group, Technische Universität Bergakademie Freiberg, Germany), we started to work on the problem of separating the magnetic field due to the magnetization of the globe's crust from the magnetic field due to convection in the liquid metallic core. The techniques involved are variants, in a spherical context, from those developed within the IMPINGE associate team for paleomagnetism, see Section 6.1.1.

4.3. Inverse source problems in EEG

Participants: Paul Asensio, Laurent Baratchart, Juliette Leblond, Jean-Paul Marmorat, Masimba Nemaire.

Solving overdetermined Cauchy problems for the Laplace equation on a spherical layer (in 3-D) in order to extrapolate incomplete data (see Section 3.2.1) is a necessary ingredient of the team's approach to inverse source problems, in particular for applications to EEG, see [9]. Indeed, the latter involves propagating the initial conditions through several layers of different conductivities, from the boundary shell down to the center of the domain where the singularities (*i.e.* the sources) lie. Once propagated to the innermost sphere, it turns out that traces of the boundary data on 2-D cross sections coincide with analytic functions with branched singularities in the slicing plane [8], [42]. The singularities are related to the actual location of the sources, namely their moduli reach in turn a maximum when the plane contains one of the sources. Hence we are back to the 2-D framework of Section 3.3.3, and recovering these singularities can be performed *via* best rational approximation. The goal is to produce a fast and sufficiently accurate initial guess on the number and location of the sources in order to run heavier descent algorithms on the direct problem, which are more precise but computationally costly and often fail to converge if not properly initialized. Our belief is that such a localization process can add a geometric, valuable piece of information to the standard temporal analysis of EEG signal records.

Numerical experiments obtained with our software FindSources3D give very good results on simulated data and we are now engaged in the process of handling real experimental data, simultaneously recorded by EEG and MEG devices, in collaboration with our partners at INS, hospital la Timone, Marseille (see Section 6.1.3).

Furthermore, another approach is being studied for EEG, that consists in regularizing the inverse source problem by a total variation constraint on the source term (a measure), added to the quadratic data approximation criterion. It is similar to the path that is taken for inverse magnetization problems (see Sections 4.2 and 6.1.1), and it presently focuses on surface-distributed models.

4.4. Identification and design of microwave devices

Participants: Laurent Baratchart, Sylvain Chevillard, Jean-Paul Marmorat, Martine Olivi, Fabien Seyfert.

This is joint work with Stéphane Bila (Xlim, Limoges).

One of the best training grounds for function-theoretic applications by the team is the identification and design of physical systems whose performance is assessed frequency-wise. This is the case of electromagnetic resonant systems which are of common use in telecommunications.

In space telecommunications (satellite transmissions), constraints specific to on-board technology lead to the use of filters with resonant cavities in the microwave range. These filters serve multiplexing purposes (before or after amplification), and consist of a sequence of cylindrical hollow bodies, magnetically coupled by irises (orthogonal double slits). The electromagnetic wave that traverses the cavities satisfies the Maxwell equations, forcing the tangent electrical field along the body of the cavity to be zero. A deeper study of the Helmholtz equation states that an essentially discrete set of wave vectors is selected. In the considered range of frequency, the electrical field in each cavity can be decomposed along two orthogonal modes, perpendicular to the axis of the cavity (other modes are far off in the frequency domain, and their influence can be neglected).

Figure 1. Picture of a 6-cavities dual mode filter. Each cavity (except the last one) has 3 screws to couple the modes within the cavity, so that 16 quantities must be optimized. Quantities such as the diameter and length of the cavities, or the width of the 11 slits are fixed during the design phase.

Each cavity (see Figure 1) has three screws, horizontal, vertical and midway (horizontal and vertical are two arbitrary directions, the third direction makes an angle of 45 or 135 degrees, the easy case is when all cavities show the same orientation, and when the directions of the irises are the same, as well as the input and output slits). Since screws are conductors, they behave as capacitors; besides, the electrical field on the surface has to be zero, which modifies the boundary conditions of one of the two modes (for the other mode, the electrical field is zero hence it is not influenced by the screw), the third screw acts as a coupling between the two modes. The effect of an iris is opposite to that of a screw: no condition is imposed on a hole, which results in a coupling between two horizontal (or two vertical) modes of adjacent cavities (in fact the iris is the union of two rectangles, the important parameter being their width). The design of a filter consists in finding the size of each cavity, and the width of each iris. Subsequently, the filter can be constructed and tuned by adjusting the screws. Finally, the screws are glued once a satisfactory response has been obtained. In what follows, we shall consider a typical example, a filter designed by the CNES in Toulouse, with four cavities near 11 GHz.

Near the resonance frequency, a good approximation to the Helmholtz equations is given by a second order differential equation. Thus, one obtains an electrical model of the filter as a sequence of electrically-coupled resonant circuits, each circuit being modeled by two resonators, one per mode, the resonance frequency of which represents the frequency of a mode, and whose resistance accounts for electric losses (surface currents) in the cavities.

This way, the filter can be seen as a quadripole, with two ports, when plugged onto a resistor at one end and fed with some potential at the other end. One is now interested in the power which is transmitted and reflected. This leads one to define a scattering matrix S, which may be considered as the transfer function of a stable causal linear dynamical system, with two inputs and two outputs. Its diagonal terms $S_{1,1}$, $S_{2,2}$ correspond to reflections at each port, while $S_{1,2}$, $S_{2,1}$ correspond to transmission. These functions can be measured at certain frequencies (on the imaginary axis). The matrix S is approximately rational of order 4 times the number of cavities (that is 16 in the example on Figure 2), and the key step consists in expressing the components of the equivalent electrical circuit as functions of the S_{ij} (since there are no formulas expressing the lengths of the screws in terms of parameters of this electrical model). This representation is also useful to analyze the numerical simulations of the Maxwell equations, and to check the quality of a design, in particular the absence of higher resonant modes.

In fact, resonance is not studied via the electrical model, but via a low-pass equivalent circuit obtained upon linearizing near the central frequency, which is no longer conjugate symmetric (*i.e.* the underlying system may no longer have real coefficients) but whose degree is divided by 2 (8 in the example).

In short, the strategy for identification is as follows:

- measuring the scattering matrix of the filter near the optimal frequency over twice the pass band (which is 80MHz in the example).
- Solving bounded extremal problems for the transmission and the reflection (the modulus of he response being respectively close to 0 and 1 outside the interval measurement, cf. Section 3.3.1) in order to get a models for the scattering matrix as an analytic matrix-valued function. This provides us with a scattering matrix known to be close to a rational matrix of order roughly 1/4 of the number of data points.
- Approximating this scattering matrix by a true rational transfer-function of appropriate degree (8 in this example) via the Endymion or RARL2 software (cf. Section 3.3.2.2).
- A state space realization of S, viewed as a transfer function, can then be obtained, where additional symmetry constraints coming from the reciprocity law and possibly other physical features of the device have to be imposed.
- Finally one builds a realization of the approximant and looks for a change of variables that eliminates non-physical couplings. This is obtained by using algebraic-solvers and continuation algorithms on the group of orthogonal complex matrices (symmetry forces this type of transformation).

The final approximation is of high quality. This can be interpreted as a confirmation of the linearity assumption on the system: the relative L^2 error is less than 10^{-3}. This is illustrated by a reflection diagram (Figure 2).

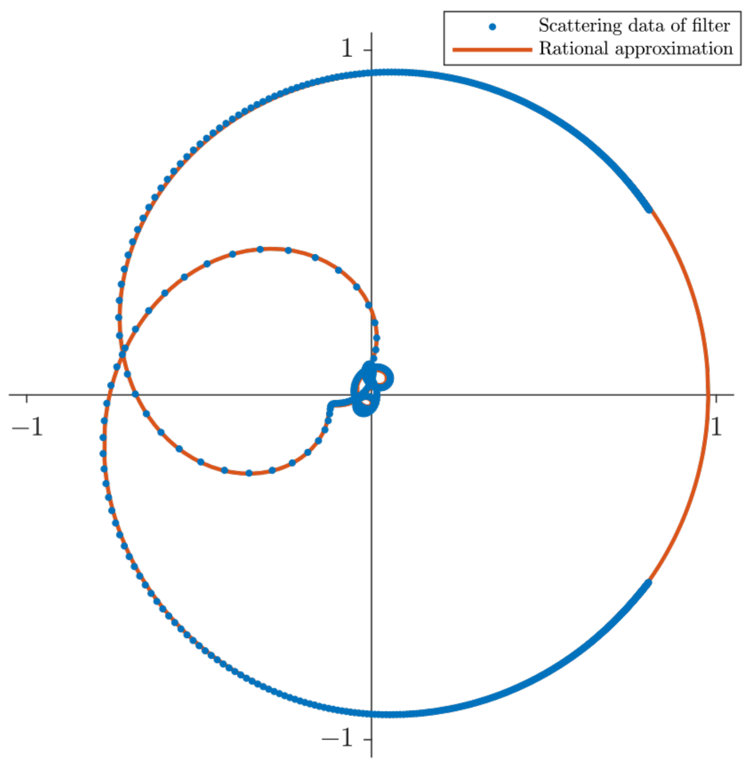


Figure 2. Nyquist Diagram of S_{22}. The rational approximation is of degree 8.

The above considerations are valid for a large class of filters. These developments have also been used for the design of non-symmetric filters, which are useful for the synthesis of repeating devices.

The team further investigates problems relative to the design of optimal responses for microwave devices. The resolution of a quasi-convex Zolotarev problems was proposed, in order to derive guaranteed optimal multi-band filter responses subject to modulus constraints [12]. This generalizes the classical single band design techniques based on Chebyshev polynomials and elliptic functions. The approach relies on the fact that the modulus of the scattering parameter $|S_{1,2}|$ admits a simple expression in terms of the filtering function $D = |S_{1,1}|/|S_{1,2}|$, namely

$$|S_{1,2}|^2 = \frac{1}{1+D^2}.$$

The filtering function appears to be the ratio of two polynomials p_1/p_2, the numerator of the reflection and transmission scattering factors, that may be chosen freely. The denominator q is then obtained as the unique stable unitary polynomial solving the classical Feldtkeller spectral equation:

$$qq^* = p_1 p_1^* + p_2 p_2^*.$$

The relative simplicity of the derivation of a filter's response, under modulus constraints, owes much to the possibility of forgetting about Feldtkeller's equation and express all design constraints in terms of the filtering function. This no longer the case when considering the synthesis N-port devices for $N > 3$, like multiplexers, routers and power dividers, or when considering the synthesis of filters under matching conditions. The efficient derivation of multiplexers responses is the subject of recent investigation by Factas, using techniques based on constrained Nevanlinna-Pick interpolation (see Section 6.2).

Through contacts with CNES (Toulouse) and UPV (Bilbao), Apics got additionally involved in the design of amplifiers which, unlike filters, are active devices. A prominent issue here is stability. A twenty years back, it was not possible to simulate unstable responses, and only after building a device could one detect instability. The advent of so-called *harmonic balance* techniques, which compute steady state responses of linear elements in the frequency domain and look for a periodic state in the time domain of a network connecting these linear elements *via* static non-linearities made it possible to compute the harmonic response of a (possibly nonlinear and unstable) device [79]. This has had tremendous impact on design, and there is a growing demand for software analyzers. The team is also becoming active in this area.

In this connection, there are two types of stability involved. The first is stability of a fixed point around which the linearized transfer function accounts for small signal amplification. The second is stability of a limit cycle which is reached when the input signal is no longer small and truly nonlinear amplification is attained (*e.g.* because of saturation). Applications by the team so far have been concerned with the first type of stability, and emphasis is put on defining and extracting the "unstable part" of the response, see Section 6.3. The stability check for limit cycles has made important theoretical advances, and numerical algorithms are now under investigation.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Robotic tuning: a nice outcome of our long lasting experience in the field of computer assisted tuning for microwave devices

A contract was signed with the French small and midsize business (SMB) Inoveos for the realization of a robotic prototype for the mass tuning of microwave devices. In addition to Inria, this project includes the university of Limoges Xlim and the engineering center Cisteme https://cisteme.net. Our team will be responsible of the driving software of the robot based on our long lasting experience in circuit extraction methods and in connection with our tools Presto-HF and Dedale-HF. Among the technical and scientific challenges for us on this project we can list:

- Improvement of the computational efficiency of our circuit methods in order to be compatible with real-time measurements techniques of filter. Typically a circuital extraction needs to be performed in less than 1 second when dealing with a filter of order 10.
- Handling the ambiguity resulting from the use of multiple solutions coupling topologies yielding several equivalent circuits for a single DUT (device under tuning).

6. New Results

6.1. Inverse problems for Poisson-Laplace equations

Participants: Paul Asensio, Laurent Baratchart, Sylvain Chevillard, Juliette Leblond, Jean-Paul Marmorat, Konstantinos Mavreas, Masimba Nemaire.

6.1.1. Inverse magnetization issues from planar data

The overall goal is here to determine magnetic properties of rock samples (*e.g.* meteorites or stalactites), from weak field measurements close to the sample that can nowadays be obtained using SQUIDs (superconducting quantum interference devices). Depending on the geometry of the rock sample, the magnetization distribution can either be considered to lie in a plane (thin sample) or in a parallelepiped of thickness r. Some of our results apply to both frameworks (the former appears as a limiting case when r goes to 0), while others concern the 2-D case and have no 3-D counterpart as yet.

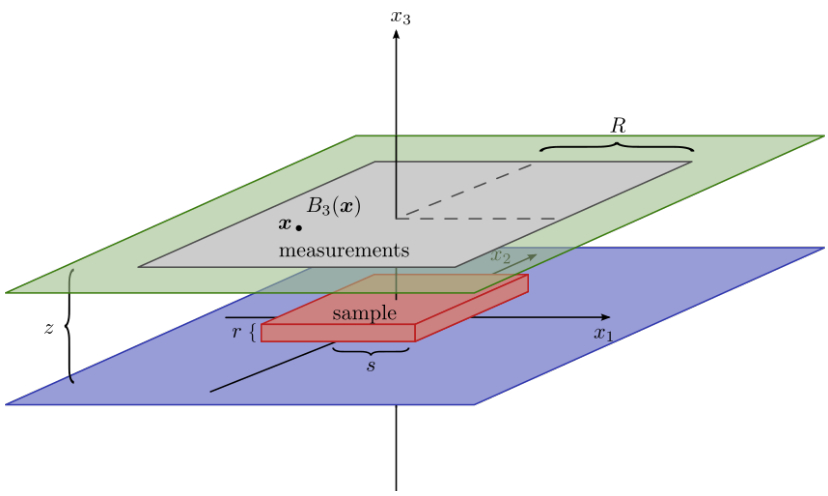


Figure 3. Schematic view of the experimental setup

Figure 3 presents a schematic view of the experimental setup: the sample lies on a horizontal plane at height 0 and its support is included in a parallelepiped. The vertical component B_3 of the field produced by the sample is measured in points of a horizontal square at height z.

We pursued our investigation of the recovery of magnetizations modeled by signed measures on thin samples, and we singled out an interesting class that we call slender samples. These are sets of zero measure in $\mathbb{R}^3$, the complement of which has all its connected components of infinite measure. For such samples, we showed that consistent recovery is possible, in the Morozov discrepancy limit, by penalizing the total variation when either the support of the magnetization is purely 1-unrectifiable (which holds in particular for dipolar models) or the magnetization is unidirectional (an assumption of physical interest because igneous rocks acquire magnetization by cooling down in some ambient field). These notions play a role similar to sparsity in this infinite-dimensional context. An article has been published to report on these results [16]. Moreover, in the case of planar samples (which are certainly slender), a loop decomposition of divergence free measures was obtained, which sharpens in the 2-D setting the structure theorem of [77], and allowed us to prove, using in addition the real analyticity of the operators relating the magnetization to the field, that the argument of the minimum of the regularized criterion $\|f - B_3\mu\|_2^2 + \lambda\|\mu\|_{TV}$ is unique; here, μ is the measure representing the magnetization with respect to which the criterion gets optimized, f is the data and $\lambda > 0$ a regularization parameter, while $\|\mu\|_{TV}$ is the total variation of μ. An implementation using a variant of the FISTA algorithm has been set up which yields promising results when measurements are carried out on a relatively large surface patch. Yet, a deeper understanding on how to adjust the parameters of the method is required. This topic is studied in collaboration with D. Hardin and C. Villalobos from Vanderbilt University.

We also continued investigating the recovery of the moment of a magnetization, an important physical quantity which is in principle easier to reconstruct than the full magnetization because it is simply a vector in $\mathbb{R}^3$ that only depends on the field (*i.e.* magnetizations that produce the zero field also have zero moment). For the case of thin samples, we published an article reporting the construction of linear estimators for the moment from the field, based on the solution of certain bounded extremal problems in the range of the adjoint of the forward operator [15]. On a related side, we also setup other linear estimators based on asymptotic results, in the previous years. These estimators are not limited to thin samples and can in principle estimate the net moment of 3D samples, provided that the dimensions of the sample are small with respect to the measurement area. Numerical experiments confirm that linear estimators (both kinds) make essential use of field values taken at the boundary of the measurement area, and are easily blurred by noise. We experimentally confirmed this sensitivity on a rather simple case: a small spherule has been magnetized in a controlled way by our partners at MIT, and its net moment has been measured by a classical magnetometer. The spherule has then been measured with the SQUID microscope, with several choices for important parameters (height of the sensor with respect to the spherule, sensitivity of the instrument, size of the 2D rectangle on which measurements are performed, size of the sample step). We applied our (asymptotics based) linear estimator on these experimental maps and they turn out to be clearly affected, especially when the data at the edges of the map are involved. The nature of the noise due to the microscope itself (electronic and quantization noise) might play an important role, as it is known to be non-white, and therefore can affect our methods which sum it up. Subsequently, we now envisage the possibility of modeling the structure of the noise to pre-process the data.

Finally, we considered a simplified 2-D setup for magnetizations and magnetic potentials (of which the magnetic field is the gradient). When both the sample and the measurement set are parallel intervals, we set up some best approximation issues related to inverse recovery and relevant BEP problems in Hardy classes of holomorphic functions, see Section 3.3.1 and [25], which is joint work with E. Pozzi (Department of Mathematics and Statistics, St Louis Univ., St Louis, Missouri, USA). Note that, in the present case, the criterion no longer acts on the boundary of the holomorphy domain (namely, the upper half-plane), but on a strict subset thereof, while the constraint acts on the support of the approximating function. Both involve functions in the Hilbert Hardy space of the upper half-plane.

6.1.2. Inverse magnetization issues from sparse cylindrical data

The team Factas was a partner of the ANR project MagLune on Lunar magnetism, headed by the Geophysics and Planetology Department of Cerege, CNRS, Aix-en-Provence, which ended this year (see Section 8.2.1). Recent studies let geoscientists think that the Moon used to have a magnetic dynamo for a while. However, the exact process that triggered and fed this dynamo is still not understood, much less why it stopped. The overall goal of the project was to devise models to explain how this dynamo phenomenon was possible on the Moon.

The geophysicists from Cerege went a couple of times to NASA to perform measurements on a few hundreds of samples brought back from the Moon by Apollo missions. The samples are kept inside bags with a protective atmosphere, and geophysicists are not allowed to open the bags, nor to take out samples from NASA facilities. Moreover, the process must be carried out efficiently as a fee is due to NASA by the time when handling these moon samples. Therefore, measurements were performed with some specific magnetometer designed by our colleagues from Cerege. This device measures the components of the magnetic field produced by the sample, at some discrete set of points located on circles belonging to three cylinders (see Figure 4). The objective of Factas is to enhance the numerical efficiency of post-processing data obtained with this magnetometer.

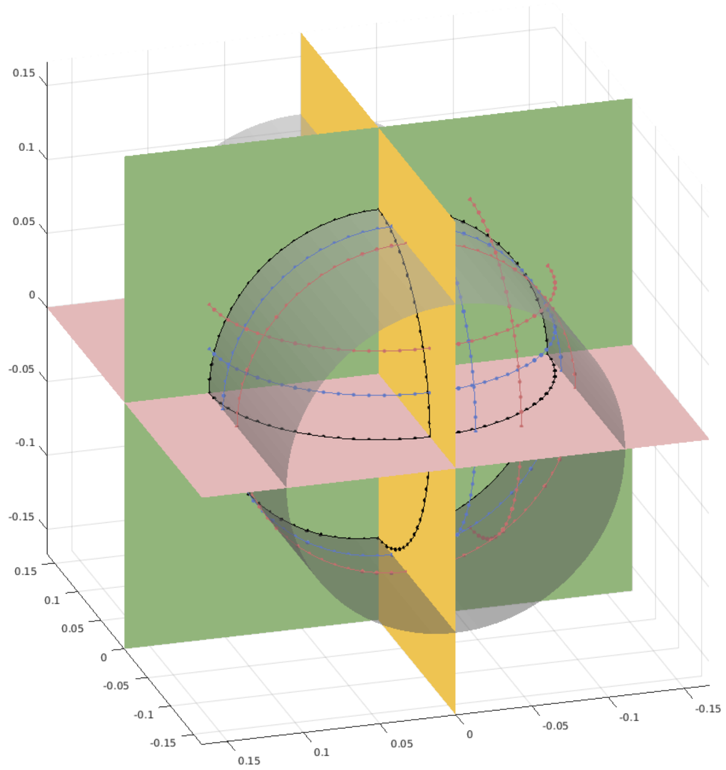


Figure 4. Typical measurements obtained with the instrument of Cerege. Measurements of the field are performed on nine circles, given as sections of three cylinders. On each circle, only one component of the field is measured: the component B_h along the axis of the corresponding cylinder (blue points), the component B_n radial with respect to the circle (black points), or the component B_τ tangential to the circle (red points).

Under the hypothesis that the field can be well explained by a single magnetic pointwise dipole, and using ideas similar to those underlying the FindSources3D tool (see Sections 3.4.3 and 6.1.3), we try to recover the position and the moment of the dipole using the available measurements. This work, which is still on-going, constitutes the topic of the PhD thesis of K. Mavreas, whose defense is scheduled on January 31, 2020. In a given cylinder, using the associated cylindrical system of coordinates, recovering the position of the dipole boils down to determine its height z, its radial distance ρ and its azimuth ϕ. We use the fact that, whatever component of the field is measured, the (square of the) measurements performed on the circle at height h correspond to a rational function of the form $p(z)/(z-u_h)^5$ where p is a polynomial of degree at most 4 and u_h is the complex number $u_h = \frac{1+\rho^2+(h-z)^2}{\rho} e^{i\phi}$. The numerator p depends on the moment of the dipole, on the height h and on the kind of component which is measured. In contrast, u_h can be estimated by rational approximation techniques, which allows one to obtain ϕ directly and gives the relation $\rho|u_h| = 1+\rho^2 + (h-z)^2$. Combining the relations obtained at several heights, we proposed several methods to estimate ρ and z.

This year has been mostly devoted to running numerical experiments on synthetic examples. The first important observation is that the minimization criterion that we use to recover u_h can have local minima achieving very small values, and that can sometimes erroneously be considered as the global minimum. We started studying theoretically this phenomenon, see Section 6.7.1. This means that the relative error $\varepsilon = |u_h - \widetilde{u_h}|/|u_h|$ between the theoretical minimum u_h and the value $\widetilde{u_h}$ estimated by our algorithm can vary from almost 0 to more than 50%, even when the data used as measurements exactly correspond to the field produced by a magnetic dipole. The second important observation is that the statistical distribution of ε (when the position of the dipole is uniformly chosen within a cylinder with a moment uniformly chosen on the unit sphere) depends on the measured component of the field. Figure 5 shows the distribution experimentally observed. The vertical component of the field noticeably leads to better estimates for u_h than both other components. The third important observation that we made is that the presence of noise on the measurements, even moderate, significantly alters the quality of the estimation of u_h. Figure 6 shows the distribution experimentally observed in the same conditions as before, but using data contaminated with a random normal noise with standard deviation 5% of the maximal absolute value of the measured component.

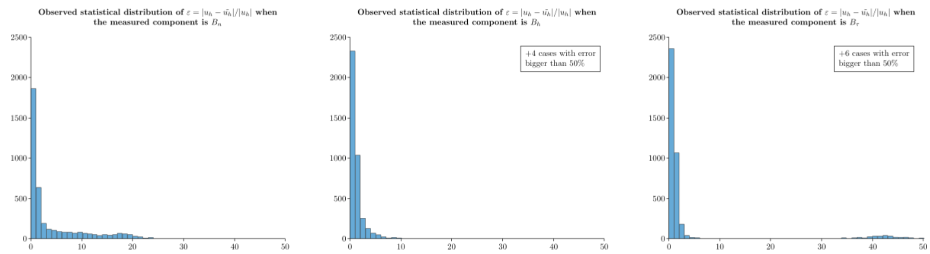


Figure 5. Different statistical behavior of the error of the recovered pole position, depending on the measured component of the field. Each bar indicates the number of cases observed with an error within the range of abscissas of the bar. The experiment has been performed with 4000 dipoles whose position and moment were randomly chosen (uniformly inside a cylinder, and on the unit sphere, respectively).

These observations are somehow bad news, as the method we propose is based on recovering the position of the dipole by using the values u_h collected at several heights h. However, our experiments also revealed an unexpected good news: while the estimation of u_h itself is often bad, as soon as the data are not perfect, its argument (from which ϕ is immediately deduced) turns out to be fairly well recovered. This is illustrated in Figure 7 which shows, on the set of experiments of Figure 6, the position of the 4000 dipoles, with a color indicating whether ε is big (left part of the figure) and whether the error on the argument of u_h is big (right part of the figure). As can be seen, the angular error is most of the time smaller than $10°$, even for dipoles for which ε is fairly big. This phenomenon is probably due to the fact that local minima of the criterion tends to have a complex argument close to the complex argument of the global minimum, a phenomenon that we started to study theoretically (see Section 6.7.1).

6.1.3. Inverse problems in medical imaging

In 3-D, functional or clinically active regions in the cortex are often modeled by pointwise sources that have to be localized from measurements, taken by electrodes on the scalp, of an electrical potential satisfying a Laplace equation (EEG, electroencephalography). In the works [8], [42] on the behavior of poles in best rational approximants of fixed degree to functions with branch points, it was shown how to proceed via best

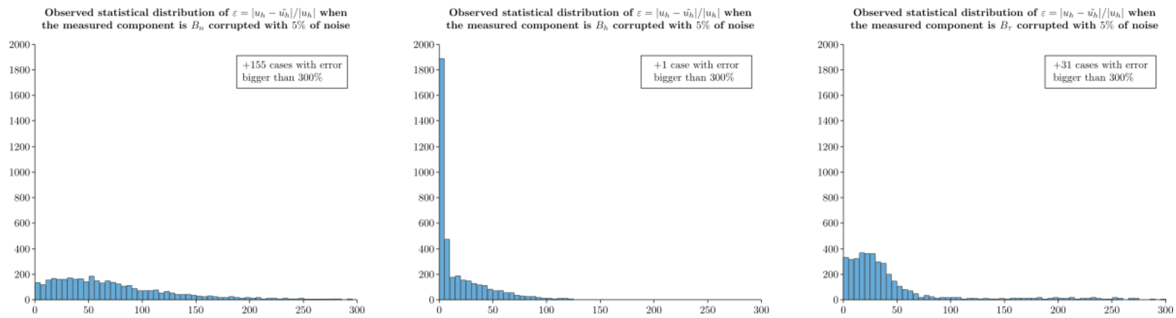


Figure 6. Statistical behavior of the error of the recovered pole position, when the measurement are corrupted with a centered Gaussian noise with standard deviation 5% of the maximal absolute value of the measured component. The setup is otherwise the same as in Figure 5.

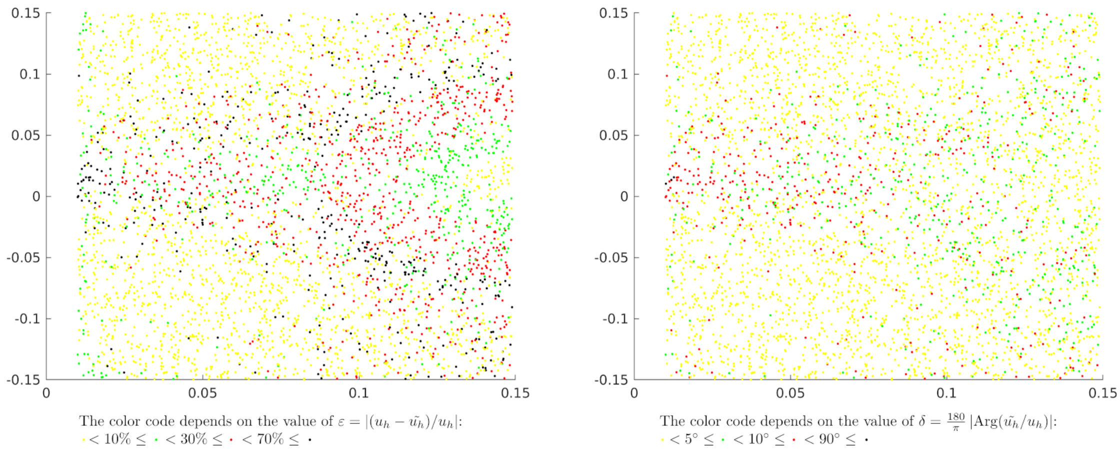


Figure 7. Each dot corresponds to the position of a dipole of the set of experiments described in Figure 6. What is shown is indeed (ρ, z) where ρ and z correspond to, respectively, the radial distance and height of the dipole position, expressed in cylindrical coordinates. The position is displayed with a dot whose color indicates the order of magnitude of the modulus of the relative error (figure on the left) and of the angle error (figure on the right) committed in the recovery of the value u_h.

rational approximation on a sequence of 2-D disks cut along the inner sphere, for the case where there are finitely many sources (see Section 4.3).

In this connection, a dedicated software FindSources3D (FS3D, see Section 3.4.3) is being developed, in collaboration with the Inria team Athena and the CMA - Mines ParisTech. Its Matlab version now incorporates the treatment of MEG data, the aim being to handle simultaneous EEG–MEG recordings available from our partners at INS, hospital la Timone, Marseille. Indeed, it is now possible to use simultaneously EEG and MEG measurement devices, in order to measure both the electrical potential and a component of the magnetic field (its normal component on the MEG helmet, that can be assumed to be spherical). This enhances the accuracy of our source recovery algorithms. Note that FS3D takes as inputs actual EEG measurements, like time signals, and performs a suitable singular value decomposition in order to separate independent sources.

It appears that, in the rational approximation step, *multiple* poles possess a nice behavior with respect to branched singularities. This is due to the very physical assumptions on the model from dipolar current sources: for EEG data that correspond to measurements of the electrical potential, one should consider *triple* poles; this will also be the case for MEG – magneto-encephalography – data. However, for (magnetic) field data produced by magnetic dipolar sources, like in Section 6.1.2, one should consider poles of order five. Though numerically observed in [9], there is no mathematical justification so far why multiple poles generate such strong accumulation of the poles of the approximants (see Section 6.7.1). This intriguing property, however, is definitely helping source recovery and will be the topic of further study. It is used in order to automatically estimate the “most plausible” number of sources (numerically: up to 3, at the moment).

This year, we started considering a different class of models, not necessarily dipolar, and related estimation algorithms. Such models may be supported on the surface of the cortex or in the volume of the encephalon. We represent sources by vector-valued measures, and in order to favor sparsity in this infinite-dimensional setting we use a TV (i.e. total variation) regularization term as in Section 6.1.1. The approach follows that of [16] and is implemented through two different algorithms, whose convergence properties are currently being studied. Tests on synthetic data from a few dipolar sources provide results of different qualities that need to be better understood. In particular, a weight is being added in the TV term in order to better identify deep sources. This is the topic of the starting PhD research of P. Asensio and M. Nemaire. Ultimately, the results will be compared to those of FS3D and other available software tools.

6.2. Matching problems and their applications

Participants: Laurent Baratchart, Martine Olivi, Gibin Bose, David Martinez Martinez, Fabien Seyfert.

6.2.1. Multiplexer synthesis via interpolation and common junction design

In the context of David Martinez Martinez’s PhD funded partly by CNES the synthesis of multiplexer responses was considered using multipoint matching techniques. Indeed, synthesizing the response of multiplexer composed of a set of channel filters connected via common manifold junction to a common port can be seen as a matrix version application of our multipoint matching result for filters [7]. For short a simultaneous matching solutions is sought for, where each channel filter matches the load it is connected at specified matching frequencies. The difficulty here is that the load seen by each filter, depends explicitly of the response of the other filters by means of the common junction’s response: the multiplexer synthesis problem is therefore, in general, strictly harder than the filter multipoint matching problem, and can’t be solved by a sequential solving of independent «scalar» problems. A notable exception to this statement is obtained when a totally decoupling common junction is considered. This somehow artificial situation was taken as a start of a continuation algorithm, during which the decoupling junction response is moved step by step via a linear trajectory towards the target junction while the simultaneous matching problem is solved all along via a differential predictor corrector method. Whereas all «accidents» of branch point type that can occur during this procedure are not classified yet, one major obstruction to the continuation process is the occurrence of manifold peaks. The latter are due to resonances occurring in the manifold junction and yield total reflection at some frequencies of the channel ports. When latter coincide with the matching frequencies of a particular channel filter, the simultaneous matching problem has no solution, and the continuation algorithm fails irredeemably.

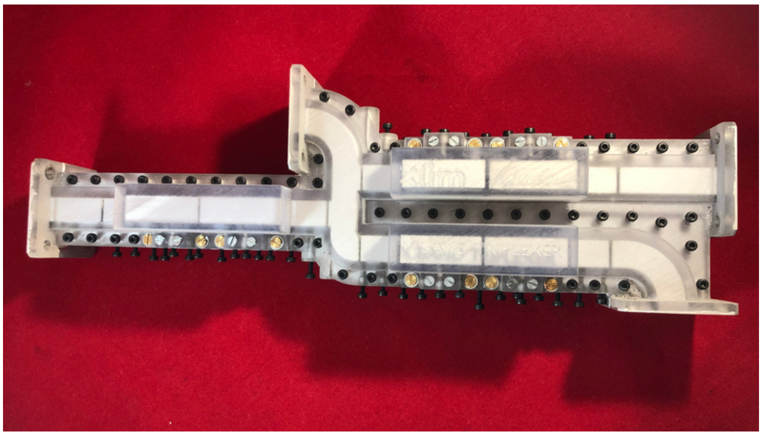


Figure 8. Compact triplexer synthesized via matrix multi-point interpolation techniques and realized via 3D printing.

We therefore gave a full characterization of this manifold peaks and designed a heuristic approach to avoid their appearance during the continuation process. We showed that they only depend on the out of band response of the channel filters, and can in first approximation be considered as constant along the continuation process and estimated by a full wave simulation of each channel filter. This is then used within a triangular adjustment procedure that looks for possible manifold length adjustments (within the channel filters, and between that channel filters and the manifold junction) that guaranties the absence of manifold peaks within the band of each channel filter. Details of this procedure that give important information to the designer about the feasibility of an effective multiplexer response by means of given manifold T-junction, and this before any channel filter optimization procedure, are detailed in [23], [18] and were presented at Eumc 2019. In connection with the previously described continuation procedure, it was used to design a compact triplexer, based on frequency specifications considered as «hard to fulfill» and furnished by CNES. The triplexer was then realized using 3D printing techniques at Xlim (S. Bila and O. Tantot) our long standing academical partners on these topics (see Figure 8). This work is part of the PhD thesis [14] defended by David Martinez Martinez at the end of June.

6.2.2. Uniform matching and global optimality considerations: application to a reference tracking problem

This problem was proposed by Pauline Kergus, PhD student at Onera (Toulouse). In her PhD, she studied the following data driven problem: given frequency measurements of a plant, find a controller which allows to follow a given reference model. The approach she proposed was to directly identify the controller from frequency measurements induced on the controller by the closed loop. Of course the quality of the controller, and in particular its stability, highly depend on the chosen reference model. The question is thus: how to choose a good reference model M with a minimum of information on the plant? The reference model is linked to the sensitivity function S by the relation $M + S = 1$. The sensitivity function is an important design tool in control. To ensure closed loop stability, it should be stable and satisfy some interpolation conditions at the unstable poles and zeros of the plant [28]. Its shape reflect the performances of the closed loop: S should be small at low frequencies to ensure a good tracking accuracy, as well as disturbance rejection; while to ensure noise rejection, S should go to 1 at infinity (the reference model $1 - S$ should be small at high frequencies). The shaping problem for the sensitivity function can be stated in a manner almost similar to the matching problem described below: find a Schur function with minimum infinite norm in a frequency band $[0, w_c]$, where w_c is the chosen cutoff frequency, while satisfying some interpolatory constraints. The main difference that prevents for using the convex relaxation method proposed below is the condition at infinity. An alternative optimization method is under study. To get a non-optimal solution to the problem, Pauline Kergus proposed a simple way to enforce the interpolation conditions from a given well-shaped reference model. To compute the unstable poles and zeros of the plant, which is the minimal required information, she uses our software PISA https://project.inria.fr/pisa/working/project/. Examples illustrating the advantages and limitations of the method were studied. The results were reported in the journal paper [17] and presented at the CDC 2019 in Nice.

6.3. Stability assessment of microwave amplifiers and design of oscillators

Participants: Laurent Baratchart, Sylvain Chevillard, Martine Olivi, Fabien Seyfert, Sébastien Fueyo, Adam Cooman.

The goal is here to help design amplifiers and oscillators, in particular to detect instability at an early stage of the design. This topic is studied in the doctoral work of S. Fueyo, co-advised with J.-B. Pomet (from the McTao Inria project-team). Application to oscillator design methodologies is studied in collaboration with Smain Amari from the Royal Military College of Canada (Kingston, Canada).

As opposed to Filters and Antennas, Amplifiers and Oscillators are active components that intrinsically entail a non-linear functioning. The latter is due to the use of transistors governed by electric laws exhibiting saturation effects, and therefore inducing input/output characteristics that are no longer proportional to the magnitude of the input signal. Hence, they typically produce non-linear distortions. A central question arising in the design of amplifiers is to assess stability. The latter may be understood around a functioning point when no input but noise is considered, or else around a periodic trajectory when an input signal at a specified frequency is applied. For oscillators, a precise estimation of their oscillating frequency is crucial during the design process. For devices operating at relatively low frequencies, time domain simulations perform satisfactorily to check stability. For complex microwave amplifiers and oscillators, the situation is however drastically different: the time step necessary to integrate the transmission line's dynamical equations (which behave like a simple electrical wire at low frequency) becomes so small that simulations are intractable in reasonable time. Moreover, most linear components of such circuits are known through their frequency response, and a preliminary, numerically unstable step is then needed to obtain their impulse response, prior to any time domain simulation.

For these reasons, the analysis of such systems is carried out in the frequency domain. In the case of stability issues around a functioning point, where only small input signals are considered, the stability of the linearized system obtained by a first order approximation of each non-linear component can be studied *via* the transfer impedance functions computed at some ports of the circuit. In recent years, we showed that under realistic dissipativity assumptions at high frequency for the building blocks of the circuit, these transfer functions are meromorphic in the complex frequency variable s, with at most finitely many unstable poles in the right half-plane [4]. Dwelling on the unstable/stable decomposition in Hardy Spaces, we developed a procedure to assess the stability or instability of the transfer functions at hand, from their evaluation on a finite frequency grid [11], that was further improved in [10] to address the design of oscillators, in collaboration with Smain Amari. This has resulted in the development of a software library called Pisa (see Section 3.4.1, aiming at making these techniques available to practitioners. Research in this direction now focuses on the links between the width of the measurement band, the density of the measurement points, and the precision with which an unstable pole, located within a certain depth into the complex plane, can be identified.

Extensions of the procedure to the strong signal case, where linearisation is considered around a periodic trajectory, have received attention over the last two years. When stability is studied around a periodic trajectory, determined in practice by Harmonic Balance algorithms, linearization yields a linear time varying dynamical system with periodic coefficients and a periodic trajectory thereof. While in finite dimension the stability of such systems is well understood via the Floquet theory, this is no longer the case in the present setting which is infinite dimensional, due to the presence of delays. Dwelling on the theory of retarded systems, S. Fueyo's PhD work has shown last year that, for general circuits, the monodromy operator of the linearized system along its periodic trajectory is a compact perturbation of a high frequency, non dynamical operator, which is stable under a realistic passivity assumption at high frequency. Therefore, only finitely many unstable points can arise in the spectrum of the monodromy operator, and this year we established a connection between these and the singularities of the harmonic transfer function, viewed as a holomorphic function with values in periodic L^2 functions. One difficulty, however, is that these singularities need not affect all Fourier coefficients, whereas harmonic balance techniques can only estimate finitely many of them. This issue, that was apparently not singled out by practitioners, is currently under examination.

We also wrote an article reporting about the stability of the high frequency system, and recast this result in terms of exponential stability of certain delay systems [24].

6.4. The Hardy-Hodge decomposition

Participants: Laurent Baratchart, Masimba Nemaire.

In a joint work with T. Qian and P. Dang from the university of Macao, we proved in previous years that on a compact hypersurface Σ embedded in $\mathbb{R}^n$, a $\mathbb{R}^n$-valued vector field of L^p class decomposes as the sum of a harmonic gradient from inside Σ, a harmonic gradient from outside Σ, and a tangent divergence-free field, provided that $2-\varepsilon < p < 2+\varepsilon'$, where ε and ε' depend on the Lipschitz constant of the surface. We also proved that the decomposition is valid for $1 < p < \infty$ when Σ is VMO-smooth (*i.e.*Σ is locally the graph of Lipschitz function with derivatives in VMO). By projection onto the tangent space, this gives a Helmholtz-Hodge decomposition for vector fields on a Lipschitz hypersurface, which is apparently new since existing results deal with smooth surfaces. In fact, the Helmholtz-Hodge decomposition holds on Lipschitz surfaces (not just hypersurfaces), The Hardy-Hodge decomposition generalizes the classical Plemelj formulas from complex analysis. We pursued this year the writing of an article on this topic, and we also found that this decomposition yields a description of silent magnetizations distributions of L^p-class on a surface. A natural endeavor is now to use this description, *via* balayage, to describe volumetric silent magnetizations.

6.5. Identification of resonating frequencies of compact metallic objects in electromagnetic inverse scattering

Participants: Laurent Baratchart, Martine Olivi, Fabien Seyfert.

We started an academic collaboration with LEAT (Univ. Nice, France, pers. involved: Jean-Yves Dauvignac, Nicolas Fortino, Yasmina Zaki) on the topic of inverse scattering using frequency dependent measurements. As opposed to classical electromagnetic imaging where several spatially located sensors are used to identify the shape of an object by means of scattering data at a single frequency, a discrimination process between different metallic objects is here being sought for by means of a single, or a reduced number of sensors that operate on a whole frequency band. For short the spatial multiplicity and complexity of antenna sensors is here traded against a simpler architecture performing a frequency sweep.

The setting is shown on Figure 9. The total field $E_t(r,\theta,\phi)$ is the sum of the incident field E_i (here a plane wave) and scattered field E_s, that is at every point in space we have $E_t = E_i + E_s$. A harmonic time dependency ($e^{j\omega t}$, where j is the imaginary unit: $j^2 = -1$) is supposed for the incident wave, so that by linearity of Maxwell equations and after a transient state, following holds,

$$E_s(r_o,\theta_o,\phi_o) = H(s = j\omega,\theta_o,\phi_o)E_i(r_e,\theta_e,\phi_e).$$

The subscripts o and e stand here for «observation point» and «emission point»: the scattered field at the observation point is therefore related to the emitted planar wave field at the emission point via the transfer function $H(s = j\omega,\theta_o,\phi_o)$. The emission point is here supposed fixed, so the dependency in e is omitted in H. Under regularity conditions on the scatterer's boundary the function H can be shown to admit an analytic continuation into the complex left half plane for the s variable, away from a discrete set (with a possible accumulation point a infinity) where it admits poles. Thus, H is a meromorphic function in the variable s. Its poles are called the resonating frequencies of the scattering object. Recovering these resonating frequencies from frequency scattering measurement, that is measurements of H at particular $s = j\omega_i's$ is the primary objective of this project.

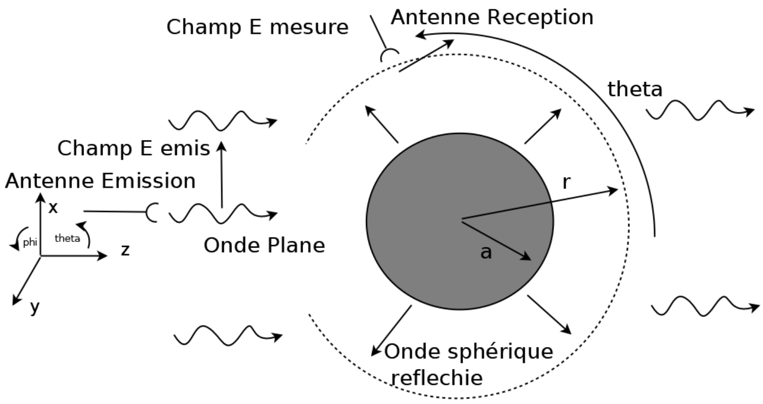


Figure 9. Sphere illuminated by an electromagnetic plane wave - measurement of the scattered wave

In order to gain some insight we started a full study of the particular case when the scatterer is a spherical PEC (Perfectly Electric Conductor). In this case Maxwell equations can be solved «explicitly» by means of expansions in series of vectorial spherical harmonics. We showed in particular that in this case H admits following simple structure:

$$H(\omega, \theta_o, \phi_o) = R(s, \theta_o, \phi_o)e^{-\tau_1(\theta_o,\phi_o)s} + C(\theta_o, \phi_o)e^{-\tau_2(\theta_o,\phi_o)s},$$

where R is a meromorphic functions with poles at zeros of the spherical Hankel functions and their derivatives and C is independent of the frequency. Identification procedures, surprisingly close to the ones we developed in connection with amplifier stability analysis, are currently being studied to gain information about the resonating frequencies by means of a rational approximation of the function R once it has been de-embedded. Generalization of this analysis and procedure will be considered for arbitrarily compact PEC objects.

6.6. Imaging and modeling ancient materials

Participants: Vanna Lisa Coli, Juliette Leblond, Pat Vatiwutipong.

This is a recent activity of the team, linked to image classification in archaeology in the framework of the project ToMaT (see Regional Initiatives below) and to the post-doctoral stay of V. L. Coli; it is pursued in collaboration with L. Blanc-Féraud (project-team Morpheme, I3S-CNRS/Inria Sophia/iBV), D. Binder (CEPAM-CNRS, Nice), in particular.

The pottery style is classically used as the main cultural marker within Neolithic studies. Archaeological analyses focus on pottery technology, and particularly on the first stages of pottery manufacturing processes. These stages are the most demonstrative for identifying the technical traditions, as they are considered as crucial in apprenticeship processes. Until now, the identification of pottery manufacturing methods was based on macro-traces analysis, i.e. surface topography, breaks and discontinuities indicating the type of elements (coils, slabs, ...) and the way they were put together for building the pots. Overcoming the limitations inherent to the macroscopic pottery examination requires a complete access to the internal structure of the pots. Micro-computed tomography (μCT) has recently been used for exploring ancient materials microstructure. This non-invasive method provides quantitative data for a big set of proxies and is perfectly adapted to the analysis of Cultural heritage materials.

The main challenge of our current analyses aims to overcome the lack of existing protocols to apply in order to quantify observations. In order to characterize the manufacturing sequences, the mapping of the paste variability (distribution and composition of temper) and the discontinuities linked to different classes of pores, fabrics and/or organic inclusions appears promising. The totality of the acquired images composes a set of 2-D and 3-D surface and volume data at different resolutions and with specific physical characteristics related to each acquisition modality (multimodal and multi-scale data). Specific shape recognition methods need to be developed by application of robust imaging techniques and 3-D-shapes recognition algorithms.

In a first step, we devised a method to isolate pores from the 3-D data volumes in binary 3-D images, to which we apply a process named Hough transform (derived from Radon transform). This method, of which the generalization from 2-D to 3-D is quite recent, allows us to evaluate the presence of parallel lines going through the pores. The quantity of such lines is a good indicator of the “coiling” manufacturing, that it allows to distinguish from the other “spiral patchwork” patchwork technique, in particular. These progresses are described in [20], [22], [21], and the object of an article in preparation.

The Hough and Radon transforms can also be applied to 2-D slices of the available 3-D images displaying pores locations. In this framework, the use of Radon transform to evaluate the density of points in the image that do belong to (or almost) parallel lines appears to be quite efficient, as was seen during P. Vatiwutipong’s internship.

Other possibilities of investigation will be analyzed as well, such as machine learning techniques.

6.7. Behavior of poles in rational and meromorphic approximation

Participants: Laurent Baratchart, Sylvain Chevillard, Juliette Leblond, Martine Olivi, Fabien Seyfert.

6.7.1. Rational approximation

The numerous experiments that we performed on synthetic data in the context of the MagLune project (see Sections 6.1.2 and 8.2.1) revealed an intriguing behavior of the local minima of the optimization problem underlying our method. In the context of that application, we are provided with sampled values on the unit circle $\mathbb{T}$ of a function f which is known to be of the form $f(z) = p(z)/(z-\beta)^5$ where $p(z) \in \mathbb{C}_4[z]$ is a polynomial of degree at most 4 with complex coefficients and $\beta \in \mathbb{D}$ belongs to the unit disk. A key problem consists in recovering β from the values of f on the unit circle. The same problem occurs in the core of FindSources3D (see 3.4.3 and 6.1.3) with p being of degree at most 2 and a pole of order 3 rather than 5.

In order to estimate β, we seek for the global minimum on $\mathbb{C}_4[z] \times \mathbb{D}$ of the function ϕ defined by

$$\phi : (q, \alpha) \mapsto \left\| \frac{q(z)}{(z-\alpha)^5} - f(z) \right\|_{L^2(\mathbb{T})}.$$

When f is actually a rational function of the considered form, ϕ obviously has a unique global minimum where it reaches the value 0. We experimentally observed that ϕ usually has several local minima, some of them achieving very small values, and these minima often have a complex argument close to the argument of β. This behavior is unusual and contrasts with the fact the function

$$\psi : (q, \alpha_1, \cdots, \alpha_5) \mapsto \left\| \frac{q(z)}{\prod_{i=1}^{5} (z-\alpha_i)} - f(z) \right\|_{L^2(\mathbb{T})}$$

is known to have a unique local minimum on $\mathbb{C}_4[z] \times \mathbb{D}^5$ (which is global) when f is a rational function of the same form.

In order to understand the reasons underlying our observations, we started studying the theoretical properties of the critical points of ϕ, in the general case of a pole of order $n \in \mathbb{N}^*$ and with a polynomial of degree less or equal to $n-1$ at the numerator. Our results so far are the following.

We introduce the family $(g_j^{(\alpha)})_{j\in\mathbb{N}^*}$ where $g_j^{(\alpha)}(z) = (1-\overline{\alpha}z)^{j-1}/(z-\alpha)^j$ which is an orthogonal basis (for the usual $L^2(\mathbb{T})$ Hilbert product) of the space of rational functions with a single pole (of arbitrary order) in α. Thanks to this family, we prove that (q,α) is a critical point of ϕ if and only if f is orthogonal either to $g_n^{(\alpha)}$ or $g_{n+1}^{(\alpha)}$ and, for such a given α, $q/(z-\alpha)^n$ is the orthogonal projection of f onto the rational functions of that form. The case when f is orthogonal to $g_n^{(\alpha)}$ combined with the fact that $q/(z-\alpha)^n$ is the orthogonal projection of f implies a pole-zero simplification of $q/(z-\alpha)^n$ at $z=\alpha$ and we conjecture that it exactly corresponds to local *maxima* of ϕ with respect to variable α. We also conjecture that the other case exactly corresponds to local *minima* of ϕ. We are currently working on proving these conjectures, which should not be too hard.

We also obtained an explicit algebraic equation characterizing α, and we know how to solve it when f is of the form $1/(z-\beta)^k$ $(1\le k\le n)$. For small values of n, we proved (and conjecture that it holds for any n) that there are $2k-1$ solutions in the unit disk, all lying on the diameter passing though β. This is a remarkable result that somehow theoretically confirms the kind of experimental observations we got. The theoretical case of a function f with a non trivial numerator seems currently out of reach, though.

6.7.2. Meromorphic approximation

We showed that best meromorphic approximation on a contour, in the uniform norm, to functions with countably many branched singularities with polar closure inside the contour produces poles whose counting measure accumulate weak-* to the Green equilibrium distribution on the cut of minimal capacity outside of which the function is single-valued. This is joint work with M. Yattselev (University of Indianapolis, Purdue University at Indianapolis). An article is currently being written on this topic.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. Contract CNES-Inria-Xlim

This contract (reference Inria: 11282) accompanied the PhD of David Martinez Martinez and focused on the development of efficient techniques for the design of matching network tailored for frequency varying loads. Applications of the latter to the design output multiplexers occurring in space applications has also been considered (see new results section). The contract ended mid 2019.

7.1.2. Contract Inria-Inoveos

A contract was signed with the SMB company Inoveos in order to build a prototypical robot dedicated to the automatic tuning of microwave devices, see Section 5.1.1.

8. Partnerships and Cooperations

8.1. Regional Initiatives

- The team co-advises a PhD (G. Bose) with the CMA team of LEAT (http://leat.unice.fr/pages/activites/cma.html) funded by the Labex UCN@Sophia on the co-conception of Antennas and Filters.

- The team participates in the project ToMaT, “Multiscale Tomography: imaging and modeling ancient materials, technical traditions and transfers”, funded by the Idex UCA$^{\text{Jedi}}$ (“programme structurant Matière, Lumière, Interactions”). This project brings together researchers in archaeological, physical, and mathematical sciences, with the purpose of modeling and detecting low level signals in 3-D images of ancient potteries. The other concerned scientists are from CEPAM-CNRS-UCA (project coordinator: Didier Binder), Nice http://www.cepam.cnrs.fr, the team Morpheme, CNRS-I3S-Inria http://www.inria.fr/equipes/morpheme, and IPANEMA, CNRS, Ministère de la Culture et de la Communication, Université Versailles Saint Quentin http://ipanema.cnrs.fr/. Since March 2018, they co-advise together the post-doctoral research of Vanna Lisa Coli, see Section 6.6, and this year the internship training of Pat Vatiwutipong.

8.2. National Initiatives

8.2.1. ANR MagLune

The ANR project MagLune (Magnétisme de la Lune) was active from July 2014 to August 2019. It involved the Cerege (Centre de Recherche et d’Enseignement de Géosciences de l’Environnement, joint laboratory between Université Aix-Marseille, CNRS and IRD), the IPGP (Institut de Physique du Globe de Paris) and ISTerre (Institut des Sciences de la Terre). Associated with Cerege were Inria (Apics, then Factas team) and Irphe (Institut de Recherche sur les Phénomènes Hors Équilibre, joint laboratory between Université Aix-Marseille, CNRS and École Centrale de Marseille). The goal of this project (led by geologists) was to understand the past magnetic activity of the Moon, especially to answer the question whether it had a dynamo in the past and which mechanisms were at work to generate it. Factas participated in the project by providing mathematical tools and algorithms to recover the remanent magnetization of rock samples from the moon on the basis of measurements of the magnetic field it generates. The techniques described in Section 6.1 were instrumental for this purpose.

8.2.2. ANR Repka

ANR-18-CE40-0035, “REProducing Kernels in Analysis and beyond”, starting April 2019 (for 48 months).

Led by Aix-Marseille Univ. (IMM), involving Factas team, together with Bordeaux (IMB), Paris-Est, Toulouse Universities.

The project consists of several interrelated tasks dealing with topical problems in modern complex analysis, operator theory and their important applications to other fields of mathematics including approximation theory, probability, and control theory. The project is centered around the notion of the so-called reproducing kernel of a Hilbert space of holomorphic functions. Reproducing kernels are very powerful objects playing an important role in numerous domains such as determinantal point processes, signal theory, Sturm-Liouville and Schrödinger equations.

This project supports the PhD of M. Nemaire within Factas, co-advised by IMB partners.

8.3. European Initiatives

8.3.1. Collaborations with Major European Organizations

Factas is part of the European Research Network on System Identification (ERNSI) since 1992.

System identification deals with the derivation, estimation and validation of mathematical models of dynamical phenomena from experimental data.

8.4. International Initiatives

8.4.1. Inria International Partners

8.4.1.1. Informal International Partners

Following two Inria Associate teams (2013-2018) and a MIT-France seed funding (2014-2018), the team has a strong and regular collaboration with the Earth and Planetary Sciences department at Massachusetts Institute of Technology (Cambridge, MA, USA) and with the Mathematics department of Vanderbilt University (Nashville, TN, USA) on inverse problems for magnetic microscopy applied to the analysis of ancient rock magnetism.

8.5. International Research Visitors

8.5.1. Visits of International Scientists

- Smain Amari (Royal Military College of Canada, Kingston, Canada), February 4-9.
- Jonathan Partington (Univ. of Leeds, England), February 4-7.
- Dmitry Ponomarev (T.U. Vienna, Vienna, Austria), June 24.
- Élodie Pozzi (St Louis Univ., St Louis, Missouri, USA), Brett Wick (Washington Univ., St Louis, Missouri, USA), January 9-10.
- Yves Rolain (Vrije Universiteit Brussel, VUB, Brussels, Belgium), February 5-7.
- Maxim Yattselev (University of Indianapolis, Purdue University at Indianapolis, USA), June 29-July 1.

8.5.1.1. Internships

- Paul Asensio, École Centrale Lyon, *Study of silent current sources in electroencephalography (EEG) and magnetoencephalography (MEG)*; advisors: L. Baratchart, J. Leblond.
- Masimba Nemaire, MathMods Master, *Study of silent current sources in EEG and MEG*; advisors: L. Baratchart, J. Leblond.
- Tuong Vy Nguyen Hoang, *Mathematical Circuit Modeling for Antennas*; advisors: F. Seyfert, M. Olivi.
- Pat Vatiwutipong, MathMods Master, *Properties of the d-Radon transform and applications to imaging issues in archaeology*; advisors: V. L. Coli, J. Leblond.

8.6. List of international and industrial partners

Figure 10 sums up who are our main collaborators, users and competitors.

9. Dissemination

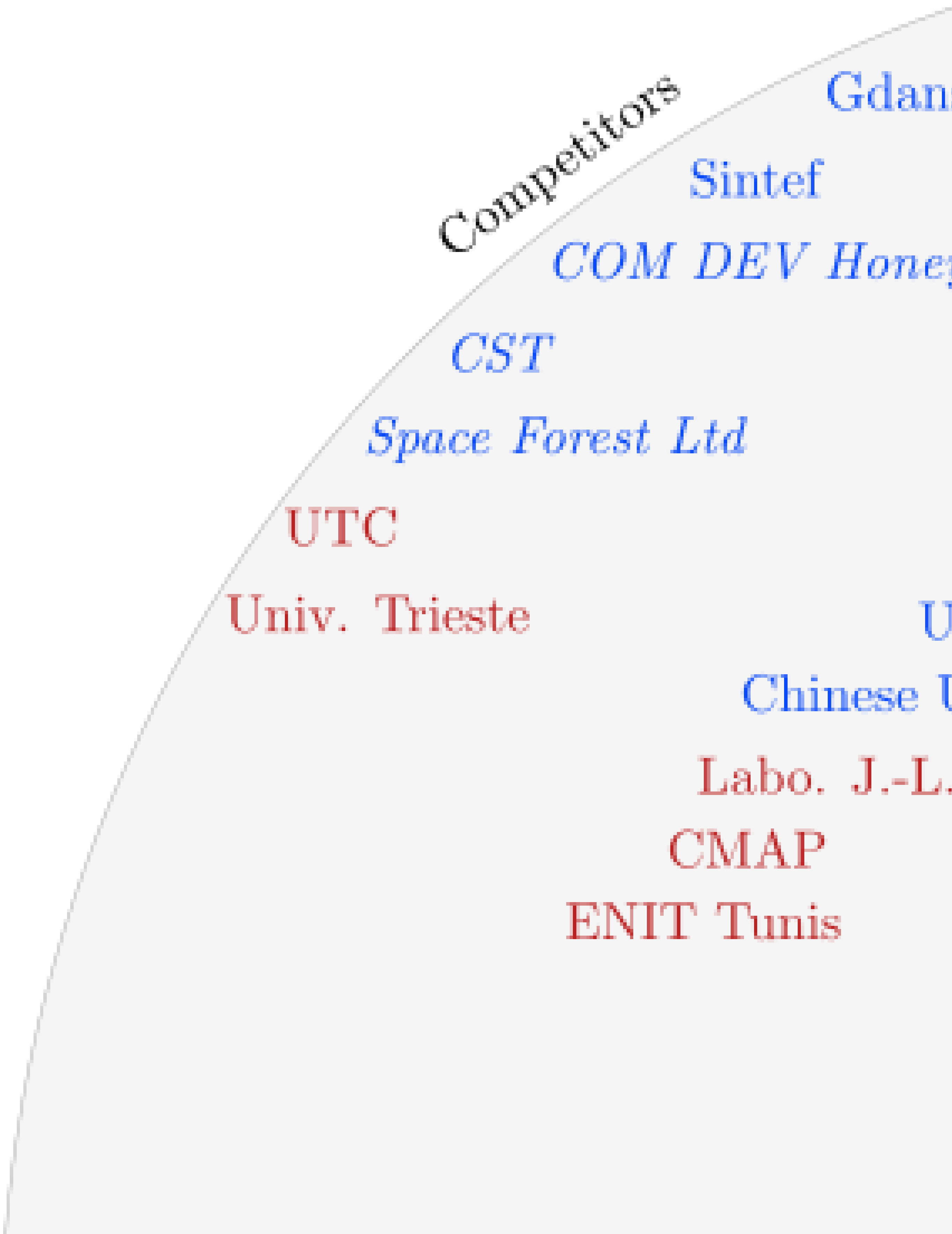
9.1. Promoting Scientific Activities

- L. Baratchart gave an oral communication at NCMIP 2019 in Cachan,
- V. L. Coli gave oral communications at the 2nd “Journée Matériaux UCA”, Sophia Antipolis, September, and at the workshop “Céramiques imprimées de Méditerranée occidentale. Matières premières, productions, usages” of the ANR CIMO, Nice, France, March, http://www.cepam.cnrs.fr/sites/cimo/.
- D. Martinez Martinez gave an oral communication at «Journées Nationales des Microondes», Caen, France and at «European microwave Conference (EuMC) 2019», Paris, France.
- F. Seyfert was invited to give a lecture at the Technical University of Cartagena University (Spain) and gave an invited talk at the workshop «Rational approximation for Electrical Engineering», Moscow, Russia sponsored by Huawei.

9.1.1. Scientific Events: Selection

9.1.1.1. Member of the Conference Program Committees

L. Baratchart was on the program committee of “Applied Inverse Problems” (AIP) 20019, Grenoble, France http://www.aip2019-grenoble.fr.


Competitors
Sintef
COM DEV
CST
Space Forest Ltd
UTC
Univ. Trieste
Chinese
Labo.
CMAP
ENIT Tunis

9.1.2. Journal

9.1.2.1. Member of the Editorial Boards

L. Baratchart is on the editorial board of the journals “Computational Methods and Function Theory” and “Complex Analysis and Operator Theory”.

9.1.2.2. Reviewer - Reviewing Activities

- J. Leblond was a reviewer for the journals *Engineering with Computers*, *Inverse Problems*.
- F. Seyfert was a reviewer for IEEE Transactions on Microwave Theory and Techniques

9.1.3. Invited Talks

- L. Baratchart gave an invited address at the conference “One-Dimensional Complex Analysis and Operator Theory” in Saint Petersburg, May 13-17, https://sites.google.com/view/sft2019/home/conference. He was an invited speaker at the workshop «Rational approximation for Electrical Engineering», Moscow, Russia, sponsored by Huawei, and lectured at the Macao university of sciences and techniques, in April. Macao University of Sciences and Technology in April.
- L. Baratchart and J. Leblond were invited to give talks at AIP 2019, Grenoble, France, July, http://www.aip2019-grenoble.fr.
- S. Chevillard was invited to give a talk at a NFS-sponsored workshop on magnetic imaging organized outside the American Geophysical Union meeting (December 7-8).
- J. Leblond was an invited speaker at the final workshop of the ANR FastRelax, Lyon, France, May, http://fastrelax.gforge.inria.fr/FastRelax2019.html.

9.1.4. Scientific Expertise

- L. Baratchart was a member of selection panel 40 (Mathematics) of the Agence Nationale de la Recherche (ANR).
- J. Leblond was an external reviewer for a promotion evaluation process at Chapman University (Orange, CA, USA).
- F. Seyfert was a reviewer for the National Science Centre of Poland

9.1.5. Research Administration

- J. Leblond is a member of the “Conseil Scientifique” and of the “Commission Administrative Paritaire” of Inria.
- M. Olivi is a member of the CLDD (Commission Locale de Développement Durable) and in charge, with P. Bourgeois, of coordination.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Colles: S. Chevillard has given “Colles” (oral examination preparing undergraduate students for the competitive examination to enter French Engineering Schools) at Centre International de Valbonne (CIV) (2 hours per week) until June 2019.

9.2.2. Supervision

PhD in progress: K. Mavreas, *Inverse source problems in planetary sciences: dipole localization in Moon rocks from sparse magnetic data*, since October 2015, advisors: S. Chevillard, J. Leblond; defense scheduled January 31, 2020.

PhD in progress: G. Bose, *Filter Design to Match Antennas*, since December 2016, advisors: F. Ferrero, F. Seyfert and M. Olivi.

PhD in progress: S. Fueyo, *Cycles limites et stabilité dans les circuits*, since October 2016, advisors: L. Baratchart and J.-B. Pomet (Inria Sophia, McTao).

PhD in progress: P. Asensio, *Inverse source estimation problems in EEG and MEG*, since November 2019, advisors: L. Baratchart, J. Leblond.

PhD in progress: M. Nemaire, *Inverse potential problems with application to quasi-static electromagnetics*, since October 2019, advisors: L. Baratchart, J. Leblond, S. Kupin (IMB, Univ. Bordeaux).

Post-doc. in progress: V. L. Coli, *Multiscale Tomography: imaging and modeling ancient materials*, since March 2018, advisors: J. Leblond, L. Blanc-Féraud (project-team Morpheme, I3S-CNRS/Inria Sophia/iBV), D. Binder (CEPAM-CNRS, Nice).

9.2.3. Juries

L. Baratchart was a reviewer of the “Mémoire d’habilitation” of Moncef Mahjoub, ENIT, Tunis, September 2.

J. Leblond was a member of the PhD committees of I. Santos (Univ. Paul Sabatier, Toulouse, February), S. Amraoui and K. Maksymenko (Univ. Côte d’Azur, December).

M. Olivi was a member of the HdR committees of F. Seyfert (Univ. Côte d’Azur, February 6), C. Poussot-Vassals (Univ. Toulouse, July 12) and of the PhD committees of D. Martinez Martinez (Univ. Limoges, June 20) and P. Kergus (Univ. Toulouse, October 18)

F. Seyfert was a member of the PhD committee of Johan Sence (Univ. Limoges, November 15) and D. Martinez Martinez (Univ. Limoges, June 20).

9.3. Popularization

9.3.1. Internal or external Inria responsibilities

M. Olivi was responsible for Scientific Mediation and president of the Committee MASTIC (Commission d’Animation et de Médiation Scientifique) https://project.inria.fr/mastic/ until October 30.

9.3.2. Articles and contents

M. Olivi wrote a review of the book “Algorithms: la bombe à retardement” by C. O’Neil for Interstice https://interstices.info/sciences-du-numerique-et-impact-sur-la-societe/

9.3.3. Education

“La fête des Maths de l’ESPE Nice-Liégeard” (March 5 and 26): M. Olivi animated two half-day workshop sessions “jouons avec des expériences scientifiques” https://pixees.fr/jouons-avec-des-experiences-scientifiques/ for primary school students.

9.3.4. Interventions

- “Fête de la science: Mouans-Sartoux fête les sciences du quotidien” (October 10-11 for scholars: 8 classes, October 12 for public: 1000 people): M. Olivi animated the activity “jouer à transmettre des images” in collaboration with the “espace de l’art concret” https://www.espacedelartconcret.fr/.
- “Stage MathC2+” (June 19-22): M. Olivi animated a workshop session on “How to analyze sounds with mathematical functions”.
- V. L. Coli gave a talk “Archéologie et mathématiques : algorithmes pour l’identification des gestes des premiers potiers”, and participated to the organization of the exhibition of the ANR project CIMO, Forum des Sciences, 80 years of CNRS, October, CIV, Valbonne.
- Fabien Seyfert gave a pitch on Factas activities during the visit of the company SICAME (March 27) and Martine Olivi gave a pitch on Factas activities for the celebration of InriaTech 10th birthday (April 3)

9.3.5. Internal action

- S. Chevillard gave a talk “Réchauffement climatique : où en est-on ? où va-t-on ?” at the c@fé-in of the Research Center, November.
- V. L. Coli gave a talk “Archéologie et mathématiques : algorithmes pour l’identification des gestes des premiers potiers” at the c@fé-in of the Research Center, October. She also participated to the organization of the “1er Colloque doctoral préhistoire, paléoenvironnement, archéosciences”, November, MSHS, Nice, https://www.cepam.cnrs.fr/evenement/1er-colloque-doctoral-prehistoire-paleoenvironnement-archeosciences/, where she gave a talk “Approches mathématiques pour la caractérisation des potteries néolithiques”.
- M. Olivi co-organized about 10 “cafés scientifiques” (c@fé-in’s and cafés Techno, 30 to 80 participants each) https://project.inria.fr/mastic/category/cafein/

9.3.6. Creation of media or tools for science outreach

M. Olivi co-supervised the creation of new scientific wooden objects by SNJ AZUR (funds from APOCS region): pixel art and transmission of images https://pixees.fr/jouer-a-transmettre-des-images/, IA machine. She also co-supervised the creation of videos by Thibaut Ehlinger (internship) and Gregory Casala (apprenti), funds from Class’Code and the national network, see https://pixees.fr/pause-ta-science-une-chaine-pour-decrypter-les-objets-scientifiques/.

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Project-Team FOCUS

Foundations of Component-based Ubiquitous Systems

IN COLLABORATION WITH: Dipartimento di Informatica - Scienza e Ingegneria (DISI), Universita' di Bologna

IN PARTNERSHIP WITH:
Université de Bologne (Italie)

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Distributed programming and Software engineering

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Project-Team FOCUS

Creation of the Project-Team: 2010 January 01

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A1.4. - Ubiquitous Systems
A2.1.1. - Semantics of programming languages
A2.1.6. - Concurrent programming
A2.1.7. - Distributed programming
A2.4.3. - Proofs

Other Research Topics and Application Domains:

B6.1. - Software industry
B6.3. - Network functions
B6.4. - Internet of things
B9.5.1. - Computer science

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2. Overall Objectives

2.1. Overall Objectives

Ubiquitous Computing refers to the situation in which computing facilities are embedded or integrated into everyday objects and activities. Networks are large-scale, including both hardware devices and software agents. The systems are highly mobile and dynamic: programs or devices may move and often execute in networks owned and operated by others; new devices or software pieces may be added; the operating environment or the software requirements may change. The systems are also heterogeneous and open: the pieces that form a system may be quite different from each other, built by different people or industries, even using different infrastructures or programming languages; the constituents of a system only have a partial knowledge of the overall system, and may only know, or be aware of, a subset of the entities that operate on the system.

A prominent recent phenomenon in Computer Science is the emerging of interaction and communication as key architectural and programming concepts. This is especially visible in ubiquitous systems. Complex distributed systems are being thought of and designed as structured composition of computational units, usually referred to as *components*. These components are supposed to interact with each other and such interactions are supposed to be orchestrated into conversations and dialogues. In the remainder, we will write *CBUS* for Component-Based Ubiquitous Systems.

In CBUS, the systems are complex. In the same way as for complex systems in other disciplines, such as physics, economics, biology, so in CBUS theories are needed that allow us to understand the systems, design or program them, analyze them.

Focus investigates the semantic foundations for CBUS. The foundations are intended as instrumental to formalizing and verifying important computational properties of the systems, as well as to proposing linguistic constructs for them. Prototypes are developed to test the implementability and usability of the models and the techniques. Throughout our work, ‘interaction’ and ’component’ are central concepts.

The members of the project have a solid experience in algebraic and logical models of computation, and related techniques, and this is the basis for our study of ubiquitous systems. The use of foundational models inevitably leads to opportunities for developing the foundational models themselves, with particular interest for issues of expressiveness and for the transplant of concepts or techniques from a model to another one.

3. Research Program

3.1. Foundations 1: Models

The objective of Focus is to develop concepts, techniques, and possibly also tools, that may contribute to the analysis and synthesis of CBUS. Fundamental to these activities is *modeling*. Therefore designing, developing and studying computational models appropriate for CBUS is a central activity of the project. The models are used to formalise and verify important computational properties of the systems, as well as to propose new linguistic constructs.

The models we study are in the process calculi (e.g., the π-calculus) and λ-calculus tradition. Such models, with their emphasis on algebra, well address compositionality—a central property in our approach to problems. Accordingly, the techniques we employ are mainly operational techniques based on notions of behavioural equivalence, and techniques based on algebra, mathematical logics, and type theory.

3.2. Foundations 2: Foundational calculi and interaction

Modern distributed systems have witnessed a clear shift towards interaction and conversations as basic building blocks for software architects and programmers. The systems are made by components, that are supposed to interact and carry out dialogues in order to achieve some predefined goal; Web services are a good example of this. Process calculi are models that have been designed precisely with the goal of understanding interaction and composition. The theory and tools that have been developed on top of process calculi can set a basis with which CBUS challenges can be tackled. Indeed industrial proposals of languages for Web services such as BPEL are strongly inspired by process calculi, notably the π-calculus.

3.3. Foundations 3: Type systems and logics

Type systems and logics for reasoning on computations are among the most successful outcomes in the history of the research in λ-calculus and (more recently) in process calculi. Type systems can also represent a powerful means of specifying dialogues among components of CBUS. For instance—again referring to Web services—current languages for specifying interactions only express basic connectivity, ignoring causality and timing aspects (e.g., an intended order on the messages), and the alternative is to use Turing Complete languages that are however undecidable. Types can come at hand here: they can express causality and order information on messages [53], [49], [54], while remaining decidable systems.

3.4. Foundations 4: Implicit computational complexity

A number of elegant and powerful results have been recently obtained in implicit computational complexity in the λ-calculus in which ideas from Linear Logics enable a fine-grained control over computations. This experience can be profitable when tackling issues of CBUS related to resource consumption, such as resources allocation, access to resources, certification of bounds on resource consumption (e.g., ensuring that a service will answer to a request in time polynomial with respect to the size of the input data).

4. Application Domains

4.1. Ubiquitous Systems

The main application domain for Focus are ubiquitous systems, broadly systems whose distinctive features are: mobility, high dynamicity, heterogeneity, variable availability (the availability of services offered by the constituent parts of a system may fluctuate, and similarly the guarantees offered by single components may not be the same all the time), open-endedness, complexity (the systems are made by a large number of components, with sophisticated architectural structures). In Focus we are particularly interested in the following aspects.

- *Linguistic primitives* for programming dialogues among components.
- *Contracts* expressing the functionalities offered by components.
- *Adaptability and evolvability* of the behaviour of components.
- *Verification* of properties of component systems.
- Bounds on component *resource consumption* (e.g., time and space consumed).

4.2. Service Oriented Computing and Cloud Computing

Today the component-based methodology often refers to Service Oriented Computing. This is a specialized form of component-based approach. According to W3C, a service-oriented architecture is "a set of components which can be invoked, and whose interface descriptions can be published and discovered". In the early days of Service Oriented Computing, the term services was strictly related to that of Web Services. Nowadays, it has a much broader meaning as exemplified by the XaaS (everything as a service) paradigm: based on modern virtualization technologies, Cloud computing offers the possibility to build sophisticated service systems on virtualized infrastructures accessible from everywhere and from any kind of computing device. Such infrastructures are usually examples of sophisticated service oriented architectures that, differently from traditional service systems, should also be capable to elastically adapt on demand to the user requests.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

- Ugo Dal Lago has been awarded an ERC CoG for his project "Differential Program Semantics" (DIAPASoN), which started on March 1st, 2019.
- Francesco Gavazzo has received the award for "Best Italian PhD Thesis in Theoretical Computer Science", by the Italian Chapter of EATCS (European Association for Theoretical Computer Science)
- Raphaëlle Crubillé has been awarded the "prix de thèse Gilles Kahn 2019 (Societé Informatique de France and Académie des Sciences)

6. New Software and Platforms

6.1. HoCA

Higher-Order Complexity Analysis

KEYWORDS: Ocaml - Verification - Runtime Complexity Analysis

SCIENTIFIC DESCRIPTION: Over the last decade, various tools for the static analysis of resource properties of programs have emerged. In particular, the rewriting community has recently developed several tools for the time complexity analysis of term rewrite systems. These tools have matured and are nowadays able to treat non-trivial programs, in a fully automatic setting. However, none of these automatic complexity analysers can deal with higher-order functions, a pervasive feature of functional programs. HoCA (Higher-Order Complexity Analyser) overcomes this limitation by translating higher-order programs – in the form of side-effect free OCaml programs - into equivalent first-order rewrite systems. At the heart of our tool lies Reynold's defunctionalization technique. Defunctionalization however is not enough. Resulting programs have a recursive structure too complicated to be analysed automatically in all but trivial cases. To overcome this issue, HoCA integrates a handful of well established program transformation techniques, noteworthy dead-code elimination, inlining, instantiation and uncurrying. A complexity bound on the resulting first-order program can be relayed back reliably to the higher-order program of interest. A detailed description of HoCA is available on http://arxiv.org/abs/1506.05043.

FUNCTIONAL DESCRIPTION: HoCA is an abbreviation for Higher-Order Complexity Analysis, and is meant as a laboratory for the automated complexity analysis of higher-order functional programs. Currently, HoCA consists of one executable pcf2trs which translates a pure subset of OCaml to term rewrite systems, in a complexity reflecting manner. As a first step, HoCA desugars the given program to a variation of Plotkin's PCF with data-constructors. Via Reynold's defunctionalization, the PCF program is turned into an applicative term rewrite system (ATRS for short), call-by-value reductions of the PCF program are simulated by the ATRS step-by-step, on the ATRS, and various complexity reflecting transformations are performed: inlining, dead-code-elminiation, instantiation of higher-order variables through a call-flow-analysis and finally uncurrying. This results finally in a first-order rewrite system, whose runtime-complexity reflects the complexity of the initial program, asymptotically.

- Participants: Martin Avanzini and Ugo Dal Lago
- Contact: Ugo Dal Lago
- URL: http://cbr.uibk.ac.at/tools/hoca/

6.2. JOLIE

Java Orchestration Language Interpreter Engine

KEYWORD: Microservices

SCIENTIFIC DESCRIPTION: Jolie enforces a strict separation of concerns between behaviour, describing the logic of the application, and deployment, describing the communication capabilities. The behaviour is defined using the typical constructs of structured sequential programming, communication primitives, and operators to deal with concurrency (parallel composition and input choice). Jolie communication primitives comprise two modalities of interaction typical of Service-Oriented Architectures (SOAs), namely one-way (sends an asynchronous message) and request-response (sends a message and waits for an answer). A main feature of the Jolie language is that it allows one to switch among many communication media and data protocols in a simple, uniform way. Since it targets the field of SOAs, Jolie supports the main communication media (TCP/IP sockets, Bluetooth L2CAP, Java RMI, and Unix local sockets) and data protocols (HTTP, JSON-RPC, XML-RPC, SOAP and their respective SSL versions) from this area.

FUNCTIONAL DESCRIPTION: Jolie is a language for programming service-oriented and microservice applications. It directly supports service-oriented abstractions such as service, port, and session. Jolie allows to program a service behaviour, possibly obtained by composing existing services, and supports the main communication protocols and data formats used in service-oriented architectures. Differently from other service-oriented programming languages such as WS-BPEL, Jolie is based on a user-friendly Java-like syntax (more readable than the verbose XML syntax of WS-BPEL). Moreover, the kernel of Jolie is equipped with a formal operational semantics. Jolie is used to provide proof of concepts around Focus activities.

RELEASE FUNCTIONAL DESCRIPTION: There are many fixes to the HTTP extension, improvements to the embedding engine for Javascript programs, and improvements to the support tools jolie2java and wsdl2jolie.

NEWS OF THE YEAR: During 2019 the Jolie project saw three major actions.

The first action regards the build system used for the development of the language, which has been transitioned to Maven, the main build automation tool used for Java projects. The move to Maven is dictated by two needs. The first is to streamline the development and release processes of Jolie, as Maven greatly helps in obtaining, updating, and managing library dependencies. The second necessity addressed by Maven is helping in partitioning the many sub-projects that constitute the Jolie codebase, reducing development and testing times. Having Jolie as a Maven project also helps in providing Jolie sub-components (as Maven libraries) to other projects. Finally, the move to Maven is set within a larger effort to expedite the inclusion in the main Jolie development branch of contributions by new members of its growing community.

The second action regards the transition to Netty as a common framework to support communication protocols and data formats in Jolie. Netty is a widely-adopted Java framework for the development of network applications, and it was used in 2018 to successfully support several IoT communication protocols and data formats in a Jolie spin-off project, called JIoT. The work in 2019 integrated into the Jolie codebase the protocols and data format developed within the JIoT project and pushed towards the integration of the Netty development branch into the main branch of the Jolie project (i.e., re-implementing using Netty the many protocol and data-formats already supported by Jolie). The Netty development branch is currently in a beta phase and it is subject to thorough in-production tests, to ensure consistent behaviour with the previous implementation.

The third action regards the development and support for a new official IDE for Jolie. Hence, along with the ones already existing for the Atom and Sublime Text text editors, Jolie developers can use the Jolie plugin (based on the Language Server Protocol) for the Visual Studio Code text editor to obtain syntax highlighting, documentation aids, file navigation, syntax checking, semantic checking, and quick-run shortcuts for their Jolie programs.

In addition to the above actions, in 2019 Jolie transitioned through three minor releases and a major one, from 1.7.1 to 1.8.2. The minor releases mainly fixed bugs, improved performance, and included new protocol/data-format functionalities. The major release included a slim-down of the notation for the composition of statements, types definitions, and tree structures, for a terser codebase. Upgrades to 1.8.2 also introduced: timeouts for solicit-response invocations to handle the interruption of long-standing requests, more user-friendly messages from the Jolie interpreter, including easier-to-parse errors and the pretty-printing of data structures, for a more effective development and debugging experience.

In 2019 Jolie also saw the development of a new Jolie library, called TQuery, which is a query framework integrated into the Jolie language for the data handling/querying of Jolie trees. Tquery is based on a tree-based instantiation (language and semantics) of MQuery, a sound variant of the Aggregation Framework, the query language of the most popular document-oriented database: MongoDB. Usage scenarios for Tquery are (but not limited to) eHealth, the Internet-of-Things, and Edge Computing, where data should be handled in an ephemeral way, i.e., in a real-time manner but with the constraint that data shall not persist in the system.

- Participants: Claudio Guidi, Fabrizio Montesi, Maurizio Gabbrielli, Saverio Giallorenzo and Ivan Lanese
- Contact: Fabrizio Montesi
- URL: http://www.jolie-lang.org/

6.3. NightSplitter

KEYWORD: Constraint-based programming

FUNCTIONAL DESCRIPTION: Nightsplitter deals with the group preference optimization problem. We propose to split users into subgroups trying to optimize members' satisfaction as much as possible. In a large city with a huge volume of activity information, designing subgroup activities and avoiding time conflict is a challenging task. Currently, the Demo is available only for restaurant and movie activities in the city of Paris.

- Contact: Tong Liu
- URL: http://cs.unibo.it/t.liu/nightsplitter/

6.4. AIOCJ

Adaptive Interaction-Oriented Choreographies in Jolie

KEYWORD: Dynamic adaptation

SCIENTIFIC DESCRIPTION: AIOCJ is an open-source choreographic programming language for developing adaptive systems. It allows one to describe a full distributed system as a unique choreographic program and to generate code for each role avoiding by construction errors such as deadlocks. Furthermore, it supports dynamic adaptation of the distributed system via adaptation rules.

FUNCTIONAL DESCRIPTION: AIOCJ is a framework for programming adaptive distributed systems based on message passing. AIOCJ comes as a plugin for Eclipse, AIOCJ-ecl, allowing to edit descriptions of distributed systems written as adaptive interaction-oriented choreographies (AIOC). From interaction-oriented choreographies the description of single participants can be automatically derived. Adaptation is specified by rules allowing one to replace predetermined parts of the AIOC with a new behaviour. A suitable protocol ensures that all the participants are updated in a coordinated way. As a result, the distributed system follows the specification given by the AIOC under all changing sets of adaptation rules and environment conditions. In particular, the system is always deadlock free. AIOCJ can interact with external services, seen as functions, by specifying their URL and the protocol they support (HTTP, SOAP, ...). Deadlock-freedom guarantees of the application are preserved provided that those services do not block.

NEWS OF THE YEAR: In 2019 we performed a major upgrade to AIOCJ: the possibility to introduce new roles, absent from a running choreography, within a given adaptation rule. The inclusion of new roles is supported by a slight, incremental change in the AIOCJ syntax and by a new component of the AIOCJ runtime environment.

- Participants: Ivan Lanese, Jacopo Mauro, Maurizio Gabbrielli, Mila Dalla Preda and Saverio Giallorenzo
- Contact: Saverio Giallorenzo
- URL: http://www.cs.unibo.it/projects/jolie/aiocj.html

6.5. CauDEr

Causal-consistent Debugger for Erlang

KEYWORDS: Debug - Reversible computing

SCIENTIFIC DESCRIPTION: The CauDEr reversible debugger is based on the theory of causal-consistent reversibility, which states that any action can be undone provided that its consequences, if any, are undone beforehand. This theory relies on a causal semantic for the target language, and can be used even if different processes have different notions of time

FUNCTIONAL DESCRIPTION: CauDEr is a debugger allowing one to explore the execution of concurrent Erlang programs both forward and backward. Notably, when going backward, any action can be undone provided that its consequences, if any, are undone beforehand. The debugger also provides commands to automatically find relevant past actions (e.g., send of a given message) and undo them, including their consequences. Forward computation can be driven by a log taken from a computation in the standard Erlang/OTP environment. An action in the log can be selected and replayed together with all and only its causes. The debugger enables one to find a bug by following the causality links from the visible misbehaviour to the bug. The debugger takes an Erlang program but debugging is done on its translation into Core Erlang.

NEWS OF THE YEAR: Work in 2019 consisted in maintenance, bug fixing and some minor refinements, in particular on the logging part.

- Partner: Universitat Politècnica de València
- Contact: Ivan Lanese
- URL: https://github.com/mistupv/cauder

6.6. SUNNY-AS

SUNNY FOR ALGORITHM SELECTION

KEYWORDS: Optimisation - Machine learning

FUNCTIONAL DESCRIPTION: SUNNY-AS is a portfolio solver derived from SUNNY-CP for Algorithm Selection Problems (ASLIB). The goal of SUNNY-AS is to provide a flexible, configurable, and usable portfolio solver that can be set up and executed just like a regular individual solver.

- Contact: Tong Liu
- URL: https://github.com/lteu/oasc

6.7. eco-imp

Expected Cost Analysis for Imperative Programs

KEYWORDS: Software Verification - Automation - Runtime Complexity Analysis - Randomized algorithms

FUNCTIONAL DESCRIPTION: Eco-imp is a cost analyser for probabilistic and non-deterministic imperative programs. Particularly, it features dedicated support for sampling from distributions, and can thereby accurately reason about the average case complexity of randomized algorithms, in a fully automatic fashion. The tool is based on an adaption of the ert-calculus of Kaminski et al., extended to the more general setting of cost analysis where the programmer is free to specify a (non-uniform) cost measure on programs. The main distinctive feature of eco-imp, though, is the combination of this calculus with an expected value analysis. This provides the glue to analyse program components in complete independence, that is, the analysis is modular and thus scalable. As a consequence, confirmed by our experiments, eco-imp runs on average orders of magnitude faster than comparable tools: execution times of several seconds become milliseconds.

- Contact: Martin Avanzini
- URL: http://www-sop.inria.fr/members/Martin.Avanzini/software/eco-imp/

7. New Results

7.1. Service-Oriented and Cloud Computing

Participants: Mario Bravetti, Maurizio Gabbrielli, Saverio Giallorenzo, Claudio Guidi, Ivan Lanese, Cosimo Laneve, Fabrizio Montesi, Gianluigi Zavattaro, Stefano Pio Zingaro.

7.1.1. Service-Oriented Computing and Internet of Things

Session types, i.e. types for structuring service communication, are recently being integrated into mainstream programming languages. In practice, a very important notion for dealing with such types is that of subtyping, since it allows for typing larger classes of system, where a program has not precisely the expected behavior but a similar one. We recently showed that, when asynchronous communication is considered, unfortunately, such a subtyping relation is undecidable. In [27] we present an algorithm (the first one that does not restrict type syntax or limit communication) and a tool for checking asynchronous subtyping which is sound, but not complete: in some cases it terminates without returning a final verdict. In [29] we discuss the relationship between session types and service behavioural contracts and we show the existence of a fully abstract interpretation of session types into a fragment of contracts, mapping subtyping into binary compliance-preserving contract refinement. This also yields an original undecidability result for asynchronous contract refinement.

In [43] we elaborate on our previous work on choreographies, which specify in a single artefact the expected behaviour of all the participants in a service oriented system. In particular, we extend dynamic choreographies, which model system updates at runtime, with the feature of dynamic inclusion of new unforeseen participants. In [30] we propose, in the context of platooning (a freight organization system where a group of vehicles follows a predefined trajectory maintaining a desired spatial pattern), a two layered, composable technical solution for federated platooning: a decentralized overlay network that regulates the interactions among the stakeholders, useful to mitigate issues linked to data safety and trustworthiness; and a dynamic federation platform, needed to monitor and interrupt deviant behaviors of federated members.

Finally, in [44] we focused on the use of our service-oriented language Jolie in an Internet of Things (IoT) setting. Technically, a key feature of Jolie is that it supports uniform linguistic abstractions to exploit heterogeneous communication stacks, i.e. for service oriented computing, protocols such as TCP/IP, Bluetooth, and RMI at transport level, and HTTP and SOAP at application level. We extend Jolie in order to support, uniformly as well, also the two most adopted protocols for IoT communication, i.e. CoAP and MQTT, and we report our experience on a case study on home automation.

7.1.2. Cloud Computing

In [18] we investigate the problem of modeling the optimal and automatic deployment of cloud applications and we experiment such an approach by applying it to the Abstract Behavioural Specification language ABS. In [28] we show that automated deployment, proven undecidable in the general case, is, instead, algorithmically treatable for the specific case of microservices: we implement an automatic optimal deployment tool and compute deployment plans for a realistic microservice architecture. In [35] we propose a core formal programming model (combining features from λ-calculus and π-calculus) for serverless computing, also known as Functions-as-a-Service: a recent paradigm aimed at simplifying the programming of cloud applications. The idea is that developers design applications in terms of functions and the infrastructure deals automatically with cloud deployment in terms of distribution and scaling.

7.2. Models for Reliability

Participants: Ivan Lanese, Doriana Medic.

7.2.1. Reversibility

We have continued the study of reversibility started in the past years. First, we continued to study reversibility in the context of the Erlang programming language. In particular, we devised a technique to record a program execution and replay it [37] inside the causal-consistent reversible debugger for Erlang we developed in the last years. More precisely, we may not replay the exact same execution, but any execution which is causal-consistent to it. We proved that this is enough to replay misbehaviours, hence to look for the bugs causing them. Second, we compared [48] various approaches to causal-consistent reversibility in CCS and π-calculus. In CCS, we showed that the two main approaches for causal-consistent reversibility, namely the ones of RCCS [51] and of CCSk [55] give rise to isomorphic LTSs (up to some structural rules). In π-calculus, we showed that one can define a causal semantics for π-calculus parametric on the data structure used to track extruded names, and that different instances capture causal semantics from the literature. All such semantics can be used to define (different) causal-consistent reversible semantics. As a final contribution, we studied reversibility in the context of Petri nets [41]. There, we do not considered causal-consistent reversibility, but a notion of local reversibility typical of Petri nets. In particular, we say that a transition is reversible if one can add a set of effect-reverses (an effect-reverse, if it can trigger, undoes the effect of the transition) to undo it in each marking reachable by it, without changing the set of reachable markings. We showed that, contrarily to what happens in bounded nets, transition reversibility is not decidable in general unbounded nets. It is however decidable in some significant subclasses of Petri nets, in particular all transitions of cyclic nets (nets where the initial marking is reachable from any state) are reversible. Finally, we show how to restructure nets by adding new places so to make their transitions reversible without altering their behaviour.

7.3. Probabilistic Systems and Resource Control

Participants: Martin Avanzini, Mario Bravetti, Raphaelle Crubillé, Ugo Dal Lago, Francesco Gavazzo, Gabriele Vanoni, Akira Yoshimizu.

7.3.1. Probabilistic Programming and Static Analysis

In FoCUS, we are interested in studying probabilistic higher-order programming languages and, more generally, the fundamental properties of probabilistic computation when placed in an interactive scenario, for instance concurrency. One of the most basic but nevertheless desirable properties of programs is of course termination. Termination can be seen as a minimal guarantee about the time complexity of the underlying program. When probabilistic choice comes into play, termination can be defined by stipulating that a program is terminating if its probability of convergence is 1, this way giving rise to the notion of *almost sure termination*. Alternatively, a probabilistic program is said to be *positively* almost surely terminating if its average runtime is finite. The latter condition easily implies the former. Termination, already undecidable for deterministic (universal) programming languages, remains so in the presence of probabilistic choice, even becoming provably harder.

The FoCUS team has been the first in advocating the use of types to guarantee probabilistic termination, in the form of a monadic sized-type system [17]. Developed in collaboration with Grellois by Dal Lago, this system substantially generalises usual sized-types, and allows this way to capture probabilistic, higher-order programs which terminate almost surely. Complementary, in collaboration with Ghyselen, Avanzini and Dal Lago have recently defined a formal system for reasoning about the *expected runtime* of higher-order probabilistic programs, through a *refinement type system* capable of *modeling probabilistic effects* with exceptional accuracy [26]. To the best of our knowledge, this provides the first formal methodology for *average case complexity analysis* of higher-order programs. Remarkably, the system is also *extensionally complete*.

In 2018, we have started to investigate the foundations for *probabilistic abstract reduction systems* (*probabilistic ARSs*), which constitute a general framework to study fundamental properties of probabilistic computations, such as termination or confluence. In 2019, we have significantly revised this initial development [11]. Particularly, we have refined Lyapunov ranking functions by conceiving them as *probabilistic embeddings*. The ramifications of this work are two-fold. First, we obtain a sound and complete method for reasoning about strong positive almost sure termination. Second, this method has been instantiated in the setting of (first-order) *probabilistic rewrite systems*, giving rise to the notion of *barycentric algebras*, generalising the well-known interpretation method. Barycentric algebras have been integrated in the termination prover *NaTT*[0], confirming the feasibility of the approach.

We have also worked on higher-order model checking as a way to prove termination of probabilsitic variations on higher-order recursion schemes [36], obtaining encouraging results. More specifically, an algorithm for approximating the probability of convergence of any such scheme has been designed and proved sound, although the problem of precisely computing the probability of convergence is shown to be undecidable at order 2 or higher. Finally, we have published a new version of a contribution we wrote in 2017 about how implicit computational complexity could help in proving that certain cryptographic constructions have the desired complexity-theoretic properties [12].

7.3.2. Higher-Order end Effectful Programs: Relational Reasoning

In FoCUS, we are also interested in relational reasoning about programs written in higher-order programming languages. In the recent years, this research has been directed to effectful programs, namely programs whose behaviour is not purely functional. Moreover, there has recently been a shift in our interests, driven by the projects REPAS and DIAPASoN, towards quantitative kinds of relational reasoning, in which programs are not necessarily dubbed equivalent (or not), but rather put at a certain distance.

The first contribution we had in this direction is due to Dal Lago and Gavazzo [31], who generalized the so-called open normal-form bisimilarity technique to higher-order programs exhibiting any kind of monadic effect. The key ingredient here is that of a relator, and allows to lift relations on a set to relations on monadic extensions to the same set. This allows to define open normal-form bisimilarity, and to prove it correct. This, together, with other contributions, have also appeared in Gavazzo's PhD Thesis, which has been successfully defended in April 2019 [10], and which has been awarder the Prize for the Best PhD Thesis in Theoretical Computer Science by the Italian Chapter of the EATCS.

We have also given the notion of differential logical relations [33], a generalization of Plotkin's logical relations in which programs are dubbed being at a certain *distance* rather than being just *equivalent*. Noticeably, this distance is not necessarily numeric, but is itself functional if the compared programs have a non-ground type. This allows to evaluate the distance between programs taking into account the possible actions the environment can make on the compared programs.

7.3.3. Alternative Probabilistic Models

We are also interested in exploring probabilistic models going beyond the usual ones, in which determinisitic programming languages are endowed with discrete probabilistic choice.

[0]See https://www.trs.css.i.nagoya-u.ac.jp/NaTT/.

We have first of all studied bayesian λ-calculi, namely λ-calculi in which not only an operator for probabilistic choice is available, but also one for *scoring*, which serves as the basis to model conditioning in probabilistic programming. We give a geometry of interaction model for such a typed λ-calculus [34], namely a paradigmatic calculus for higher-order Bayesian programming in the style of PCF. The model is based on the category of measurable spaces and partial measurable functions, and is proved adequate with respect to both a distribution-based and a sampling-based operational semantics.

We have also introduced a probabilistic extension of a framework to specify and analyze software product lines [15]. We define a syntax of the language including probabilistic operators and define operational and denotational semantics for it. We prove that the expected equivalence between these two semantic frameworks holds. Our probabilistic framework is supported by a set of scripts to show the model behavior.

7.4. Verification Techniques

Participants: Ugo Dal Lago, Adrien Durier, Daniel Hirschkoff, Ivan Lanese, Cosimo Laneve, Davide Sangiorgi, Akira Yoshimizu, Gianluigi Zavattaro.

Extensional properties are those properties that constrain the behavioural descriptions of a system (i.e., how a system looks like from the outside). Examples of such properties include classical functional correctness, deadlock freedom and resource usage.

In the last year of the Focus project, we have worked on three main topics: (*i*) *name mobility and coinductive techniques*, (*ii*) *deadlock analysis*, and (*iii*) *cost analysis of properties* of languages for actors and for smart contracts.

7.4.1. Name Mobility and Coinductive Techniques

In [19], we propose proof techniques for bisimilarity based on unique solution of equations. The results essentially state that an equation (or a system of equations) whose infinite unfolding never produces a divergence has the unique-solution property. We distinguishing between different forms of divergence; derive an abstract formulation of the theorems, on generic LTSs; adapt the theorems to other equivalences such as trace equivalence, and to preorders such as trace inclusion; we compare the resulting techniques to enhancements of the bisimulation proof method (the ‘up-to techniques’). In [20], we study how to adapt such techniques to higher-order languages. In such languages proving behavioural equivalences is known to be hard, because interactions involve complex values, namely terms of the language. The soundness of proof techniques is usually delicate and difficult to establish. The language considered is the Higher-Order π-calculus.

The contribution [42] studies the representation of the call-by-need λ-calculus in the pure message-passing concurrency of the π-calculus, precisely the Local Asynchronous π-calculus, that has sharper semantic properties than the ordinary π-calculus. We exploit such properties to study the validity of of β-reduction (meaning that the source and target terms of a beta-reduction are mapped onto behaviourally equivalent processes). Nearly all results presented fail in the ordinary π-calculus.

In [45], we investigate basic properties of the Erlang concurrency model. This model is based on asynchronous communication through mailboxes accessed via pattern matching. In particular, we consider Core Erlang (which is an intermediate step in Erlang compilation) and we define, on top of its operational semantics, an observational semantics following the approach used to define asynchronous bisimulation for the π-calculus. Our work allows us to shed some light on the management of process identifiers in Erlang, different from the various forms of name mobility already studied in the literature. In fact, we need to modify standard definitions to cope with such specific features of Erlang.

The paper [25] reviews the origins and the history of enhancements of the bisimulation and coinduction proof methods.

7.4.2. Deadlock Analysis

The contributions [22] and [50] address deadlock analysis of Java-like programs. The two papers respectively cover two relevant features of these languages: (*i*) multi-threading and reentrant locks and (*ii*) co-ordination primitives (wait, notify and notifyAll). In both cases, we define a behavioral type system that associates abstract models to programs (lams and Petri Nets with inhibitor arcs) and define an algorithm for detecting deadlocks. The two systems are consistent and our technique is intended to be an effective tool for the deadlock analysis of programming languages.

The paper [16] addresses the π-calculus. It defines a type system for guaranteing that typable processes never produce a run-time error and, even if they may diverge, there is always a chance for them to finish their work, i.e., to reduce to an idle process (a stronger property than deadlock freedom). The type system uses so-called *non-idempotent intersections* and, therefore, applies to a large class of processes. Indeed, despite the fact that the underlying property is $\prod_2^0$-complete, there is a way to show that the system is complete, i.e., that any well-behaved process is typable, although for obvious reasons infinitely many derivations need to be considered.

7.4.3. Static Analysis of Properties of Concurrent Programs

We have analyzed the computational time of actor programs, following a technique similar to [52], and we have begun a new research direction that deals with the analysis of Solidity smart contracts.

In [23], we propose a technique for estimating the computational time of programs in an actor model. To this aim, we define a compositional translation function returning cost equations, which are fed to an automatic off-the-shelf solver for obtaining the time bounds. Our approach is based on so-called *synchronization sets* that capture possible difficult synchronization patterns between actors and helps make the analysis efficient and precise. The approach is proven to correctly over-approximate the worst computational time of an actor model of concurrent programs. The technique is complemented by a prototype analyzer that returns upper bound of costs for the actor model.

In [38], we analyze the bahaviour of smart contracts, namely programs stored on some blockchain that control the transfer of assets between parties under certain conditions. In particular, we focus on the interactions of smart contracts and external actors (usually, humans) in order to maximize objective functions. 5 To this aim, we define a core language of programs, which is reminiscent of Solidity, with a minimal set of smart contract primitives and we describe the whole system as a parallel composition of smart contracts and users. We therefore express the system behaviour as a first order logic formula in Presburger arithmetics and study the maximum profit for each actor by solving arithmetic constraints.

7.5. Computer Science Education

Participants: Michael Lodi, Simone Martini.

We study why and how to teach computer science principles (nowadays often referred to as “computational thinking”, CT), in the context of K-12 education. We are interested in philosophical, sociological, and historical motivations to teach computer science. Furthermore, we study what concepts and skills related to computer science are not only technical abilities, but have a general value for all students. Finally, we try to find/produce/evaluate suitable materials (tools, languages, lesson plans...) to teach these concepts, taking into account: difficulties in learning CS concepts (particularly programming); stereotypes about computer science (teachers’ and students’ mindset); teacher training (both non-specialist and disciplinary teachers); innovative teaching methodologies (primarily based on constructivist and constructionist learning theories).

7.5.1. Computational Thinking, Unplugged Activities, and Constructionism

We reviewed some relevant literature related to learning CS and, more specifically, programming in a constructivist and constructionist light. We investigated some cognitive aspects, for example, the notional machine and its role in understanding, misunderstanding, and difficulties of learning to program. We reviewed programming languages for learning to program, with particular focus on educational characteristics of block-based languages [24].

We analyzed the widespread but debated pedagogical approach of “unplugged activities”: activities without a computer, like physical games, used to teach CS concepts. We explicitly connect computational thinking to the “CS Unplugged” pedagogical approach, by analyzing a representative sample of CS Unplugged activities in light of CT. We found the activities map well onto commonly accepted CT concepts, although caution must be taken not to regard CS Unplugged as being a complete approach to CT education [14].

Moreover, we found similarities (e.g., kinesthetic activities) and differences (e.g., structured vs. creative activities) between Unplugged and constructivism or constructionism. We argue there is a tension between the constructivist need to link the CS concepts to actual implementations and the challenge of teaching CS principles without computers, to undermine the misconceptions of CS as “the science of computers” [13].

7.5.2. CS in Primary School

We designed, produced and implemented in a primary school some “unplugged + plugged” teaching materials and lesson plans [47]. The unplugged activities are structured as an incremental discovery, scaffolded by the instructors, of the fundamental concepts of structured programming (e.g., sequence, conditionals, loops, variables) but also complexity in terms of computational steps and generalization of algorithms. The plugged activities follow the creative learning approach, using Scratch as the primary tool, both for free creative expression and for learning other disciplines (e.g., drawing regular polygons).

7.5.3. Growth Mindset and Transfer

Every person holds an idea (mindset) about intelligence: someone thinks it is a fixed trait, like eye colour (fixed mindset), while others believe it can grow like muscles (growth mindset). The latter is beneficial for students to have better results, particularly in STEM disciplines, and to not being influenced by stereotypes. Computer science is a subject that can be affected by fixed ideas (“geek gene”), and some (small) studies showed it can induce fixed ideas. By contrast, some claims stating that studying CS can foster a GM have emerged. However, educational research shows that the transfer of competences is hard. We measured [40] some indicators (e.g., mindset, computer science mindset) at the beginning and the end of a high school year in different classes, both CS and non-CS oriented. At the end of the year, none of the classes showed a statistically significant change in their mindset. Interestingly, non-CS oriented classes showed a significant decrease in their computer science growth mindset, which is not desirable.

7.6. Constraint Programming

Participants: Maurizio Gabbrielli, Liu Tong.

In Focus, we sometimes make use of constraint solvers (e.g., cloud computing, service-oriented computing). Since a few years we have thus began to develop tools based on constraints and constraint solvers.

In [39] we have used constraints in the setting of Service Function Chaining (SFC) deployment. SFCs represent sequences of Virtual Network Functions that compose a service. They are found within Network Function Virtualization (NFV) and Software Defined Networking (SDN) technologies, that recently acquired a great momentum thanks to their promise of being a flexible and cost-effective solution for replacing hardware-based, vendor-dependent network middleboxes with software appliances running on general purpose hardware in the cloud.

We employ constraint programming to solve the SFC design problem. Indeed we argue that constraint programming can be effectively used to address this kind of problems because it provides expressive and flexible modeling languages which come with powerful solvers, thus providing efficient and scalable performance.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

In 2019 we have started the Innovation Lab on Blockchain and New Technologies (https://site.unibo.it/blockchain-and-newtechnologies/en). The Lab is a new joint laboratory of the Computer Science and Engineering Department of the University of Bologna and KPMG Advisory S.p.A. that is committed to scientific research and technology transfer of systems based on blockchain and new technologies. The laboratory joins the efforts of several researchers of the Department and uses the experience in technology transfer of KPMG Advisory S.p.A.

The Lab has received a grant of 10KE from KPMG and a grant of 10KE from CIRFOOD, one of the biggest Italian companies in organised commercial and collective catering.

9. Partnerships and Cooperations

9.1. National Initiatives

- DCore (Causal debugging for concurrent systems) is a 4-years ANR project that started on March 2019. The overall objective of the project is to develop a semantically well-founded, novel form of concurrent debugging, which we call "causal debugging". Causal debugging will comprise and integrate two main engines: (i) a reversible execution engine that allows programmers to backtrack and replay a concurrent or distributed program execution and (ii) a causal analysis engine that allows programmers to analyze concurrent executions to understand why some desired program properties could be violated. Main persons involved: Lanese, Medic.
- REPAS (Reliable and Privacy-Aware Software Systems via Bisimulation Metrics) is an ANR Project that started on October 2016 and that will finish on October 2020. The project aims at investigating quantitative notions and tools for proving program correctness and protecting privacy. In particular, the focus will be put on bisimulation metrics, which are the natural extension of bisimulation to quantitative systems. As a key application, we will develop a mechanism to protect the privacy of users when their location traces are collected. Main persons involved: Dal Lago, Gavazzo, Sangiorgi.
- COCAHOLA (Cost models for Complexity Analyses of Higher-Order Languages) is an ANR Project that started on October 2016 and that finished on October 2019. The project aims at developing complexity analyses of higher-order computations. The focus is not on analyzing fixed programs, but whole programming languages. The aim is the identification of adequate units of measurement for time and space, i.e. what are called *reasonable* cost models. Main persons involved: Dal Lago, Martini.
- PROGRAMme ("What is a program? Historical and philosophical perspectives"), is an ANR project started on October 2017 and that will finish on October 2022; PI: Liesbeth De Mol (CNRS/Université de Lille3). The aim of this project is to develop a coherent analysis and pluralistic understanding of "computer program" and its implications to theory and practice. Main person involved: Martini.

9.2. European Initiatives

9.2.1. FP7 & H2020 Projects

- BEHAPI (Behavioural Application Program Interfaces) is an European Project H2020-MSCA-RISE-2017, running in the period March 2018 - February 2022. The topic of the project is behavioural types, as a suite of technologies that formalise the intended usage of API interfaces. Indeed, currently APIs are typically flat structures, i.e. sets of service/method signatures specifying the expected service parameters and the kind of results one should expect in return. However, correct API usage also requires the individual services to be invoked in a specific order. Despite its importance, the latter information is either often omitted, or stated informally via textual descriptions. The expected benefits of behavioural types include guarantees such as service compliance, deadlock freedom, dynamic adaptation in the presence of failure, load balancing etc. The project aims to bring the existing prototype tools based on these technologies to mainstream programming languages and development frameworks used in industry.

- ICT COST Action IC1405 (Reversible computation - extending horizons of computing). Initiated at the end of April 2015 and with a 4-year duration, this COST Action studies reversible computation and its potential applications, which include circuits, low-power computing, simulation, biological modeling, reliability and debugging. Reversible computation is an emerging paradigm that extends the standard forwards-only mode of computation with the ability to execute in reverse, so that computation can run backwards as naturally as it can go forwards.

  Main persons involved: Lanese (vice-chair of the action).

9.2.2. Collaborations with Major European Organizations

We list here the cooperations and contacts with other groups, without repeating those already listed in previous sections.

- ENS Lyon (on concurrency models and resource control). Contact person(s) in Focus: Dal Lago, Martini, Sangiorgi. Some visit exchanges during the year, in both directions. A joint PhD (Adrien Durier).
- University of Innsbruck (on termination and complexity analysis of probabilistic programs). Contact person(s) in Focus: Avanzini. Some short visits during the year.
- University of Southern Denmark (on service-oriented computing). Contact person(s) in Focus: Gabbrielli, Lanese, Zavattaro.
- Universitat Politecnica de Valencia, Spain (on reversibility for Erlang). Contact person(s) in Focus: Lanese. Some visit exchanges during the year, in both directions.
- Laboratoire d'Informatique, Université Paris Nord, Villetaneuse (on implicit computational complexity). Contact person(s) in Focus: Dal Lago, Martini.
- Institut de Mathématiques de Luminy, Marseille (on lambda-calculi, linear logic and semantics). Contact person(s) in Focus: Dal Lago, Martini.
- Team PPS, IRIF Lab, University of Paris-Diderot Paris 7 (on logics for processes, resource control). Contact person(s) in Focus: Dal Lago, Martini, Sangiorgi. Some short visits in both directions during the year.
- IRILL Lab, Paris (on models for the representation of dependencies in distributed package based software distributions). Contact person(s) in Focus: Gabbrielli, Zavattaro. Some short visits in both directions during the year.
- IMDEA Software, Madrid (G. Barthe) (on implicit computational complexity for cryptography). Contact person(s) in Focus: Dal Lago. Some visits during the year.

9.3. International Initiatives

9.3.1. Inria Associate Teams Not Involved in an Inria International Lab

9.3.1.1. CRECOGI

Title: Concurrent, Resourceful and Effectful Computation by Geometry of Interaction

International Partner (Institution - Laboratory - Researcher):

Kyoto (Japan) - Research Institute for Mathematical Sciences - Naohiko Hoshino

Start year: 2018

See also: http://crecogi.cs.unibo.it

The field of denotational semantics has successfully produced useful compositional reasoning principles for program correctness, such as program logics, fixed-point induction, logical relations, etc. The limit of denotational semantics was however that it applies only to high-level languages and to extensional properties. The situation has changed after the introduction of game semantics and the geometry of interaction (GoI), in which the meaning of programs is formalized in terms of movements of tokens, through which programs "talk to" or "play against" each other, thus having an operational flavour which renders them suitable as target language for compilers. The majority of the literature on GoI and games only considers sequential functional languages. Moreover, computational effects (e.g. state or I/O) are rarely taken into account, meaning that they are far from being applicable to an industrial scenario. This project's objective is to develop a semantic framework for concurrent, resourceful, and effectful computation, with particular emphasis on probabilistic and quantum effects. This is justified by the greater and greater interest which is spreading around these two computation paradigms, motivated by applications to AI and by the efficiency quantum parallelism induces.

9.3.2. Participation in Other International Programs

Focus has taken part in the creation of the Microservices Community (http://microservices.sdu.dk/), an international community interested in the software paradigm of Microservices. Main aims of the community are: i) sharing knowledge and fostering collaborations about microservices among research institutions, private companies, universities, and public organisations (like municipalities); ii) discussing open issues and solutions from different points of view, to create foundations for both innovation and basic research.

U. Dal Lago is "Partner Investigator" in the project "Verification and analysis of quantum programs", whose Chief Investigator is Prof Yuan Feng, University of Technology Sydney. The project is funded by the Australian Research Council.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

The following researchers have visited Focus for short periods; we list them together with the title of the talk they have given during their stay, or the topic discussed during their stay.

- Ornela Dardha (University of Glasgow) and Laura Bocchi (University of Kent): collaboration within BehAPI RISE H2020 project, September 2019.
- Guilhem Jaber (University of Nantes): "Game semantics for higher-order functions with state", December 2019.
- Naohiko Hoshino, April 2019 and October 2019.
- Gilles Barthe, May 2019.
- Boaz Barak, July 2019.
- Francesco Dagnino, "Generalizing Inference Systems by Corules", November 2019.

9.4.1.1. Sabbatical programme

Simone Martini has been Fellow at the Collegium - Lyon Institute for Advanced Studies, since September 2018 and until June 2019 https://collegium.universite-lyon.fr.

9.4.1.2. Research Stays Abroad

- Ugo Dal Lago has spent overall a few weeks in Japan: RIMS (Kyoto) and NII (Tokyo), as part of ongoing collaborations with Naohiko Hoshino and Shin-ya Katsumata.
- Ivan Lanese has visited Xibis Limited and University of Leicester, UK (in particular Irek Ulidowski and Emilio Tuosto) from 3/7/2019 to 2/8/2019, to work on choreographies, and the University of Torun, Poland (in particular Lukasz Mikulski and Kamila Barylska), from 13/8/2019 to 29/8/2019, to work on reversible Petri nets.
- Cosimo Laneve and Gianluigi Zavattaro have spent overall a few weeks in Malta visit to Prof. Adrian Francalanza at the University of Malta within the BehAPI RISE H2020 project.
- Michael Lodi has visited Prof. Tim Bell and the Computer Science Education Research Group at the Department of Computer Science and Software Engineering, University of Canterbury, Christchurch, New Zealand, from 26th of October 2018 to 17th of April 2019, as part of his Ph.D. course.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events: Organisation

10.1.1.1. General Chair, Scientific Chair

Mario Bravetti has been scientfiic co-organizer for Int. PhD School and Bootcamp on Behavioural Application Program Interfaces (BehAPI 2019), Leicester, UK.

Ugo Dal Lago has organized the Second Workshop on Probabilistic Interactive and Higher-Order Computation (6-7 February 2019) http://pihoc2019.cs.unibo.it/.

10.1.1.2. Member of the Organizing Committees

Local Organising Committee:

Michael Lodi has been a member of the Local Organising Committee of the 13th Conference of European Science Education Research Association (ESERA '19). Bologna, 26th - 30th August 2019

Steering Committee membership:

I. Lanese: Conference on Reversible Computation (RC); IFIP Int. Conference on Formal Techniques for Distributed Objects, Components and Systems (FORTE); Interaction and Concurrency Experience (ICE)

D. Sangiorgi: Int. Conference on Concurrency Theory (CONCUR)

10.1.2. Scientific Events: Selection

10.1.2.1. Member of the Conference Program Committees

M. Bravetti: 22nd International Conference on Fundamental Approaches to Software Engineering (FASE/ETAPS 2019); IEEE International Conference on Big Data (BigData 2019); 19th IEEE International Conference on Software Quality, Reliability, and Security (QRS 2019); 8th IPM International Conference on Fundamentals of Software Engineering (FSEN 2019)

U. Dal Lago: Annual ACM/IEEE Symposium on Logic in Computer Science (LICS 2019; 47th ACM SIGPLAN Symposium on Principles of Programming Languages (POPL 2020); 28th European Symposium on Programming (ESOP 2019); 4th International Conference on Formal Structures for Computation and Deduction (FSCD 2019)

I. Lanese: 11th Conference on Reversible Computation (RC 2019); 12th Interaction and Concurrency Experience (ICE 2019); 16th International Conference on Formal Aspects of Component Software (FACS 2019); 12th IEEE International Conference on Service-Oriented Computing and Applications (SOCA 2019); First Workshop on Artificial Intelligence and fOrmal VERification, Logic, Automata, and sYnthesis (OVERLAY 2019); 4th Workshop on Formal Reasoning about Causation, Responsibility, and Explanations in Science and Technology (CREST 2019); 2nd International Conference on Microservices (MICROSERVICES 2019); 12th Innovations in Software Engineering Conference (ISEC 2019)

S. Martini: Workshop on History of Formal Methods (HFM2019); Fifth International Conference on History and Philosophy of Computing (HAPOC 5).

D. Sangiorgi: 22nd International Conference on Foundations of Software Science and Computation Structures (FOSSACS); 44th International Symposium on Mathematical Foundations of Computer Science (MFCS); 12th A.P. Ershov Informatics Conference (PSI); Workshop on History of Formal Methods (HFM2019); 15th International Conference on Software Technologies (ICSOFT)

G. Zavattaro: 17th International Conference on Service Oriented Computing (ICSOC'19); International Conference TOOLS 50+1: Technology of Object-Oriented Languages and Systems (TOOLS'19); 30th International Conference on Concurrency Theory (CONCUR'19); 34th ACM/SIGAPP Symposium On Applied Computing – track on Microservices, DevOps, and Service-Oriented Architecture (ACM-SAC 2019)

10.1.3. Journals

10.1.3.1. Member of the Editorial Boards

M. Bravetti: Journal of Universal Computer Science.

U. Dal Lago: Logical Methods in Computer Science; Mathematical Structures in Computer Science; Acta Informatica.

M. Gabbrielli: Int. Journal Theory and Practice of Logic Programming.

C. Laneve: Frontiers in ICT (Section Formal Methods).

I. Lanese: Editor in chief of the Open Journal of Communications and Software (Scientific Online).

D. Sangiorgi: Acta Informatica, Distributed Computing, RAIRO Theoretical Informatics and Applications.

10.1.4. Invited Talks

U. Dal Lago: Bellairs Workshop on Higher-Order Probabilistic Computation; 1st Computer Science Workshop; “Mission 10000 Conference: Quantum Science and Technologies”

D. Sangiorgi: International Conference TOOLS 50+1: Technology of Object-Oriented Languages and Systems (TOOLS’19)

Schools:

M. Avanzini: International School on Rewriting, Paris, France, 1–6 July, 2019

U. Dal Lago: 1st “Caleidoscope” Summer School

G. Zavattaro: BehAPI Summer School: Behavioural Approaches for API-Economy with Applications, Leicester, UK, 8–12 July, 2019

10.1.5. Leadership within the Scientific Community

U. Dal Lago has been elected member of the Scientific Council of the Italian Chapter IC-EATCS (November 2017).

S. Martini is a member of the Council of the Commission on History and Philosophy of Computing, an organism of the International Union for History and Philosophy of Science, 2017-2021.

G. Zavattaro is member of the scientific committee of GRIN (GRuppo INformatici), Italy.

10.1.6. Administration duties

M. Gabbrielli is Deputy Head of the Department of Computer Science and Engineering, University of Bologna, since May 2018.

D. Sangiorgi is coordinator of postgraduate studies at the Department of Computer Science and Engineering, University of Bologna.

G. Zavattaro is coordinator of undergraduate studies at the Department of Computer Science and Engineering, University of Bologna.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

- Mario Bravetti

  Master: “Linguaggi, Compilatori e Modelli Computazionali”, 120 hours, 1st year, University of Bologna, Italy.

- Ugo Dal Lago

  Undergraduate: “Algorithms and Data Structures for Biology”, 60 hours, 2nd year, University of Bologna, Italy. 20 hours, 1st year, University of Bologna, Italy.

  Undergraduate: “Optimization”, 36 hours, 2nd year, University of Bologna, Italy.

  Master: “Foundations of Logic for Computer Science”, 24 Hours, 2nd year. University of Bologna, Italy.

  Master: “Cryptography”, 40 Hours, 2nd year, University of Bologna, Italy’.

  Master: “Languages and Algorithms for AI: Machine Learning Theory”, 32 Hours, 1st year, University of Bologna, Italy’.

- Maurizio Gabbrielli

  Undergraduate: “Programming languages”, 40 hours, 2nd year, University of Bologna, Italy.

  Master: “Artificial Intelligence”, 60 hours, 2nd year, University of Bologna, Italy.

- Francesco Gavazzo

  Undergraduate: “Programming languages”, 30 hours, 2nd year, University of Bologna, Italy.

  Undergraduate: “Basic Computer Skills”. 30 hours, BSc Medical Chemistry and Pharmaceutical Technology, BSc Biology, University of Bologna.

- Ivan Lanese

  Undergraduate: “Architettura degli Elaboratori”, 66 hours, 1st year, University of Bologna, Italy.

  Master: “Ingegneria del Software Orientata ai Servizi”, 22 hours, 2nd year, University of Bologna, Italy.

  Master: “Algorithms and data structures for computational biology”, 36 hours, 1at year, University of Bologna, Italy.

  Master: “Programming for bioinformatics”, 30 hours, 1st year, University of Bologna, Italy.

- Cosimo Laneve

  Undergraduate: “Programmazione”, 70 hours, 1st year, University of Bologna, Italy.

  Master: “Analisi di Programmi”, 42 hours, 1st year, University of Bologna, Italy.

- Simone Martini

  Master: “Introduction to Algorithms and Programming”, 32 hours, 1st year, University of Bologna, Italy.

- Davide Sangiorgi

  Undergraduate: “Operating Systems”, 110 hours, 2nd year, University of Bologna, Italy.

  Undergraduate: “Computer abilities for biologists”, 8 hours, 1st year, University of Bologna, Italy.

- Gianluigi Zavattaro

Master: “Scalable and Cloud Programming”, 50 hours, 2nd year, University of Bologna, Italy.

Undergraduate: “Algoritmi e strutture dati”, 60 hours, 2nd year, University of Bologna, Italy.

Master: “Languages and Algorithms for Artificial Intelligence”, 32 hours, 1st year, University of Bologna, Italy (Master in Artificial Intelligence).

10.2.2. Supervision

Below are the details on the PhD students in Focus: starting date, topic or provisional title of the thesis, supervisor(s).

- Melissa Antonellii, November 2019. “Probabilistic Arithmetic and Almost-sure Termination”. Supervisor Ugo Dal Lago.
- Adrien Durier, September 2016, "Proving behavioural properties of higher-order concurrent languages", ENS de Lyon and University of Bologna. Supervisors: Daniel Hirschkoff and Davide Sangiorgi.
- Michael Lodi, January 2017, “Introducing Computational Thinking in K-12 Education: Historical, Epistemological, Cognitive and Affective Aspects”. Supervisor: S. Martini.
- Gabriele Vanoni, November 2018. “Optimal Reduction, Geometry of Interaction, and the Space-Time Tradeoff”. Supervisor Ugo Dal Lago.
- Stefano Pio Zingaro, November 2016, “High level languages for Internet of Things applications”. Supervisor: Maurizio Gabbrielli.

PhD thesis completed in 2018:

- Raphaelle Crubillé, October 2015, “Bisimulation Metrics and Probabilistic Lambda Calculi”, Université Denis Diderot and University of Bologna. Supervisors Thomas Ehrhard and Ugo Dal Lago.
- Francesco Gavazzo, October 2015, “Coinductive Techniques for Effectful Lambda Calculi”. Supervisor U. Dal Lago.
- Tong Liu, November 2015, “Constraint based languages for Software Defined Networks”. Supervisor: Maurizio Gabbrielli.

10.2.3. Juries

G. Zavattaro has been member of the PhD evaluation committee of Doriana Medic, supervisor Claudio Antares Mezzina, IMT Lucca, Italy.

10.3. Popularization

Michael Lodi and Simone Martini have carried out extended work of scientific popularization, including the following.

- They are members of the technical committee of Olimpiadi del Problem Solving (at Italian Ministry of Education), http://www.olimpiadiproblemsolving.com; this involves preparation of material and supervision and jury during the finals.
- Simone Martini has given the following talks, among others:
  - De la création d’une “théorie mathématique du calcul” à la “pensée informatique”. Quatrième journée académique sur l’enseignement de l’informatique, Marseille (avril 2019)
  - To code or not to code: the school curriculum facing the digital revolution. Collegium—Lyon Institute for Advanced Studies (Juin 2019)
  - Logic and computing in Italy at the birth of the Italian Computer Science, Roma Tre, September 2019

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[3] P. COPPOLA, S. MARTINI.*Optimizing optimal reduction: A type inference algorithm for elementary affine logic*, in "ACM Trans. Comput. Log.", 2006, vol. 7, n^o 2, p. 219-260

[4] M. GABBRIELLI, S. MARTINI.*Programming Languages: Principles and Paradigms*, Springer, 2010

[5] D. HIRSCHKOFF, É. LOZES, D. SANGIORGI.*On the Expressiveness of the Ambient Logic*, in "Logical Methods in Computer Science", 2006, vol. 2, n^o 2

[6] U. D. LAGO, M. GABOARDI.*Linear Dependent Types and Relative Completeness*, in "Proceedings of the 26th Annual IEEE Symposium on Logic in Computer Science, LICS 2011", IEEE Computer Society, 2011, p. 133-142

[7] I. LANESE, C. A. MEZZINA, J. STEFANI.*Reversibility in the higher-order π-calculus*, in "Theor. Comput. Sci.", 2016, vol. 625, p. 25–84, https://doi.org/10.1016/j.tcs.2016.02.019

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[12] P. BAILLOT, G. BARTHE, U. DAL LAGO.*Implicit Computational Complexity of Subrecursive Definitions and Applications to Cryptographic Proofs*, in "Journal of Automated Reasoning", December 2019, vol. 63, n^o 4, p. 813-855 [*DOI :* 10.1007/978-3-662-48899-7_15], https://hal.archives-ouvertes.fr/hal-01197456

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Project-Team GRAPHDECO

GRAPHics and DEsign with hEterogeneous COntent

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Interaction and visualization

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Project-Team GRAPHDECO

Creation of the Team: 2015 January 01, updated into Project-Team: 2015 July 01

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1. Team, Visitors, External Collaborators

Research Scientists

George Drettakis [Team leader, Inria, Senior Researcher, HDR]
Adrien Bousseau [Inria, Researcher, HDR]

External Collaborator

Frédo Durand [MIT]

Technical Staff

Sebastien Morgenthaler [Inria, Engineer]
Siddhant Prakash [Inria, Engineer, from Feb 2019 until Oct 2019]
Sebastian Vizcay [Inria, Engineer, until Oct 2019]
Bastien Wailly [Inria, Engineer]

PhD Students

Johanna Delanoy [Inria, PhD Student, until Jun 2019]
Valentin Deschaintre [Optis/ANSYS, PhD Student, until Oct 2019, granted by CIFRE]
Stavros Diolatzis [Inria, PhD Student]
Felix Hahnlein [Inria, PhD Student, from Feb 2019]
David Jourdan [Inria, PhD Student]
Georgios Kopanas [Inria, PhD Student, from Dec 2019]
Julien Philip [Inria, PhD Student]
Siddhant Prakash [Inria, PhD Student, from Nov 2019]
Simon Rodriguez [Ministère de l'Enseignement Supérieur et de la Recherche, PhD Student]
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Tibor Stanko [Inria, Post-Doctoral Fellow]
Yulia Gryaditskaya [Inria, Post-Doctoral Fellow]

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Sophie Honnorat [Inria, Administrative Assistant]

2. Overall Objectives

2.1. General Presentation

In traditional Computer Graphics (CG) input is *accurately modeled* by hand by artists. The artists first create the 3D geometry – i.e., the polygons and surfaces used to represent the 3D scene. They then need to assign colors, textures and more generally material properties to each piece of geometry in the scene. Finally they also define the position, type and intensity of the lights. This modeling process is illustrated schematically in Fig. 1(left)). Creating all this 3D content involves a high level of training and skills, and is reserved to a small minority of expert modelers. This tedious process is a significant distraction for creative exploration, during which artists and designers are primarily interested in obtaining compelling imagery and prototypes rather than in accurately specifying all the ingredients listed above. Designers also often want to explore many variations of a concept, which requires them to repeat the above steps multiple times.

Once the 3D elements are in place, a *rendering* algorithm is employed to generate a shaded, realistic image (Fig. 1(right)). Costly rendering algorithms are then required to simulate light transport (or *global illumination*) from the light sources to the camera, accounting for the complex interactions between light and materials and the visibility between objects. Such rendering algorithms only provide meaningful results if the input has been *accurately* modeled and is *complete*, which is prohibitive as discussed above.

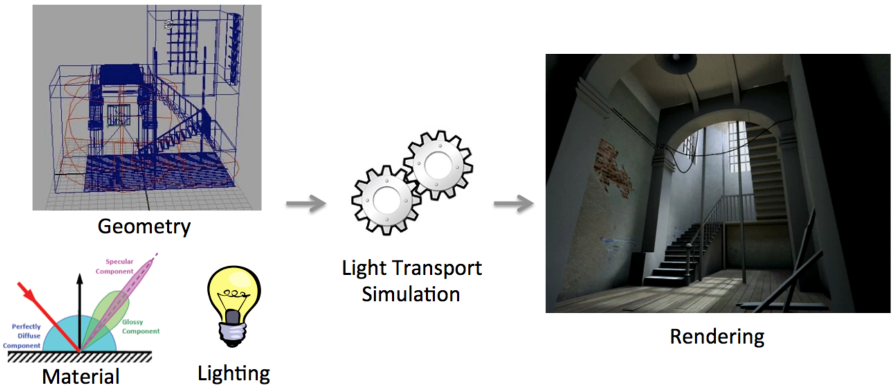


Figure 1. Traditional computer graphics pipeline. Rendering from www.thegnomonworkshop.com

A major recent development is that many alternative sources of 3D content are becoming available. Cheap depth sensors allow anyone to capture real objects but the resulting 3D models are often *uncertain*, since the reconstruction can be inaccurate and is most often incomplete. There have also been significant advances in casual content creation, e.g., sketch-based modeling tools. The resulting models are often approximate since people rarely draw accurate perspective and proportions. These models also often lack details, which can be seen as a form of uncertainty since a variety of refined models could correspond to the rough one. Finally, in recent years we have witnessed the emergence of new usage of 3D content for rapid prototyping, which aims at accelerating the transition from rough ideas to physical artifacts.

The inability to handle *uncertainty* in the data is a major shortcoming of CG today as it prevents the direct use of cheap and casual sources of 3D content for the design and rendering of high-quality images. The abundance and ease of access to *inaccurate*, *incomplete* and *heterogeneous* 3D content imposes the need to *rethink the foundations of 3D computer graphics* to allow *uncertainty* to be treated in inherent manner in Computer Graphics, from design all the way to rendering and prototyping.

The technological shifts we mention above, together with developments in computer vision, user-friendly sketch-based modeling, online tutorials, but also image, video and 3D model repositories and 3D printing represent a great opportunity for new imaging methods. There are several significant challenges to overcome before such visual content can become widely accessible.

In GraphDeco, we have identified two major scientific challenges of our field which we will address:

- First, the design pipeline needs to be revisited to **explicitly account for the variability and uncertainty of a concept and its representations**, from early sketches to 3D models and prototypes. Professional practice also needs to be adapted and facilitated to be accessible to all.
- Second, a new approach is required to **develop computer graphics models and algorithms capable of handling uncertain and heterogeneous data** as well as traditional synthetic content.

We next describe the context of our proposed research for these two challenges. Both directions address hetereogeneous and uncertain input and (in some cases) output, and build on a set of common methodological tools.

3. Research Program

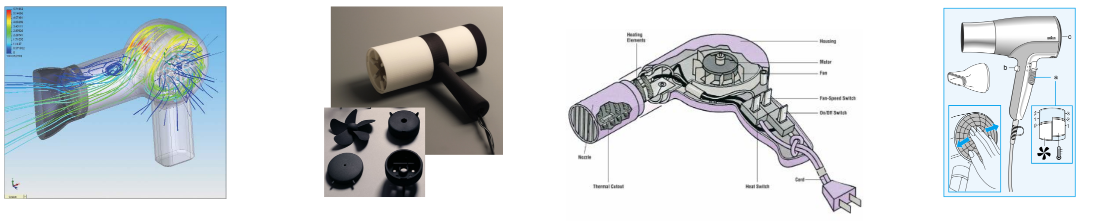
3.1. Introduction

Our research program is oriented around two main axes: 1) Computer-Assisted Design with Heterogeneous Representations and 2) Graphics with Uncertainty and Heterogeneous Content. These two axes are governed by a set of common fundamental goals, share many common methodological tools and are deeply intertwined in the development of applications.

3.1.1. Computer-Assisted Design with Heterogeneous Representations

Designers use a variety of visual representations to explore and communicate about a concept. Fig. 2 illustrates some typical representations, including sketches, hand-made prototypes, 3D models, 3D printed prototypes or instructions.

(a) Ideation sketch (b) Presentation sketch (c) Coarse prototype (d) 3D model



(f) Simulation (e) 3D Printing (g) Technical diagram (h) Instructions

Figure 2. Various representations of a hair dryer at different stages of the design process. Image source, in order: c-maeng on deviantart.com, shauntur on deviantart.com, "Prototyping and Modelmaking for Product Design" Hallgrimsson, B., Laurence King Publishers, 2012, samsher511 on turbosquid.com, my.solidworks.com, weilung tseng on cargocollective.com, howstuffworks.com, u-manual.com

The early representations of a concept, such as rough sketches and hand-made prototypes, help designers formulate their ideas and test the form and function of multiple design alternatives. These low-fidelity representations are meant to be cheap and fast to produce, to allow quick exploration of the *design space* of the concept. These representations are also often approximate to leave room for subjective interpretation and to stimulate imagination; in this sense, these representations can be considered *uncertain*. As the concept gets more finalized, time and effort are invested in the production of more detailed and accurate representations, such as high-fidelity 3D models suitable for simulation and fabrication. These detailed models can also be used to create didactic instructions for assembly and usage.

Producing these different representations of a concept requires specific skills in sketching, modeling, manufacturing and visual communication. For these reasons, professional studios often employ different experts to produce the different representations of the same concept, at the cost of extensive discussions and numerous iterations between the actors of this process. The complexity of the multi-disciplinary skills involved in the design process also hinders their adoption by laymen.

Existing solutions to facilitate design have focused on a subset of the representations used by designers. However, no solution considers all representations at once, for instance to directly convert a series of sketches into a set of physical prototypes. In addition, all existing methods assume that the concept is unique rather than ambiguous. As a result, rich information about the variability of the concept is lost during each conversion step.

We plan to facilitate design for professionals and laymen by adressing the following objectives:

- We want to assist designers in the exploration of the *design space* that captures the possible variations of a concept. By considering a concept as a *distribution* of shapes and functionalities rather than a single object, our goal is to help designers consider multiple design alternatives more quickly and effectively. Such a representation should also allow designers to preserve multiple alternatives along all steps of the design process rather than committing to a single solution early on and pay the price of this decision for all subsequent steps. We expect that preserving alternatives will facilitate communication with engineers, managers and clients, accelerate design iterations and even allow mass personalization by the end consumers.
- We want to support the various representations used by designers during concept development. While drawings and 3D models have received significant attention in past Computer Graphics research, we will also account for the various forms of rough physical prototypes made to evaluate the shape and functionality of a concept. Depending on the task at hand, our algorithms will either analyse these prototypes to generate a virtual concept, or assist the creation of these prototypes from a virtual model. We also want to develop methods capable of adapting to the different drawing and manufacturing techniques used to create sketches and prototypes. We envision design tools that conform to the habits of users rather than impose specific techniques to them.
- We want to make professional design techniques available to novices. Affordable software, hardware and online instructions are democratizing technology and design, allowing small businesses and individuals to compete with large companies. New manufacturing processes and online interfaces also allow customers to participate in the design of an object via mass personalization. However, similarly to what happened for desktop publishing thirty years ago, desktop manufacturing tools need to be simplified to account for the needs and skills of novice designers. We hope to support this trend by adapting the techniques of professionals and by automating the tasks that require significant expertise.

3.1.2. Graphics with Uncertainty and Heterogeneous Content

Our research is motivated by the observation that traditional CG algorithms have not been designed to account for uncertain data. For example, global illumination rendering assumes accurate virtual models of geometry, light and materials to simulate light transport. While these algorithms produce images of high realism, capturing effects such as shadows, reflections and interreflections, they are not applicable to the growing mass of uncertain data available nowadays.

The need to handle uncertainty in CG is timely and pressing, given the large number of *heterogeneous sources of 3D content* that have become available in recent years. These include data from cheap depth+image sensors (e.g., Kinect or the Tango), 3D reconstructions from image/video data, but also data from large 3D geometry databases, or casual 3D models created using simplified sketch-based modeling tools. Such alternate content has varying levels of *uncertainty* about the scene or objects being modelled. This includes uncertainty in geometry, but also in materials and/or lights – which are often not even available with such content. Since CG algorithms cannot be applied directly, visual effects artists spend hundreds of hours correcting inaccuracies and completing the captured data to make them useable in film and advertising.

We identify a major scientific bottleneck which is the need to treat *heterogeneous* content, i.e., containing both (mostly captured) uncertain and perfect, traditional content. Our goal is to provide solutions to this bottleneck, by explicitly and formally modeling uncertainty in CG, and to develop new algorithms that are capable of mixed rendering for this content.

Figure 3. Image-Based Rendering (IBR) techniques use input photographs and approximate 3D to produce new synthetic views.

We strive to develop methods in which heterogeneous – and often uncertain – data can be handled automatically in CG with a principled methodology. Our main focus is on *rendering* in CG, including dynamic scenes (video/animations).

Given the above, we need to address the following challenges:

- Develop a theoretical model to handle uncertainty in computer graphics. We must define a new formalism that inherently incorporates uncertainty, and must be able to express traditional CG rendering, both physically accurate and approximate approaches. Most importantly, the new formulation must elegantly handle mixed rendering of perfect synthetic data and captured uncertain content. An important element of this goal is to incorporate *cost* in the choice of algorithm and the optimizations used to obtain results, e.g., preferring solutions which may be slightly less accurate, but cheaper in computation or memory.
- The development of rendering algorithms for heterogeneous content often requires preprocessing of image and video data, which sometimes also includes depth information. An example is the decomposition of images into intrinsic layers of reflectance and lighting, which is required to perform relighting. Such solutions are also useful as image-manipulation or computational photography techniques. The challenge will be to develop such “intermediate” algorithms for the uncertain and heterogeneous data we target.
- Develop efficient rendering algorithms for uncertain and heterogeneous content, reformulating rendering in a probabilistic setting where appropriate. Such methods should allow us to develop approximate rendering algorithms using our formulation in a well-grounded manner. The formalism should include probabilistic models of how the scene, the image and the data interact. These models should be data-driven, e.g., building on the abundance of online geometry and image databases, domain-driven, e.g., based on requirements of the rendering algorithms or perceptually guided, leading to plausible solutions based on limitations of perception.

4. Highlights of the Year

4.1. Highlights of the Year

The SIGGRAPH paper "Multi-view relighting using a geometry-aware network" by J. Philip et al. [19] was presented at the Adobe Max event in November 2019 in San Fransisco. The project was part of the 11 projects selected out of 200 to be presented at Adobe MAX under the name project #LightRightSneak (Link to the video of the event).

G. Drettakis presented at the French Academy of Sciences days at Sophia-Antipolis in June: video on the Academy of Sciences site.

4.1.1. Awards

Jean-Dominique Favreau (co-supervised with the TITANE team) received the best Ph.D. thesis award 2019 (assessit prize) from IGRV.

5. New Software and Platforms

5.1. SynDraw

KEYWORDS: Non-photorealistic rendering - Vector-based drawing - Geometry Processing

FUNCTIONAL DESCRIPTION: The SynDraw library extracts occluding contours and sharp features over a 3D shape, computes all their intersections using a binary space partitioning algorithm, and finally performs a raycast to determine each sub-contour visibility. The resulting lines can then be exported as an SVG file for subsequent processing, for instance to stylize the drawing with different brush strokes. The library can also export various attributes for each line, such as its visibility and type. Finally, the library embeds tools allowing one to add noise into an SVG drawing, in order to generate multiple images from a single sketch. SynthDraw is based on the geometry processing library libIGL.

RELEASE FUNCTIONAL DESCRIPTION: This first version extracts occluding contours, boundaries, creases, ridges, valleys, suggestive contours and demarcating curves. Visibility is computed with a view graph structure. Lines can be aggregated and/or filtered. Labels and outputs include: line type, visibility, depth and aligned normal map.

- Authors: Adrien Bousseau, Bastien Wailly and Adele Saint-Denis
- Contact: Bastien Wailly

5.2. DeepSketch

KEYWORDS: 3D modeling - Sketching - Deep learning

FUNCTIONAL DESCRIPTION: DeepSketch is a sketch-based modeling system that runs in a web browser. It relies on deep learning to recognize geometric shapes in line drawings. The system follows a client/server architecture, based on the Node.js and WebGL technology. The application's main targets are iPads or Android tablets equipped with a digital pen, but it can also be used on desktop computers.

RELEASE FUNCTIONAL DESCRIPTION: This first version is built around a client/server Node.js application whose job is to transmit a drawing from the client's interface to the server where the deep networks are deployed, then transmit the results back to the client where the final shape is created and rendered in a WebGL 3D scene thanks to the THREE.js JavaScript framework. Moreover, the client is able to perform various camera transformations before drawing an object (change position, rotate in place, scale on place) by interacting with the touch screen. The user also has the ability to draw the shape's shadow to disambiguate depth/height. The deep networks are created, trained and deployed with the Caffe framework.

- Authors: Adrien Bousseau and Bastien Wailly
- Contact: Adrien Bousseau

5.3. DPP

Delaunay Point Process for image analysis

KEYWORDS: Computer vision - Shape recognition - Delaunay triangulation - Stochastic process

FUNCTIONAL DESCRIPTION: The software extract 2D geometric structures (planar graphs, polygons...) from images

- Participants: Jean-Dominique Favreau, Florent Lafarge and Adrien Bousseau
- Contact: Florent Lafarge
- Publication: Extracting Geometric Structures in Images with Delaunay Point Processes

5.4. sibr-core

System for Image-Based Rendering

KEYWORD: Graphics

SCIENTIFIC DESCRIPTION: Core functionality to support Image-Based Rendering research. The core provides basic support for camera calibration, multi-view stereo meshes and basic image-based rendering functionality. Separate dependent repositories interface with the core for each research project. This library is an evolution of the previous SIBR software, but now is much more modular.

We plan to release the core module, as well as the code for several of our research papers, as well as papers from other authors for comparisons and benchmark purposes.

FUNCTIONAL DESCRIPTION: sibr-core is a framework containing libraries and tools used internally for research projects based on Image-Base Rendering. It includes both preprocessing tools (computing data used for rendering) and rendering utilities and serves as the basis for many research projects in the group.

- Authors: Sebastien Bonopera, Jérôme Esnault, Siddhant Prakash, Simon Rodriguez, Théo Thonat, Gaurav Chaurasia, Julien Philip and George Drettakis
- Contact: George Drettakis

5.5. SGTDGP

Synthetic Ground Truth Data Generation Platform

KEYWORD: Graphics

FUNCTIONAL DESCRIPTION: The goal of this platform is to render large numbers of realistic synthetic images for use as ground truth to compare and validate image-based rendering algorithms and also to train deep neural networks developed in our team.

This pipeline consists of tree major elements that are:

- Scene exporter
- Assisted point of view generation
- Distributed rendering on Inria's high performance computing cluster

The scene exporter is able to export scenes created in the widely-used commercial modeler 3DSMAX to the Mitsuba opensource renderer format. It handles the conversion of complex materials and shade trees from 3DSMAX including materials made for VRay. The overall quality of the produced images with exported scenes have been improved thanks to a more accurate material conversion. The initial version of the exporter was extended and improved to provide better stability and to avoid any manual intervention.

From each scene we can generate a large number of images by placing multiple cameras. Most of the time those points of view has to be placed with a certain coherency. This task could be long and tedious. In the context of image-based rendering, cameras have to be placed in a row with a specific spacing. To simplify this process we have developed a set of tools to assist the placement of hundreds of cameras along a path.

The rendering is made with the open source renderer Mitsuba. The rendering pipeline is optimised to render a large number of point of view for single scene. We use a path tracing algorithm to simulate the light interaction in the scene and produce hight dynamic range images. It produces realistic images but it is computationally demanding. To speed up the process we setup an architecture that takes advantage of the Inria cluster to distribute the rendering on hundreds of CPUs cores.

The scene data (geometry, textures, materials) and the cameras are automatically transfered to remote workers and HDR images are returned to the user.

We already use this pipeline to export tens of scenes and to generate several thousands of images, which have been used for machine learning and for ground-truth image production.

We have recently integrated the platform with the sibr-core software library, allowing us to read mitsuba scenes. We have written a tool to allow camera placement to be used for rendering and for reconstruction of synthetic scenes, including alignment of the exact and reconstructed version of the scenes. This dual-representation scenes can be used for learning and as ground truth. We can also perform various operations on the ground truth data within sibr-core, e.g., compute shadow maps of both exact and reconstructed representations etc.

- Authors: Laurent Boiron, Sébastien Morgenthaler, Georgios Kopanas, Julien Philip and George Drettakis
- Contact: George Drettakis

5.6. Unity IBR

KEYWORD: Graphics

FUNCTIONAL DESCRIPTION: Unity IBR (for Image-Based Rendering in Unity) This is a software module that proceeds the development of IBR algorithms in Unity. In this case, algorithms are developed for the context of EMOTIVE EU project. The rendering technique was changed during the year to evaluate and compare which one produces better results suitable for Game Development with Unity (improvement of image quality and faster rendering). New features were also added such as rendering of bigger datasets and some debugging utilities. Software was also updated to keep compatibility with new released versions of Unity game engine. In addition, in order to develop a demo showcasing the technology, a multiplayer VR scene was created proving the integration of IBR with the rest of the engine.

- Authors: Sebastian Vizcay and George Drettakis
- Contact: George Drettakis

5.7. DeepRelighting

Deep Geometry-Aware Multi-View Relighting

KEYWORD: Graphics

SCIENTIFIC DESCRIPTION: Implementation of the paper: Multi-view Relighting using a Geometry-Aware Network (https://hal.inria.fr/hal-02125095), based on the sibr-core library.

- Participants: Julien Philip and George Drettakis
- Contact: George Drettakis
- Publication: https://hal.inria.fr/hal-02125095

5.8. SingleDeepMat

Single-image deep material acquisition

KEYWORDS: Materials - 3D - Realistic rendering - Deep learning

SCIENTIFIC DESCRIPTION: Cook-Torrance SVBRDF parameter acquisition from a single Image using Deep learning

FUNCTIONAL DESCRIPTION: Allows material acquisition from a single picture, to then be rendered in a virtual environment. Implementation of the paper https://hal.inria.fr/hal-01793826/

RELEASE FUNCTIONAL DESCRIPTION: Based on Pix2Pix implementation by AffineLayer (Github)

- Participants: Valentin Deschaintre, Miika Aittala, Frédo Durand, George Drettakis and Adrien Bousseau
- Partner: CSAIL, MIT
- Contact: Adrien Bousseau
- Publication: Single-Image SVBRDF Capture with a Rendering-Aware Deep Network
- URL: https://team.inria.fr/graphdeco/projects/deep-materials/

5.9. MultiDeepMat

Multi-image deep material acquisition

KEYWORDS: 3D - Materials - Deep learning

SCIENTIFIC DESCRIPTION: Allows material acquisition from multiple pictures, to then be rendered in a virtual environment. Implementation of the paper https://hal.inria.fr/hal-02164993

RELEASE FUNCTIONAL DESCRIPTION: Code fully rewritten since the SingleDeepMat project, but some function are imported from it.

- Participants: Valentin Deschaintre, Miika Aittala, Frédo Durand, George Drettakis and Adrien Bousseau
- Contact: Adrien Bousseau
- Publication: Flexible SVBRDF Capture with a Multi-Image Deep Network
- URL: https://team.inria.fr/graphdeco/projects/multi-materials/

5.10. GuidedDeepMat

Guided deep material acquisition

KEYWORDS: Materials - 3D - Deep learning

SCIENTIFIC DESCRIPTION: Deep large scale HD material acquisition guided by an example small scale SVBRDF

RELEASE FUNCTIONAL DESCRIPTION: Code based on the MultiDeepMat project code.

- Participants: Valentin Deschaintre, George Drettakis and Adrien Bousseau
- Contact: Adrien Bousseau

6. New Results

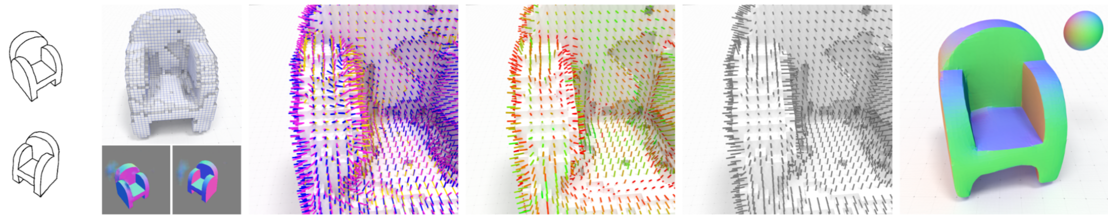
6.1. Computer-Assisted Design with Heterogeneous Representations

6.1.1. Combining Voxel and Normal Predictions for Multi-View 3D Sketching

Participants: Johanna Delanoy, Adrien Bousseau.

Recent works on data-driven sketch-based modeling use either voxel grids or normal/depth maps as geometric representations compatible with convolutional neural networks. While voxel grids can represent complete objects – including parts not visible in the sketches – their memory consumption restricts them to low-resolution predictions. In contrast, a single normal or depth map can capture fine details, but multiple maps from different viewpoints need to be predicted and fused to produce a closed surface. We propose to combine these two representations to address their respective shortcomings in the context of a multi-view sketch-based modeling system. Our method predicts a voxel grid common to all the input sketches, along with one normal map per sketch. We then use the voxel grid as a support for normal map fusion by optimizing its extracted surface such that it is consistent with the re-projected normals, while being as piecewise-smooth as possible overall (Fig. 4). We compare our method with a recent voxel prediction system, demonstrating improved recovery of sharp features over a variety of man-made objects.

This work is a collaboration with David Coeurjolly from Université de Lyon and Jacques-Olivier Lachaud from Université Savoie Mont Blanc. The work was published in the journal Computer & Graphics and presented at the SMI conference [14].



(a) Input (b) CNNs predictions (c) Candidate normals (d) Aggregated normals (e) Piecewise-smooth normals (f) Final surface

Figure 4. Our method takes as input multiple sketches of an object (a). We first apply existing deep neural networks to predict a volumetric reconstruction of the shape as well as one normal map per sketch (b). We re-project the normal maps on the voxel grid in complement to the surface normal computed from the volumetric prediction (c). We aggregate these different normals into a distribution represented by a mean vector and a standard deviation (d). We optimize this normal field to make it piecewise smooth (e) and use it to regularize the surface (f). The final surface preserves the overall shape of the predicted voxel grid as well as the sharp features of the predicted normal maps.

(a) Input optical flow (b) Rigidified optical flow (c) Stylized video

Figure 5. Our method takes as input a video and its optical flow (a). We segment the video and optimize its pixel trajectories to produce a new video that exhibits piecewise-rigid motion (b). The resulting rigidified video can be stylized with existing algorithms (c) to produce animations where the style elements (brush strokes, paper texture) produce a strong sense of 2D motion.

6.1.2. Video Motion Stylization by 2D Rigidification

Participants: Johanna Delanoy, Adrien Bousseau.

We introduce a video stylization method that increases the apparent rigidity of motion. Existing stylization methods often retain the 3D motion of the original video, making the result look like a 3D scene covered in paint rather than a 2D painting of a scene. In contrast, traditional hand-drawn animations often exhibit simplified in-plane motion, such as in the case of cut-out animations where the animator moves pieces of paper from frame to frame. Inspired by this technique, we propose to modify a video such that its content undergoes 2D rigid transforms (Fig. 5). To achieve this goal, our approach applies motion segmentation and optimization to best approximate the input optical flow with piecewise-rigid transforms, and re-renders the video such that its content follows the simplified motion. The output of our method is a new video and its optical flow, which can be fed to any existing video stylization algorithm.

This work is a collaboration with Aaron Hertzmann from Adobe Research. It was presented at the ACM/EG Expressive Symposium [21].

6.1.3. Multi-Pose Interactive Linkage Design

Participant: Adrien Bousseau.

We introduce an interactive tool for novice users to design mechanical objects made of 2.5D linkages. Users simply draw the shape of the object and a few key poses of its multiple moving parts. Our approach automatically generates a one-degree-of-freedom linkage that connects the fixed and moving parts, such that the moving parts traverse all input poses in order without any collision with the fixed and other moving parts. In addition, our approach avoids common linkage defects and favors compact linkages and smooth motion trajectories. Finally, our system automatically generates the 3D geometry of the object and its links, allowing the rapid creation of a physical mockup of the designed object (Fig. 6).

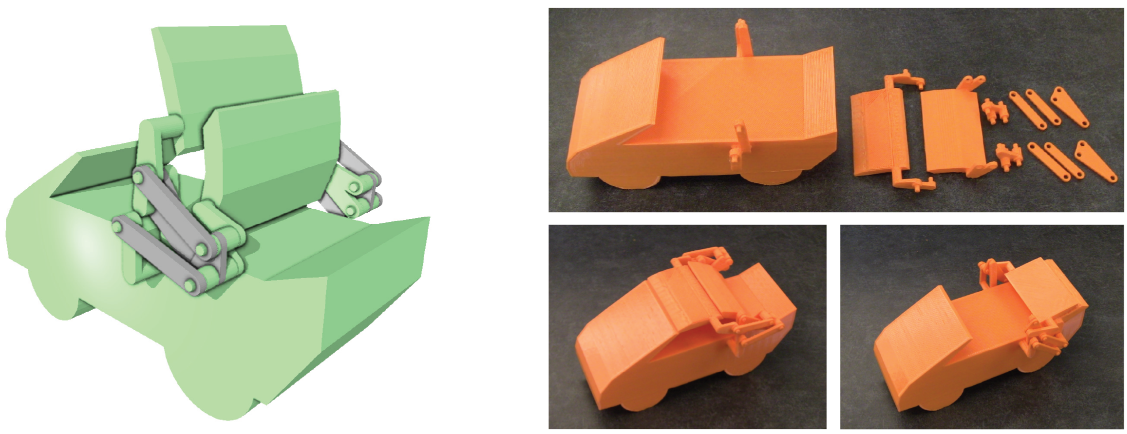


Figure 6. Our interactive system facilitates the creation (left) and fabrication (right) of mechanical objects.

This work was conducted in collaboration with Gen Nishida and Daniel G. Aliaga from Purdue University, was published in Computer Graphics Forum and presented at the Eurographics conference [18].

6.1.4. Extracting Geometric Structures in Images with Delaunay Point Processes

Participant: Adrien Bousseau.

We introduce Delaunay Point Processes, a framework for the extraction of geometric structures from images. Our approach simultaneously locates and groups geometric primitives (line segments, triangles) to form extended structures (line networks, polygons) for a variety of image analysis tasks. Similarly to traditional point processes, our approach uses Markov Chain Monte Carlo to minimize an energy that balances fidelity to the input image data with geometric priors on the output structures. However, while existing point processes struggle to model structures composed of inter-connected components, we propose to embed the point process into a Delaunay triangulation, which provides high-quality connectivity by construction. We further leverage key properties of the Delaunay triangulation to devise a fast Markov Chain Monte Carlo sampler. We demonstrate the flexibility of our approach on a variety of applications, including line network extraction, object contouring, and mesh-based image compression (see Fig. 7).

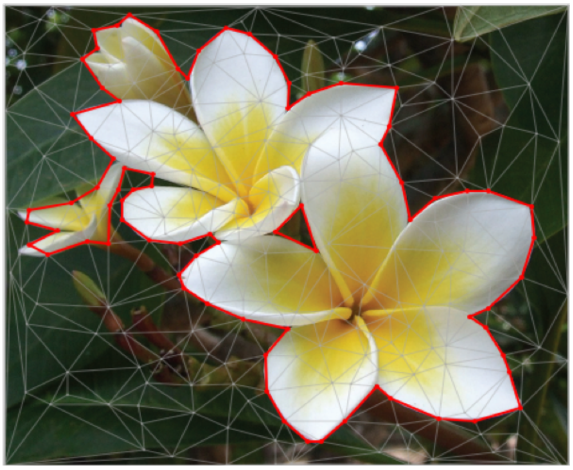


Figure 7. Our method extracts geometric structures like the countour of these flowers by optimizing a dynamic Delaunay triangulation.

This work was conducted in collaboration with Jean-Dominique Favreau and Florent Lafarge (TITANE group), and published in IEEE PAMI [16].

6.1.5. Integer-Grid Sketch Vectorization

Participants: Tibor Stanko, Adrien Bousseau.

A major challenge in line drawing vectorization is segmenting the input bitmap into separate curves. This segmentation is especially problematic for rough sketches, where curves are depicted using multiple overdrawn strokes. Inspired by feature-aligned mesh quadrangulation methods in geometry processing, we propose to extract vector curve networks by parametrizing the image with local drawing-aligned integer grids. The regular structure of the grid facilitates the extraction of clean line junctions; due to the grid's discrete nature, nearby strokes are implicitly grouped together. Our method successfully vectorizes both clean and rough line drawings, whereas previous methods focused on only one of those drawing types.

This work is an ongoing collaboration with David Bommes from University of Bern and Mikhail Bessmeltsev from University of Montreal. It is currently under review.

6.1.6. Surfacing Sparse Unorganized 3D Curves using Global Parametrization

Participants: Tibor Stanko, Adrien Bousseau.

Designers use sketching to quickly externalize ideas, often using a handful of curves to express complex shapes. Recent years have brought a plethora of new tools for creating designs directly in 3D. The output of these tools is often a set of sparse, unorganized curves. We propose a novel method for automatic conversion of such unorganized curves into clean curve networks ready for surfacing. The core of our method is a global curve-aligned parametrization, which allows us to automatically aggregate information from neighboring curves and produce an output with valid topology.

This work is an ongoing collaboration with David Bommes from University of Bern, Mikhail Bessmeltsev from University of Montreal, and Justin Solomon from MIT.

6.1.7. OpenSketch: A Richly-Annotated Dataset of Product Design Sketches

Participants: Yulia Gryaditskaya, Adrien Bousseau, Fredo Durand.

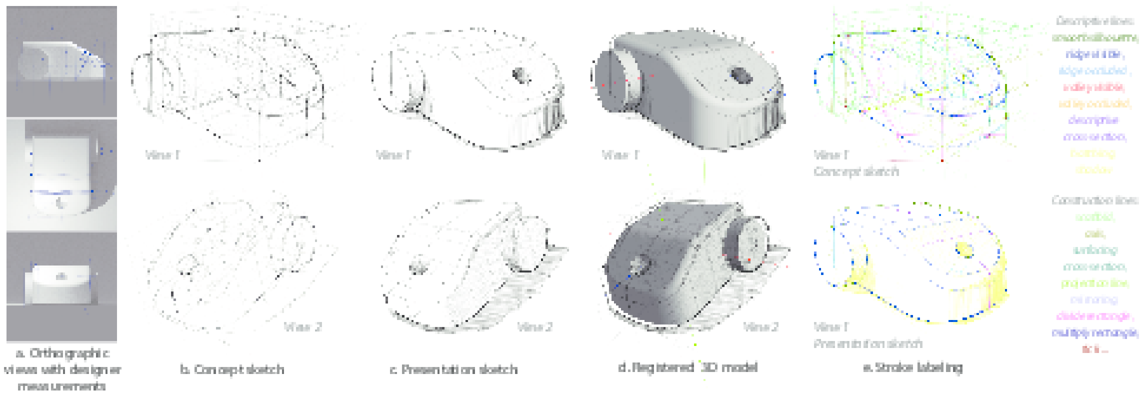


Figure 8. We showed designers three orthographic views (a) of the object and asked them to draw it from two different perspective views (b). We also asked to replicate each of their sketches as a clean presentation drawing (c). We semi-automatically registered 3D models to each sketch (d), and we manually labeled different types of lines in all concept sketches and presentation drawings from the first viewpoint (e).

Product designers extensively use sketches to create and communicate 3D shapes and thus form an ideal audience for sketch-based modeling, non-photorealistic rendering and sketch filtering. However, sketching requires significant expertise and time, making design sketches a scarce resource for the research community. We introduce *OpenSketch*, a dataset of product design sketches aimed at offering a rich source of information for a variety of computer-aided design tasks. *OpenSketch* contains more than 400 sketches representing 12 man-made objects drawn by 7 to 15 product designers of varying expertise. We provided participants with front, side and top views of these objects (Fig. 8a), and instructed them to draw from two *novel* perspective viewpoints(Fig. 8b). This drawing task forces designers to *construct the shape* from their mental vision rather than directly copy what they see. They achieve this task by employing a variety of sketching techniques and methods not observed in prior datasets. Together with industrial design teachers, we distilled a taxonomy of line types and used it to label each stroke of the 214 sketches drawn from one of the two viewpoints (Fig. 8e). While some of these lines have long been known in computer graphics, others remain to be reproduced algorithmically or exploited for shape inference. In addition, we also asked participants to produce clean presentation drawings from each of their sketches, resulting in aligned pairs of drawings of different styles (Fig. 8c). Finally, we registered each sketch to its reference 3D model by annotating sparse correspondences (Fig. 8d). We provide an analysis of our annotated sketches, which reveals systematic drawing strategies over time and shapes, as well as a positive correlation between presence of construction lines and accuracy. Our sketches, in combination with provided annotations, form challenging benchmarks for existing algorithms as well as a great source of inspiration for future developments. We illustrate the versatility of our data by using it to test a 3D reconstruction deep network trained on synthetic drawings, as well as to train a filtering network to convert concept sketches into presentation drawings. We distribute our dataset under the Creative Commons CC0 license: https://ns.inria.fr/d3/OpenSketch.

This work is a collaboration with Mark Sypesteyn, Jan Willem Hoftijzer and Sylvia Pont from TU Delft, Netherlands. This work was published at ACM Transactions on Graphics, and presented at SIGGRAPH Asia 2019 [17].

6.1.8. Intersection vs. Occlusion: a Discrete Formulation of Line Drawing 3D Reconstruction

Participants: Yulia Gryaditskaya, Adrien Bousseau, Felix Hähnlein.

The popularity of sketches in design stems from their ability to communicate complex 3D shapes with a handful of lines. Yet, this economy of means also makes sketch interpretation a challenging task, as global 3D understanding needs to emerge from scattered pen strokes. To tackle this challenge, many prior methods cast 3D reconstruction of line drawings as a global optimization that seeks to satisfy a number of geometric criteria, including orthogonality, planarity, symmetry. However, all of these methods require users to distinguish line intersections that exist in 3D from the ones that are only due to occlusions. These user annotations are critical to the success of existing algorithms, since mistakenly treating an occlusion as a true intersection would connect distant parts of the shape, with dramatic consequences on the overall optimization procedure. We propose a line drawing 3D reconstruction method that automatically discriminates 3D intersections from occlusions. This automation not only reduces user burden, it also allows our method to scale to real-world sketches composed of hundreds of pen strokes, for which the number of intersections is too high to make existing user-assisted methods practical. Our key idea is to associate each 2D intersection with a binary variable that indicates if the intersection should be preserved in 3D. Our algorithm then searches for the assignment of binary values that yields the best 3D shape, as measured with similar criteria as the ones used by prior work for 3D reconstruction. However, the combinatorial nature of this binary assignment problem prevents trying all possible configurations. Our main technical contribution is an efficient search algorithm that leverages principles of how product designers draw to reconstruct complex 3D drawings within minutes.

This work is a collaboration with Alla Sheffer (Professor at University of British Columbia) and Chenxi Liu (PhD student at University of British Columbia).

6.1.9. Data-driven sketch segmentation

Participants: Yulia Gryaditskaya, Felix Hähnlein, Adrien Bousseau.

Deep learning achieves impressive performance on image segmentation, which has motivated the recent development of deep neural networks for the related task of sketch segmentation, where the goal is to assign labels to the different strokes that compose a line drawing. However, while natural images are well represented as bitmaps, line drawings can also be represented as vector graphics, such as point sequences and point clouds. In addition to offering different trade-offs on resolution and storage, vector representations often come with additional information, such as stroke ordering and speed.

In this project, we evaluate three crucial design choices for sketch segmentation using deep-learning: which sketch representation to use, which information to encode in this representation, and which loss function to optimize. Our findings suggest that point clouds represent a competitive alternative to bitmaps for sketch segmentation, and that providing extra-geometric information improves performance.

6.1.10. Stroke-based concept sketch generation

Participants: Felix Hähnlein, Yulia Gryaditskaya, Adrien Bousseau.

State-of-the-art non-photorealisting rendering algorithms can generate lines representing salient visual features on objects. However, very few methods exist for generating lines outside of an object, as is the case for most construction lines, used in technical drawings and design sketches. Furthermore, most methods do not generate human-like strokes and do not consider the drawing order of a sketch.

In this project, we address these issues by proposing a reinforcement learning framework, where a virtual agent tries to generate a construction sketch of a given 3D model. One key element of our approach is the study and the mathematical formalization of drawing strategies used by industrial designers.

6.1.11. Designing Programmable, Self-Actuated Structures

Participants: David Jourdan, Adrien Bousseau.

Self-actuated structures are material assemblies that can deform from an initially simpler state to a more complex, curved one, by automatically deforming to shape. Most relevant to applications in manufacturing are self-actuated shapes that are fabricated flat, considerably reducing the cost and complexity of manufacturing curved 3D surfaces. While there are many ways to design self-actuated materials (e.g. using heat or water as actuation mechanisms), we use 3D printing to embed rigid patterns into prestressed fabric, which is then released and assumes a shape matching a given target when reaching static equilibrium.

While using a 3D printer to embed plastic curves into prestressed fabric is a technique that has been experimented on before, it has been mostly restricted to piecewise minimal surfaces, making it impossible to reproduce most shapes. By using a dense packing of 3-pointed stars, we are able to create convex shapes and positive gaussian curvature, moreover we found a direct link between the stars dimensions and the induced curvature, allowing us to build an inverse design tool that can faithfully reproduce some target shapes.

This is a collaboration with Mélina Skouras of Inria Rhône Alpes and Etienne Vouga of the University of Texas at Austin.

6.2. Graphics with Uncertainty and Heterogeneous Content

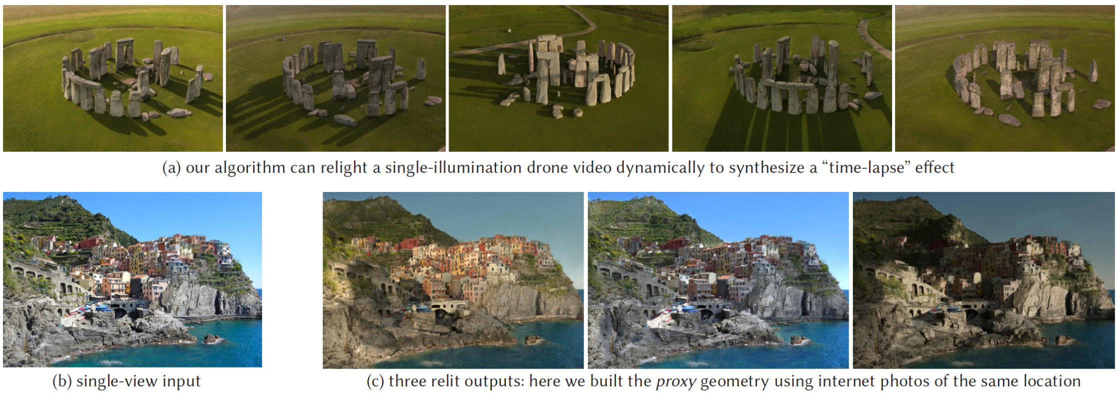


Figure 9. Results of our method: multi-view relighting using a geometry-aware network.

6.2.1. Multi-view relighting using a geometry-aware network

Participants: Julien Philip, George Drettakis.

We propose the first learning-based algorithm that can relight images in a plausible and controllable manner given multiple views of an outdoor scene. In particular, we introduce a geometry-aware neural network that utilizes multiple geometry cues (normal maps, specular direction, etc.) and source and target shadow masks computed from a noisy proxy geometry obtained by multi-view stereo. Our model is a three-stage pipeline: two subnetworks refine the source and target shadow masks, and a third performs the final relighting. Furthermore, we introduce a novel representation for the shadow masks, which we call RGB shadow images. They reproject the colors from all views into the shadowed pixels and enable our network to cope with inacuraccies in the proxy and the non-locality of the shadow casting interactions. Acquiring large-scale multi-view relighting datasets for real scenes is challenging, so we train our network on photorealistic synthetic data. At train time, we also compute a noisy stereo-based geometric proxy, this time from the synthetic renderings. This allows us to bridge the gap between the real and synthetic domains. Our model generalizes well to real scenes. It can alter the illumination of drone footage, image-based renderings, textured mesh reconstructions, and even internet photo collections (see Fig. 9).

This work was in collaboration with M. Gharbi of Adobe Research and A. Efros and T. Zhang of UC Berkeley, and was published in ACM Transactions on Graphics and presented at SIGGRAPH 2019 [19].

6.2.2. Flexible SVBRDF Capture with a Multi-Image Deep Network

Participants: Valentin Deschaintre, Frédo Durand, George Drettakis, Adrien Bousseau.

Empowered by deep learning, recent methods for material capture can estimate a spatially-varying reflectance from a single photograph. Such lightweight capture is in stark contrast with the tens or hundreds of pictures required by traditional optimization-based approaches. However, a single image is often simply not enough to observe the rich appearance of real-world materials. We present a deep-learning method capable of estimating material appearance from a variable number of uncalibrated and unordered pictures captured with a handheld camera and flash. Thanks to an order-independent fusing layer, this architecture extracts the most useful information from each picture, while benefiting from strong priors learned from data. The method can handle both view and light direction variation without calibration. We show how our method improves its prediction with the number of input pictures, and reaches high quality reconstructions with as little as 1 to 10 images – a sweet spot between existing single-image and complex multi-image approaches – see Fig. 10.

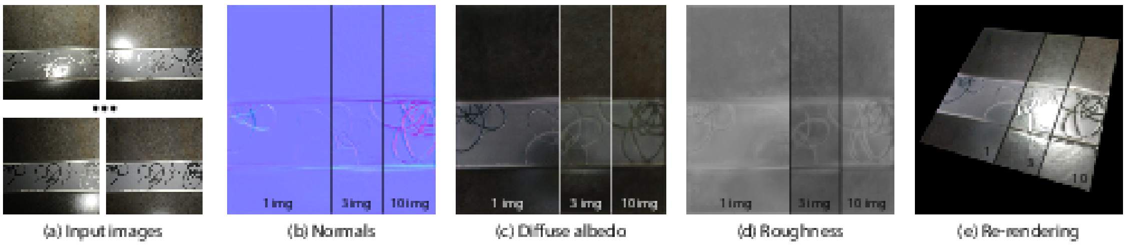


Figure 10. Our deep learning method for SVBRDF capture supports a variable number of input photographs taken with uncalibrated light-view directions (a, rectified). While a single image is enough to obtain a first plausible estimate of the SVBRDF maps, more images provide new cues to our method, improving its prediction. In this example, adding images reveals fine normal variations (b), removes highlight residuals in the diffuse albedo (c), and reveals the difference of roughness between the stone, the stripe, and the thin pattern (d).

This work is a collaboration with Miika Aittala from MIT CSAIL. This work was published in Computer Graphics Forum, and presented at EGSR 2019 [15].

A short paper and poster summarizing this work together with our 2018 "Single-Image SVBRDF Capture with a Rendering-Aware Deep Network" was published in the Siggraph Asia doctoral consortium 2019 [22].

6.2.3. Guided Acquisition of SVBRDFs

Participants: Valentin Deschaintre, George Drettakis, Adrien Bousseau.

Another project is under development to capture a large-scale SVBRDF from a few pictures of a planar surface. Many existing lightweight methods for SVBRDF capture take as input flash pictures, which need to be acquired close to the surface of interest restricting the scale of capture. We complement such small-scale inputs with a picture of the entire surface, taken under ambient lighting. Our method then fuses these two sources of information to propagate the SVBRDFs estimated from each close-up flash picture to all pixels of the large image. Thanks to our two-scale approach, we can capture surfaces several meters wide, such as walls, doors and furniture. In addition, our method can also be used to create large SVBRDFs from internet pictures, where we use artist-designed SVBRDFs as exemplars of the small-scale behavior of the surface.

6.2.4. Mixed rendering and relighting for indoor scenes

Participants: Julien Philip, Michaël Gharbi, George Drettakis.

We are investigating a mixed image rendering and relighting method that allows a user to move freely in a multi-view interior scene while altering its lighting. Our method uses a deep convolutional network trained on synthetic photo-realistic images. We adapt classical path tracing techniques to approximate complex lighting effects such as color bleeding and reflections.

6.2.5. DiCE: Dichoptic Contrast Enhancement for VR and Stereo Displays

Participant: George Drettakis.

In stereoscopic displays, such as those used in VR/AR headsets, our eyes are presented with two different views. The disparity between the views is typically used to convey depth cues, but it could be also used to enhance image appearance. We devise a novel technique that takes advantage of binocular fusion to boost perceived local contrast and visual quality of images. Since the technique is based on fixed tone curves, it has negligible computational cost and it is well suited for real-time applications, such as VR rendering. To control the trade-of between contrast gain and binocular rivalry, we conducted a series of experiments to explain the factors that dominate rivalry perception in a dichoptic presentation where two images of different contrasts are displayed (see Fig. 11). With this new finding, we can effectively enhance contrast and control rivalry in mono- and stereoscopic images, and in VR rendering, as conirmed in validation experiments.

Figure 11. Comparison of standard stereo images and the images with enhanced perceived contrast using our DiCE method. They can be cross-fused with the assistance of the dots above the images. Notice the enhanced contrast in the shadows and highlights of the scene. The stereo images are from Big Buck Bunny by Blender Foundation.

This work was in collaboration with Durham University (G. Koulieris, past postdoc of the group), Cambridge (F. Zhong, R. Mantiuk), UC Berkeley (M. Banks) and ENS Renne (M. Chambe), and was published in ACM Transactions on Graphics and presented at SIGGRAPH Asia 2019 [20].

6.2.6. Compositing Real Scenes using a relighting Network

Participants: Baptiste Nicolet, Julien Philip, George Drettakis.

Image-Based Rendering (IBR) allows for fast rendering of photorealistic novel viewpoints of real-world scenes captured by photographs. While it facilitates the very tedious traditional content creation process, it lacks user control over the appearance of the scene. We propose a novel approach to create novel scenes from a composition of multiple IBR scenes. This method relies on the use of a relighting network, which we first use to match the lighting conditions of each scene, and then to synthesize shadows between scenes in the final composition. This work has been submitted for publication.

6.2.7. Image-based Rendering of Urban Scenes based on Semantic Information

Participants: Simon Rodriguez, Siddhant Prakash, George Drettakis.

Cityscapes exhibit many hard cases for image-based rendering techniques, such as reflective and transparent surfaces. Pre-existing information about the scene can be leveraged to tackle these difficult cases. By relying on semantic information, it is possible to address those regions with tailored algorithms to improve reconstruction and rendering. This project is a collaboration with Peter Hedman from University College of London. This work has been submitted for publication.

6.2.8. Synthetic Data for Image-based Rendering

Participants: Simon Rodriguez, Thomas Leimkühler, George Drettakis.

This project explores the potential of Image-based rendering techniques in the context of real-time rendering for synthetic scenes. Accurate information can be precomputed from the input synthetic scene and used at run-time to improve the quality of approximate global illumination effects while preserving performance. This project is a collaboration with Chris Wyman and Peter Shirley from NVIDIA Research.

6.2.9. Densified Surface Light Fields for Human Capture Video

Participants: Rada Deeb, George Drettakis.

In this project, we focus on video-based rendering for mid-scale platforms. Having a mid-scale platform introduces one important problem for image-based rendering techniques due to low angular resolution. This leads to unrealistic view-dependent effects. We propose to use the temporal domain in a multidimensional surface light field approach in order to enhance the angular resolution. In addition, our approach provides a compact representation essential to dealing with the large amount of data introduced by videos compared to image-based techniques. In addition, we evaluate the use of deep encoder-decoder networks to learn a more compact representation of our multidimensional surface light field. This work is in collaboration with Edmond Boyer, MORPHEO team, Inria Grenoble.

6.2.10. Deep Bayesian Image-based Rendering

Participants: Thomas Leimkühler, George Drettakis.

Deep learning has permeated the field of computer graphics and continues to be instrumental in producing state-of-the-art research results. In the context of image-based rendering, deep architectures are now routinely used for tasks such as blending weight prediction, view extrapolation, or re-lighting. Current algorithms, however, do not take into account the different sources of uncertainty arising from the several stages of the image-based rendering pipeline. In this project, we investigate the use of Bayesian deep learning models to estimate and exploit these uncertainties. We are interested in devising principled methods which combine the expressive power of modern deep learning with the well-groundedness of classical Bayesian models.

6.2.11. Path Guiding for Metropolis Light Transport

Participants: Stavros Diolatzis, George Drettakis.

Path guiding has been proven to be an effective way to achieve faster convergence in Monte Carlo renderings by learning the incident radiance field. However, current path guiding techniques could be beaten by unguided path tracing due to their overhead or inability to incorporate the BSDF distribution factor. In our work, we improve path guiding and Metropolis light transport algorithms with low overhead product sampling between the incoming radiance and BSDF values. We demonstrate that our method has better convergence compared to the previous state-of-the-art techniques. Moreover, combining path guiding with MLT solves the global exploration issues ensuring convergence to the stationary distribution.

This work is an ongoing collaboration with Wenzel Jakob from Ecole Polytechnique Fédérale de Lausanne and Adrien Gruson from McGill University.

6.2.12. Improved Image-Based Rendering with Uncontrolled Capture

Participants: Siddhant Prakash, George Drettakis.

Current state-of-the-art Image Based Rendering (IBR) algorithms, such as Deep Blending, use per-view geometry to render candidate views and machine learning to improve rendering of novel views. The casual capture process employed introduces in visible color artifacts during rendering due to automated camera settings, and incur significant computational overhead when using per-view meshes. We aim to find a global solution to harmonize color inconsistency across the entire set of images in a given dataset, and also improve the performance of IBR algorithms by limiting the use of more advanced techniques only to regions where they are required.

6.2.13. Practical video-based rendering of dynamic stationary environments

Participants: Théo Thonat, George Drettakis.

The goal of this work is to extend traditional Image Based Rendering to capture subtle motions in real scenes. We want to allow free-viewpoint navigation with casual capture, such as a user taking photos and videos with a single smartphone and a tripod. We focus on stochastic time-dependent textures such as waves, flames or waterfalls. We have developed a video representation able to tackle the challenge of blending unsynchronized videos.

This work is a collaboration with Sylvain Paris from Adobe Research, Miika Aittala from MIT CSAIL, and Yagiz Aksoy from ETH Zurich, and has been submitted for publication.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- Valentin Deschaintre has a CIFRE PhD fellowship on Material Acquisition using Machine Learning, in collaboration with Optis - Ansys, a company specialized in material acquisition and rendering.

7.2. Bilateral Grants with Industry

- As part of a long standing collaboration with Adobe, this year Julien Philip interned with Michael Gharbi (San Francisco). This follows previous internships of J. Delanoy with Aaron Hertzmann (San Francisco) and Theo Thonnat with Sylvain Paris (Boston),
- Adrien Bousseau and Bastien Wailly worked with the InriaTech engineers to implement a sketch recognition engine in the context of a collaboration with the start-up EpicNPoc.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. EpicNPoc

Participants: Bastien Wailly, Adrien Bousseau.

EpicNPoc is a startup working on user interface design for the car industry. Together with two InriaTech engineers, we developed a small proof-of-concept that adapts our drawing recognition technology [9] to their needs. We first adapted our drawing synthesis algorithms to generate artificial sketches of user interface widgets, which include typical distortions and inaccuracies present in real sketches. The two engineers from InriaTech then used this technology to generate a large dataset of drawings, and to train a deep neural network to recognize the widgets in real drawings. The two engineers also integrated the trained network into a real-time system that recognizes widgets as they are drawn on a white board. We advised the engineers in their choice of a deep network architecture and on how to train this network to work on drawings. The result of this collaboration helped EpicNPoc appreciate the robustness of this technology, as well as to evaluate remaining challenges, such as convert the recognized widgets into working user-interface source code.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. D^3: Drawing Interpretation for 3D Design

Participants: Yulia Gryaditskaya, Tibor Stanko, Bastien Wailly, David Jourdan, Adrien Bousseau, Felix Hähnlein.

Line drawing is a fundamental tool for designers to quickly visualize 3D concepts. The goal of this ERC project is to develop algorithms capable of understanding design drawings. The first 30 months of the project allowed us to make significant progress in our understanding of how designers draw, and to propose preliminary solutions to the challenge of reconstructing 3D shapes from design drawings.

To better understand design sketching, we have collected a dataset of more than 400 professional design sketches [17]. We manually labeled the drawing techniques used in each sketch, and we registered all sketches to reference 3D models. Analyzing this data revealed systematic strategies employed by designers to convey 3D shapes, which will inspire the development of novel algorithms for drawing interpretation. In addition, our annotated sketches and associated 3D models form a challenging benchmark to test existing methods.

We proposed several methods to recover 3D information from drawings. A first family of method employs deep learning to predict what 3D shape is represented in a drawing. We applied this strategy in the context of architectural design, where we reconstruct 3D building by recognizing their constituent components (building mass, facade, window). We also presented an interactive system that allows users to create 3D objects by drawing from multiple viewpoints [14]. The second family of methods leverages geometric properties of the lines drawn to optimize the 3D reconstruction. In particular, we exploited properties of developable surfaces to reconstruct sketches of fashion items.

A long-term goal of our research is to evaluate the physical validity of a concept directly from a drawing. We obtained promising results towards this goal for the particular case of mechanical objects. We proposed an interactive system where users design the shape and motion of an articulated object, and our method automatically synthesize a mechanism that animates the object while avoiding collisions [18]. The geometry synthesized by our method is ready to be fabricated for rapid prototyping.

8.2.1.2. ERC FunGraph

Participants: George Drettakis, Thomas Leimkühler, Sébastien Morgenthaler, Rada Deeb, Stavros Diolatzis, Siddhant Prakash, Simon Rodriguez, Julien Philip.

The ERC Advanced Grant FunGraph proposes a new methodology by introducing the concepts of rendering and input uncertainty. We define output or rendering uncertainty as the expected error of a rendering solution over the parameters and algorithmic components used with respect to an ideal image, and input uncertainty as the expected error of the content over the different parameters involved in its generation, compared to an ideal scene being represented. Here the ideal scene is a perfectly accurate model of the real world, i.e., its geometry, materials and lights; the ideal image is an infinite resolution, high-dynamic range image of this scene.

By introducing methods to estimate rendering uncertainty we will quantify the expected error of previously incompatible rendering components with a unique methodology for accurate, approximate and image-based renderers. This will allow FunGraph to define unified rendering algorithms that can exploit the advantages of these very different approaches in a single algorithmic framework, providing a fundamentally different approach to rendering. A key component of these solutions is the use of captured content: we will develop methods to estimate input uncertainty and to propagate it to the unified rendering algorithms, allowing this content to be exploited by all rendering approaches.

The goal of FunGraph is to fundamentally transform computer graphics rendering, by providing a solid theoretical framework based on uncertainty to develop a new generation of rendering algorithms. These algorithms will fully exploit the spectacular – but previously disparate and disjoint – advances in rendering, and benefit from the enormous wealth offered by constantly improving captured input content.

8.2.1.3. Emotive

Participants: Julien Philip, Sebastiàn Vizcay, George Drettakis.

https://emotiveproject.eu/

Type: COOPERATION (ICT)

Instrument: Reseach Innovation Action

Objectif: Virtual Heritage

Duration: November 2016 - October 2019

Coordinator: EXUS SA (UK)

Partner: Diginext (FR), ATHENA (GR), Noho (IRL), U Glasgow (UK), U York (UK)

Inria contact: George Drettakis

Abstract: Storytelling applies to nearly everything we do. Everybody uses stories, from educators to marketers and from politicians to journalists to inform, persuade, entertain, motivate or inspire. In the cultural heritage sector, however, narrative tends to be used narrowly, as a method to communicate to the public the findings and research conducted by the domain experts of a cultural site or collection. The principal objective of the EMOTIVE project is to research, design, develop and evaluate methods and tools that can support the cultural and creative industries in creating Virtual Museums which draw on the power of 'emotive storytelling'. This means storytelling that can engage visitors, trigger their emotions, connect them to other people around the world, and enhance their understanding, imagination and, ultimately, their experience of cultural sites and content. EMOTIVE did this by providing the means to authors of cultural products to create high-quality, interactive, personalized digital stories. The project was evaluated in December with very positive initial feedback.

GRAPHDECO contributed by developing novel image-based rendering techniques to help museum curators and archeologists provide more engaging experiences. We developed a mixed reality plugin for Unity that allows the use of IBR and we developed, in collaboration with ATHENA, a VR experience used in one of the EMOTIVE user experiences using a VIVE HMD. This demo was presented at a public event in November in Glasgow, and used by over 25 museum professionals with very positive feedback.

8.3. International Initiatives

8.3.1. Inria International Partners

8.3.1.1. Informal International Partners

We maintain close collaborations with international experts, including

- McGill (Canada) (A. Gruson)
- UBC (Canada), (A. Sheffer)
- TU Delft (NL) (M. Sypesteyn, J. W. Hoftijzer and S. Pont)
- EPFL (Switzerland) (W. Jakob)
- U Bern (Switzerland) (D. Bommes)
- University College London (UK) (G. Brostow, P. Hedman)
- NVIDIA Research (USA, Finland), (C. Wyman, P. Shirley, M. Aittala)
- Adobe Research (USA), (A. Hertzmann, S. Paris, M. Gharbi)
- UC Berkeley (USA) (A. Efros)
- Purdue University (USA) (D. Aliaga, G. Nishida)
- U Texas, Austin (USA), (E. Vouga)
- George Mason University (USA) (Y. Gingold)

8.3.1.2. Inria International Chairs

Fredo Durand, Massachusetts Institute of Technology (United States)

Duration: 2016 - 2020

8.4. International Research Visitors

8.4.1. Visits of International Scientists

- Justin Solomon (MIT) in March.
- Mikhail Bessmeltsev (University of Montreal) in June.
- Aaron Hertzmann (Adobe Research) in June.
- Pierre Benard (U. Bordeaux), Daniel Sykora (U. Prague) and TT Wong (Hong Kong Polytechnic) in June.
- Tobias Ritschel (MPI Saarbrucken), Hendrik Lensch (U. Tuebingen) and Yann Gousseau (Telecom Paris) in June.
- Peter Hedman (UCL), September and October.
- Guillaume Coordonnier (ETH Zurich) in October.
- Alyosha Efros (U. Berkeley)
- Holly Rushmeier (Yale) and Abhijeet Ghosh (Imperial College London) in November.
- Niloy Mitra (UCL), Adrien Gruson (McGill) and Michael Gharbi (Adobe) in November.

8.4.1.1. Internships

J. Philip at Adobe Research, June 1st- September 28th, 2019. San Francisco.

8.4.2. Visits to International Teams

8.4.2.1. Research Stays Abroad

T. Stanko spent two weeks at University of Montreal to collaborate with Mikhail Bessmeltsev, and S. Rodriguez spent 5 weeks at NVIDIA research in Seattle (host C. Wyman).

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events: Organisation

9.1.1.1. Member of the Organizing Committees

V. Deschaintre is the Web chair of EGSR 2020.

9.1.2. Scientific Events: Selection

9.1.2.1. Member of the Conference Program Committees (PC)

Y. Gryaditskaya was a PC member of Computational Visual Media Conference (CVM) 2020. A. Bousseau was a PC member for SIGGRAPH '19, Eurographics'19 and SMI'19. G. Drettakis was a member of the PC of Pacific Graphics'19 and EGSR'19 and participated in the papers sort for SIGGRAPH'19 in January in Zurich.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- George Drettakis is an Associate Editor of Computational Visual Media (CVM).

9.1.3.2. Reviewer - Reviewing Activities

Y. Gryaditskaya was a reviewer for IEEE Transactions on Image Processing (TIP), T. Stanko for Computer Aided Geometric Design journal, V. Deschaintre for SIGGRAPH Asia, Eurographics papers and STARs, R. Deeb for JOSA A, Optics express and CVIU and T. Thonat for Computer and Graphics.

9.1.4. Invited Talks

- Y. Gryaditskaya and V. Deschaintre gave invited talks at Ecole Polytechnique in July 2019.
- V. Deschaintre gave an invited talk at the Materials and Appearance Modelling workshop in Strasbourg in July.
- J. Philip and G. Drettakis gave an invited talk on multi-view relighting using a geometry-aware network at NASA Jet Propulsion Laboratory, Pasadena in July 28th, 2019.
- A. Bousseau gave a Thinkshell Architectural Geometry Lesson, Navier Laboratory (Paris, France), "Interpreting Drawings for 3D Design".
- G. Drettakis presented at the French Academy of Sciences days at Sophia-Antipolis (June 21st, 2019) on the topic "Computer Graphics and Machine Learning". Video on the Academy of Sciences site.
- G. Drettakis presented IBR research at the following companies: Mikros Image in Paris in September and Airbus Systems in Sophia in October.

9.1.5. Leadership within the Scientific Community

G. Drettakis chairs the Eurographics (EG) working group on Rendering, and the steering committee of EG Symposium on Rendering.

9.1.6. Scientific Expertise

G. Drettakis was an evaluator for the French ANR, ERC consolidator grants and Swiss National Research foundation, and is a member of the jury of the Ph.D. thesis award of the IG-RV (https://prixigrv2018.sciencesconf.org/). A. Bousseau was an evaluator for the IdEX University of Strasbourg (postdoc and PhD fellowships) and a member of the Eurographics Ph.D. award committee.

9.1.7. Research Administration

Adrien Bousseau is a member of "comité du centre" and "comité du suivi doctoral".

9.1.8. Interventions at Conferences

- J. Delanoy presented her work at the 8th ACM/EG Expressive Symposium, 5-6 May 2019, Genoa, Italy, and at SMI 2019 (Geometry Summit), 17-21 June 2019, Vancouver, Canada.
- F. Hähnlein presented a talk about "Data-driven sketch segmentation" project at JFIGRV2019 in Marseille, and also attended NeuroSTIC2019 and the UCA Deep Learning Summer School 2019.
- J. Philip presented his paper "Multi-view relighting using a geometry network" at SIGGRAPH 2019 in Los Angeles in August.
- V. Deschaintre presented his paper "Flexible SVBRDF Capture with a Multi-Image Deep Network" at EGSR 2019 in Strasbourg in July.
- Y. Gryaditskaya presented her paper "OpenSketch: A Richly-Annotated Dataset of Product Design Sketches" at SIGGRAPH Asia 2019 in Brisbane in November.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence: T. Stanko Fondements mathématiques 1 (L1), 40h eq. TD, Université Côte d'Azur (France).

Master: G. Drettakis, A. Bousseau, Data visualization (M1), 12h eq. TD. Université Côte d'Azur (France).

9.2.2. Supervision

Ph.D.: Théo Thonat, Image-based rendering of thin and stochastic structures, defended June 2019, George Drettakis [13].

Ph.D.: Johanna Delanoy, Data-driven sketch-based modeling, defended June 2019, Adrien Bousseau [11].

Ph.D.: Valentin Deschaintre, Data-driven material capture, defended November 2019, Adrien Bousseau and George Drettakis [12].

Ph.D. in progress: David Jourdan, Interactive architectural design, since October 2018, Adrien Bousseau and Melina Skouras (Imagine)

Ph.D. in progress: Felix Hahnlein, Line Drawing Generation and Interpretation, since February 2019, Adrien Bousseau.

Ph.D. in progress: Julien Philip, Data-driven image-based rendering and relighting, since November 2016, George Drettakis.

Ph.D. in progress: Simon Rodriguez, Leveraging semantic information in image-based rendering, since November 2016, George Drettakis.

Ph.D. in progress: Stavros Diolatzis, Guiding and Learning for Illumination Algorithms, since April 2019, George Drettakis.

9.2.3. Juries

G. Drettakis was a member of the Ph.D. jury J-P. Bauchet (UCA) and Ph.D. reviewer of T. Leimkhueler (U. Saarbruecken). A. Bousseau was Ph.D. Reviewer for Marek Dvoroznak (TU Prague), Li Changjian (The University of Hong Kong) and Geoffrey Guingo (Grenoble University).

9.3. Popularization

9.3.1. Internal or external Inria responsibilities

- George Drettakis chairs the local “Jacques Morgenstern” Colloquium organizing committee and was elected a member of the Inria Scientific Council.

9.3.2. Articles and contents

J. Philip participated in the Youtube video interview: Intelligences artificielles: créatives mais perverties ? - Macroscopie La chaine - Video link - July 2019.

The work of J. Philip was the topic of a press release: L’algorithme d’apprentissage profond qui permet de changer l’éclairage des photos et de vidéos. Link to inria Press release and other media coverage Link to Pix Fan press release

The work Multi-view relighting using a geometry-aware network was presented at Adobe Max - November 2019. The project was part of the 11 projects selected out of 200 to be presented at Adobe MAX under the name project #LightRightSneak Link to the event.

Some press coverage of this event regarding the project : Link to Tech cafe listen starting at 32’00". Link to slrlouge. Link to petapixel.

10. Bibliography

Major publications by the team in recent years

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[2] S. DUCHÊNE, C. RIANT, G. CHAURASIA, J. LOPEZ-MORENO, P.-Y. LAFFONT, S. POPOV, A. BOUSSEAU, G. DRETTAKIS.*Multi-View Intrinsic Images of Outdoors Scenes with an Application to Relighting*, in "ACM Transactions on Graphics", 2015, http://www-sop.inria.fr/reves/Basilic/2015/DRCLLPD15

[3] J.-D. FAVREAU, F. LAFARGE, A. BOUSSEAU.*Fidelity vs. Simplicity: a Global Approach to Line Drawing Vectorization*, in "ACM Transactions on Graphics (SIGGRAPH Conference Proceedings)", 2016, http://www-sop.inria.fr/reves/Basilic/2016/FLB16

[4] J.-D. FAVREAU, F. LAFARGE, A. BOUSSEAU.*Photo2ClipArt: Image Abstraction and Vectorization Using Layered Linear Gradients*, in "ACM Transactions on Graphics (SIGGRAPH Asia Conference Proceedings)", November 2017, vol. 36, n° 6, http://www-sop.inria.fr/reves/Basilic/2017/FLB17

[5] P. HEDMAN, J. PHILIP, T. PRICE, J.-M. FRAHM, G. DRETTAKIS, G. BROSTOW.*Deep Blending for Free-Viewpoint Image-Based Rendering*, in "ACM Transactions on Graphics (SIGGRAPH Asia Conference Proceedings)", November 2018, vol. 37, n° 6, http://www-sop.inria.fr/reves/Basilic/2018/HPPFDB18

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[7] E. IARUSSI, D. BOMMES, A. BOUSSEAU.*BendFields: Regularized Curvature Fields from Rough Concept Sketches*, in "ACM Transactions on Graphics", 2015, http://www-sop.inria.fr/reves/Basilic/2015/IBB15

[8] G.-A. KOULIERIS, B. BUI, M. S. BANKS, G. DRETTAKIS.*Accommodation and Comfort in Head-Mounted Displays*, in "ACM Transactions on Graphics (SIGGRAPH Conference Proceedings)", July 2017, vol. 36, n° 4, 11, http://www-sop.inria.fr/reves/Basilic/2017/KBBD17

[9] G. NISHIDA, I. GARCIA-DORADO, D. G. ALIAGA, B. BENES, A. BOUSSEAU.*Interactive Sketching of Urban Procedural Models*, in "ACM Transactions on Graphics (SIGGRAPH Conference Proceedings)", 2016, http://www-sop.inria.fr/reves/Basilic/2016/NGGBB16

[10] B. XU, W. CHANG, A. SHEFFER, A. BOUSSEAU, J. MCCRAE, K. SINGH.*True2Form: 3D Curve Networks from 2D Sketches via Selective Regularization*, in "ACM Transactions on Graphics (SIGGRAPH Conference Proceedings)", 2014, vol. 33, n° 4, http://www-sop.inria.fr/reves/Basilic/2014/XCSBMS14

Publications of the year

Doctoral Dissertations and Habilitation Theses

[11] J. DELANOY.*Interpreting and Generating Artistic Depictions: Applications to Sketch-Based Modeling and Video Stylization*, Université Côte d'Azur, June 2019, https://hal.inria.fr/tel-02284941

[12] V. DESCHAINTRE.*Lightweight material acquisition using deep learning*, Université côte d'azur ; Inria - Sophia Antipolis, November 2019, https://hal.inria.fr/tel-02418445

[13] T. THONAT.*Multi-view inpainting, segmentation and video blending, for more versatile Image Based Rendering*, Université Côte d'Azur, June 2019, https://hal.inria.fr/tel-02417599

Articles in International Peer-Reviewed Journal

[14] J. DELANOY, D. COEURJOLLY, J.-O. LACHAUD, A. BOUSSEAU.*Combining Voxel and Normal Predictions for Multi-View 3D Sketching*, in "Computers and Graphics", June 2019, vol. 82, p. 65–72 [*DOI :* 10.1016/J.CAG.2019.05.024], https://hal.archives-ouvertes.fr/hal-02141469

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[21] J. DELANOY, A. BOUSSEAU, A. HERTZMANN.*Video Motion Stylization by 2D Rigidification*, in "Expressive 2019 - 8th ACM/ Eurographics Proceedings of the Symposium", Genoa, Italy, May 2019, https://hal.inria.fr/hal-02106047

Conferences without Proceedings

[22] V. DESCHAINTRE.*Material acquisition using deep learning*, in "SIGGRAPH 2019 - Asia Doctoral Consortium", Brisbane, Australia, November 2019, https://hal.archives-ouvertes.fr/hal-02388382

[23] B. WAILLY, A. BOUSSEAU.*Line rendering of 3D meshes for data-driven sketch-based modeling*, in "Journées Francaises d'Informatique Graphique et de Réalité virtuelle", Marseille, France, AFIG, October 2019, https://hal.inria.fr/hal-02391655

Project-Team GRAPHIK

GRAPHs for Inferences and Knowledge representation

IN COLLABORATION WITH: Laboratoire d'informatique, de robotique et de microélectronique de Montpellier (LIRMM)

IN PARTNERSHIP WITH:
CNRS

INRA

Institut national de recherche pour l'agriculture, l'alimentation et l'environnement

Université de Montpellier

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Data and Knowledge Representation and Processing

Table of contents

Project-Team GRAPHIK

Creation of the Project-Team: 2010 January 01

Keywords:

Computer Science and Digital Science:

A3.1.1. - Modeling, representation
A3.2.1. - Knowledge bases
A3.2.3. - Inference
A3.2.5. - Ontologies
A7.2. - Logic in Computer Science
A9.1. - Knowledge
A9.6. - Decision support
A9.7. - AI algorithmics
A9.8. - Reasoning

Other Research Topics and Application Domains:

B3.1. - Sustainable development
B9.5.6. - Data science
B9.7.2. - Open data

1. Team, Visitors, External Collaborators

Research Scientists

Jean-François Baget [Inria, Researcher]
Pierre Bisquert [INRA, Researcher]

Faculty Members

Marie-Laure Mugnier [Team leader, Univ. of Montpellier, Professor, HDR]
Michel Chein [Univ. of Montpellier, Emeritus, HDR]
Madalina Croitoru [Univ. of Montpellier, Professor, HDR]
Jérôme Fortin [Univ. of Montpellier, Associate Professor]
Michel Leclère [Univ. of Montpellier, Associate Professor]
Federico Ulliana [Univ. of Montpellier, Associate Professor]

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Meghyn Bienvenu [CNRS]
Patrice Buche [INRA]
Alain Gutierrez [CNRS]
Rallou Thomopoulos [INRA, HDR]

Technical Staff

Abdelraouf Hecham [Univ. of Montpellier, Engineer, until Jul 2019]
Martin Jedwabny [INRA, Engineer, until Aug 2019]
Olivier Rodriguez [CNRS, Engineer, until Jan 2019]
Clément Sipieter [CNRS, Engineer, until Jun 2019]
Clément Sipieter [ABES, from Jul 2019 until Sep 2019]

PhD Students

Efstathios Delivorias [Univ. of Montpellier, PhD Student]
Martin Jedwabny [Univ. of Montpellier, PhD Student, from Oct 2019]

Elie Najm [Inria, PhD Student, from Oct 2019]
Olivier Rodriguez [Inria, PhD Student, from Feb 2019]
Bruno Yun [Univ. of Montpellier, PhD Student, until Jul 2019]

Administrative Assistant

Annie Aliaga [Inria, Administrative Assistant]

2. Overall Objectives

2.1. Logic and Graph-based KR

The main research domain of GraphIK is *Knowledge Representation and Reasoning* (KR), which studies paradigms and formalisms for representing knowledge and reasoning on these representations. A large part of our work is strongly related to *data management* and *database theory*.

We develop logical languages, which mainly correspond to fragments of first-order logic. However, we also use graphs and hypergraphs (in the graph-theoretic sense) as basic objects. Indeed, we view labelled graphs as an *abstract representation* of knowledge that can be expressed in many KR languages: different kinds of conceptual graphs —historically our main focus—, the Semantic Web language RDFS, expressive rules equivalent to so-called tuple-generating-dependencies in databases, some description logics dedicated to query answering, etc. For these languages, reasoning can be based on the structure of objects (thus on graph-theoretic notions) while being sound and complete with respect to entailment in the associated logical fragments. An important issue is to study *trade-offs* between the expressivity and computational tractability of (sound and complete) reasoning in these languages.

2.2. From Theory to Applications, and Vice-versa

We study logic- and graph-based KR formalisms from three perspectives:

- theoretical (structural properties, expressiveness, translations between languages, problem complexity, algorithm design),
- software (developing tools to implement theoretical results),
- applications (formalizing practical issues and solving them with our techniques, which also feeds back into theoretical work).

2.3. Main Challenges

GraphIK focuses on some of the main challenges in KR:

- ontological query answering: querying large, complex or heterogeneous datasets, provided with an ontological layer;
- reasoning with rule-based languages;
- reasoning in presence of inconsistency and
- decision making.

2.4. Scientific Directions

Our research work is currently organized into two research lines, both with theoretical and applied sides:

1. **Ontology-mediated query answering (OMQA)**. Modern information systems are structured around an ontology, which provides a high-level vocabulary, as well as knowledge relevant to the target domain, and enables a uniform access to possibly heterogeneous data sources. As many complex tasks can be recast in terms of query answering, the question of querying data while taking into account inferences enabled by ontological knowledge has become a fundamental issue. This gives rise to the notion of a knowledge base, composed of an ontology and a factbase, both described using a KR language. The factbase can be seen as an abstraction of several data sources, and may actually remain virtual. The topical ontology-mediated query answering (OMQA) problem asks for all answers to queries that are logically entailed by the given knowledge base.
2. **Reasoning with imperfect knowledge and decision support**. To solve real-world problems we often need to consider features that cannot be expressed purely (or naturally) in classical logic. Indeed, information is often "imperfect": it can be partially contradictory, vague or uncertain, etc. These last years, we mostly considered reasoning in presence of conflicts, where contradictory information may come from the data or from the ontology. This requires to define appropriate semantics, able to provide meaningful answers to queries while taming the computational complexity increase. Reasoning becomes more complex from a conceptual viewpoint as well, hence how to explain results to an end-user is also an important issue. Such questions are natural extensions to those studied in the first axis. On the other hand, the work of this axis is also motivated by applications provided by our INRA partners, where the knowledge to be represented intrinsically features several viewpoints and involves different stakeholders with divergent priorities, while a decision has to be made. Beyond the representation of conflictual knowledge itself, this raises arbitration issues. The aim here is to support decision making by tools that help eliciting and representing relevant knowledge, including the stakeholders' preferences and motivations, compute syntheses of compatible options, and propose justified decisions.

3. Research Program

3.1. Logic-based Knowledge Representation and Reasoning

We follow the mainstream *logic-based* approach to knowledge representation (KR). First-order logic (FOL) is the reference logic in KR and most formalisms in this area can be translated into fragments (i.e., particular subsets) of FOL. This is in particular the case for description logics and existential rules, two well-known KR formalisms studied in the team.

A large part of research in this domain can be seen as studying the *trade-off* between the expressivity of languages and the complexity of (sound and complete) reasoning in these languages. The fundamental problem in KR languages is entailment checking: is a given piece of knowledge entailed by other pieces of knowledge, for instance from a knowledge base (KB)? Another important problem is *consistency* checking: is a set of knowledge pieces (for instance the knowledge base itself) consistent, i.e., is it sure that nothing absurd can be entailed from it? The *ontology-mediated query answering* problem is a topical problem (see Section 3.3). It asks for the set of answers to a query in the KB. In the case of Boolean queries (i.e., queries with a yes/no answer), it can be recast as entailment checking.

3.2. Graph-based Knowledge Representation and Reasoning

Besides logical foundations, we are interested in KR formalisms that comply, or aim at complying with the following requirements: to have good *computational* properties and to allow users of knowledge-based systems to have a maximal *understanding and control* over each step of the knowledge base building process and use.

These two requirements are the core motivations for our graph-based approach to KR. We view labelled graphs as an *abstract representation* of knowledge that can be expressed in many KR languages (different kinds of conceptual graphs —historically our main focus— the Semantic Web language RDF (Resource Description Framework), its extension RDFS (RDF Schema), expressive rules equivalent to the so-called tuple-generating-dependencies in databases, some description logics dedicated to query answering, etc.). For these languages, reasoning can be based on the structure of objects, thus based on graph-theoretic notions, while staying logically founded.

More precisely, our basic objects are labelled graphs (or hypergraphs) representing entities and relationships between these entities. These graphs have a natural translation in first-order logic. Our basic reasoning tool is graph homomorphism. The fundamental property is that graph homomorphism is sound and complete with respect to logical entailment *i.e.*, given two (labelled) graphs G and H, there is a homomorphism from G to H*if and only if* the formula assigned to G is entailed by the formula assigned to H. In other words, logical reasoning on these graphs can be performed by graph mechanisms. These knowledge constructs and the associated reasoning mechanisms can be extended (to represent rules for instance) while keeping this fundamental correspondence between graphs and logics.

3.3. Ontology-Mediated Query Answering

Querying knowledge bases has become a central problem in knowledge representation and in databases. A knowledge base (KB) is classically composed of a terminological part (metadata, ontology) and an assertional part (facts, data). Queries are supposed to be at least as expressive as the basic queries in databases, i.e., conjunctive queries, which can be seen as existentially closed conjunctions of atoms or as labelled graphs. The challenge is to define good trade-offs between the expressivity of the ontological language and the complexity of querying data in presence of ontological knowledge. Description logics have been so far the prominent family of formalisms for representing and reasoning with ontological knowledge. However, classical description logics were not designed for efficient data querying. On the other hand, database languages are able to process complex queries on huge databases, but without taking the ontology into account. There is thus a need for new languages and mechanisms, able to cope with the ever growing size of knowledge bases in the Semantic Web or in scientific domains.

This problem is related to two other problems identified as fundamental in KR:

- *Query answering with incomplete information.* Incomplete information means that it might be unknown whether a given assertion is true or false. Databases classically make the so-called closed-world assumption: every fact that cannot be retrieved or inferred from the base is assumed to be false. Knowledge bases classically make the open-world assumption: if something cannot be inferred from the base, and neither can its negation, then its truth status is unknown. The need of coping with incomplete information is a distinctive feature of querying knowledge bases with respect to querying classical databases (however, as explained above, this distinction tends to disappear). The presence of incomplete information makes the query answering task much more difficult.
- *Reasoning with rules.* Researching types of rules and adequate manners to process them is a mainstream topic in the Semantic Web, and, more generally a crucial issue for knowledge-based systems. For several years, we have been studying rules, both in their logical and their graph form, which are syntactically very simple but also very expressive. These rules, known as existential rules or Datalog+, can be seen as an abstraction of ontological knowledge expressed in the main languages used in the context of KB querying.

3.4. Inconsistency and Decision Making

While classical FOL is the kernel of many KR languages, to solve real-world problems we often need to consider features that cannot be expressed purely (or not naturally) in classical logic. The logic and graph-based formalisms used for previous points have thus to be extended with such features. The following requirements have been identified from scenarios in decision making, privileging the agronomy domain:

- to cope with inconsistency;
- to cope with defeasible knowledge;
- to take into account different and potentially conflicting viewpoints;
- to integrate decision notions (priorities, gravity, risk, benefit).

Although the solutions we develop require to be validated on the applications that motivated them, we also want them to be sufficiently generic to be applied in other contexts. One angle of attack (but not the only possible one) consists in increasing the expressivity of our core languages, while trying to preserve their essential combinatorial properties, so that algorithmic optimizations can be transferred to these extensions.

4. Application Domains

4.1. Agronomy

Agronomy is a strong expertise domain in the area of Montpellier. Some members of GraphIK are INRA researchers (computer scientists). We closely collaborate with the Montpellier research laboratory IATE, a join unit of INRA and other organisms. A major issue for INRA and more specifically IATE applications is modeling agrifood chains (i.e., the chain of all processes leading from the plants to the final products, including waste treatment). This modeling has several objectives. It provides better understanding of the processes from begin to end, which aids in decision making, with the aim of improving the quality of the products and decreasing the environmental impact. It also facilitates knowledge sharing between researchers, as well as the capitalization of expert knowledge and "know how". This last point is particularly important in areas strongly related to local know how (like in cheese or wine making), where knowledge is transmitted by experience, with the risk of non-sustainability of the specific skills. An agrifood chain analysis is a highly complex procedure since it relies on numerous criteria of various types: environmental, economical, functional, sanitary, etc. Quality objectives involve different stakeholders, technicians, managers, professional organizations, end-users, public organizations, etc. Since the goals of the implied stakeholders may be divergent dedicated knowledge and representation techniques are to be employed.

4.2. Data Journalism

One of today's major issues in data science is to design techniques and algorithms that allow analysts to efficiently infer useful information and knowledge by inspecting heterogeneous information sources, from structured data to unstructured content. We take data journalism as an emblematic use-case, which stands at the crossroad of multiple research fields: content analysis, data management, knowledge representation and reasoning, visualization and human-machine interaction. We are particularly interested in issues raised by the design of data and knowledge management systems that will support data journalism. These systems include an ontology (which typically expresses domain knowledge), heterogeneous data sources (provided with their own vocabulary and querying capabilities), and mappings that relate these data sources to the ontological vocabulary. Ontologies play a central role as they act both as a mediation layer that glue together pieces of knowledge extracted from data sources, and as an inference layer that allow to draw new knowledge.

Besides pure knowledge representation and reasoning issues, querying such systems raise issues at the crossroad of data and knowledge management. In particular, although mappings have been widely investigated in databases, they need to be revisited in the light of the reasoning capabilities enabled by the ontology. More generally, the consistency and the efficiency of the system cannot be ensured by considering the components of the system in isolation (i.e., the ontology, data sources and mappings), but require to study the interactions between these components and to consider the system as a whole.

5. Highlights of the Year

5.1. Highlights of the Year

- One of our papers ([15]) has been recognized as a **highlight of the year 2020** of the INRA department CEPIA.
- The SudoQual engine, which was developed in the context of the Qualinca research project (2012-2016), has been reused by ABES (the French National Agency for Academic Libraries) to build Paprika, a professional tool for documentalists, released this year (https://paprika.idref.fr/). SudoQual/Paprika is devoted to data curation in the context of bibliographic databases.

6. New Software and Platforms

6.1. Docamex

KEYWORD: Ontologies

SCIENTIFIC DESCRIPTION: In many agri-food companies, food quality is often managed using expertise gained through experience. Overall quality enhancement may come from sharing collective expertise. In this paper, we describe the design and implementation of a complete methodology allowing an expert knowledge base to be created and used to recommend the technical action to take to maintain food quality. We present its functional specifications, defined in cooperation with several industrial partners and technical centres over the course of several projects carried out in recent years. We propose a systematic methodology for collecting the knowledge on a given food process, from the design of a questionnaire to the synthesis of the information from completed questionnaires using a mind map approach. We then propose an original core ontology for structuring knowledge as possible causal relationships between situations of interest. We describe how mind map files generated by mind map tools are automatically imported into a conceptual graph knowledge base, before being validated and finally automatically processed in a graph-based visual tool. A specific end-user interface has been designed to ensure that end-user experts in agri-food companies can use the tool in a convenient way. Finally, our approach is compared with current research.

FUNCTIONAL DESCRIPTION: Docamex is a software dedicated to expert knowledge capitalization and visualization.

NEWS OF THE YEAR: Reliability score implemented.

- Participants: Jérôme Fortin and Patrice Buche
- Contact: Jérôme Fortin
- Publication: Expertise-based decision support for managing food quality in agri-food companies

6.2. Cogui

KEYWORDS: Knowledge database - Ontologies - GUI (Graphical User Interface)

SCIENTIFIC DESCRIPTION: Cogui is a visual tool for building and verifying graphical knowledge bases (KB). Knowledge bases are represented under graphical form (close to conceptual graphs). There is a complete correspondence with the logical existential rule (or Datalog+) framework.

FUNCTIONAL DESCRIPTION: Cogui is a freeware written in Java. It allows to graphically create a KB, to handle its structure and content, and to control it. Currently, it supports Conceptual Graphs and import/export in RDFS and Datalog+. Wizards allow to analyze and check facts with respect to some constraints, as well as to query them while taking into account inferences enabled by the ontology.

Release Functional Description: Plugin-extensible architecture, multi-project management, automatic construction of a web documentation of the ontology, adoption of semantic web conventions (IRIs and namespaces), integration of some Graal functionalities (homomorphisms and OWL 2 import), improvement of the import/export between Cogui knowledge bases and Graal dlgp format.

News Of The Year: 2019: new website and completely revised user documentation, following the release of version V3 (in 2018), which required heavy refactoring to benefit from NetBeans plugin-extensible platform architecture and graphical libraries (total replacement of the graphical editors).

- Participants: Alain Gutierrez, Michel Chein, Marie-Laure Mugnier, Michel Leclère and Madalina Croitoru
- Partner: LIRMM
- Contact: Michel Chein
- URL: http://www.lirmm.fr/cogui/

6.3. Damn

Defeasible reasoning tool for multi-agent collaboration

Keywords: Knowledge representation - Logic programming

Functional Description: Damn is an open source defeasible reasoning tool that allows the use of different semantics (ambiguity blocking/propagating with or without team defeat) in order to reason with incoherent or inconsistent knowledge. It allows the reasoning about preferences and their justification between different agents with a final aim of producing justified preferences on different outcomes (alternatives). These preferences are then used with a voting module (given certain voting strategy) to break ties and establish the chosen alternative. It is applied within the GLOPACK and NOAW projects.

News Of The Year: The HCI has been finalised: multi-users functionalities have been added (login, agents added, etc.).

- Contact: Madalina Croitoru
- URL: https://hamhec.github.io/damn/home

7. New Results

7.1. Ontology-Mediated Query Answering

Participants: Jean-François Baget, Meghyn Bienvenu, Efstathios Delivorias, Michel Leclère, Marie-Laure Mugnier, Olivier Rodriguez, Federico Ulliana.

Ontolology-mediated query answering (OMQA) is the issue of querying data while taking into account inferences enabled by ontological knowledge. From an abstract viewpoint, this gives rise to *knowledge bases*, composed of an ontology and a factbase (in database terms: a database instance under incomplete data assumption). Answers to queries are logically entailed from the knowledge base.

This year, we obtained two kinds of results: *theoretical results* on fundamental issues raised by OMQA, and *practical algorithms* for OMQA on key-value stores and RDF integration systems.

7.1.1. Fundamental issues on OMQA with existential rules

Existential rules (a.k.a. datalog+, as this framework generalizes the deductive database language datalog) have emerged as a new ontological language in the OMQA context. Techniques for query answering under existential rules mostly rely on the two classical ways of processing rules, namely forward chaining and backward chaining. In forward chaining, known as the *chase* in database theory, the rules are applied to enrich the factbase and query answering can then be solved by evaluating the query against the *saturated* factbase (as in a classical database system, i.e., with forgetting the ontological knowledge). The backward chaining process is divided into two steps: first, the query is *rewritten* using the rules into a first-order query (typically a union of conjunctive queries, but it can be a more compact form) or into a datalog query; then the rewritten query is evaluated against the factbase (again, as in a classical database system). Depending on the considered class of existential rules, the chase and/or query rewriting may terminate or not.

7.1.1.1. Decidability of chase termination for linear existential rules.

Several chase variants have long been studied in database theory. These chase variants yield logically equivalent results, but differ in their ability to detect redundancies possibly caused by the introduction of unknown individuals (nulls, blank nodes). Given a chase variant, the chase termination problem takes as input a set of existential rules and asks if this set of rules ensures the termination of the chase for any factbase. It is well-known that this problem is undecidable for all known chase variants. Hence, a crucial issue is whether chase termination becomes decidable for some known subclasses of existential rules. We considered linear existential rules, a simple yet important subclass of existential rules that generalizes database inclusion dependencies. We showed the decidability of the chase termination problem on linear rules for three main chase variants, namely skolem (a.k.a. semi-oblivious), restricted (a.k.a. standard) and core chase. The restricted chase is the most used in practice, however its study is notoriously tricky because the order in which rule applications are performed matters. Indeed, for the same factbase, some restricted chase sequences may terminate, while others may not. To obtain our results, we introduced a novel approach based on so-called derivation trees and a single notion of forbidden pattern. The simplicity of these structures make them subject to implementation. Besides the theoretical interest of a unified approach and new proofs, we provided the first positive decidability results (and complexity upper bounds) concerning the termination of the restricted chase, proving that chase termination on linear existential rules is decidable for both versions of the problem: Does every chase sequence terminate? Does some chase sequence terminate?

- *ICDT 2019 [29]. In collaboration with Michael Thomazo (Inria VALDA).*

7.1.1.2. Boundedness: Enforcing both chase termination and first-order rewritability.

We carried out the first studies on the boundedness problem for existential rules. This problem asks whether a given set of existential rules is bounded, i.e., whether there is a predefined bound on the "depth" of the chase independently from any factbase (for breadth-first chase versions, the depth corresponds to the number of breadth-first steps). It has been deeply studied in the context of datalog, where it is key to query optimization, although boundedness is undecidable in general. For datalog rules, boundedness is equivalent to a desirable property, namely first-order rewritability: a set of rules is called first-order rewritable if any conjunctive query can be rewritten into a union of conjunctive queries, whose evaluation on any factbase yields the expected answers (i.e., the relevant part of the ontology can be compiled into the rewritten query, which allows to reduce query answering to a simple query evaluation task). This equivalence does not hold for existential rules. Moreover, the notion of boundedness has to be parametrized by the chase variant, as they all behave differently with respect to termination. Beside potential practical use, the notion of boundedness is closely related to an interesting theoretical question on existential rules: what are the relationships between chase termination and first-order query rewritability? With respect to this question, we obtained the following salient result: for the oblivious and skolem (semi-oblivious) chase variants, a set of existential rules is bounded if and only if it ensures both chase termination for any factbase and first-order rewritability for any conjunctive query.

- *IJCAI 2019 [22]. In collaboration with Pierre Bourhis (Inria SPIRALS) and Sophie Tison (Inria LINKS).*

7.1.2. Practical Algorithms for OMQA on key-value stores and RDF integration systems

7.1.2.1. Ontology-mediated query answering on top of key-value stores.

Ontology-mediated query answering was mainly investigated so far based on the assumption that data conforms to relational structures (we include here RDF) and that the paradigm can be deployed on top of relational databases with conjunctive queries at the core (e.g., in SQL or SPARQL). However, this is not the prominent way on which data is today stored and exchanged, especially in the Web. Whether OMQA can be developed for non-relational structures, like those shared by increasingly popular NOSQL languages sustaining Big-Data analytics, has just begun to be investigated. Since 2016, we have been studying OMQA for key-values stores, which are systems providing fast and scalable access to JSON records. We proposed a rule language to express domain knowledge, with rules being directly applicable to key-value stores, without any translation of JSON into another data model (results published at AAAI 2016 and IJCAI 2017). In 2018-2019, we implemented a prototype for MongoDB, with a restricted part of this rule language (featuring key inclusions and mandatory keys) and tree-pattern queries, and devised optimization techniques based on parallellizing query rewriting and query answering. This work is pursued within a starting PhD thesis (Olivier Rodriguez).

- *Rule-ML 2019 [31]. In collaboration with Reza Akbarinia (Inria ZENITH).*

7.1.2.2. Ontology-mediated query answering in RDF integration systems

Within the iCODA project devoted to data journalism and the co-supervision of Maxime Buron's PhD thesis, we are considering the so-called Ontology-Based Data Access framework, which is composed of three components: the data level, the ontological level and mappings that relate data to facts described in the vocabulary of the ontology. Our framework more precisely considers heterogeneous data sources integrated through mappings into a (possibly virtual) RDF graph, provided with an RDFS ontology and RDFS entailment rules. The innovative aspects with respect to the state of the art are (i) SPARQL queries that extend classical conjunctive queries by the ability of querying data and ontological triples together, and (ii) Global-Local-As-View (GLAV) mappings, which can be seen as source-to-target existential rules. GLAV mappings enable the creation of unknown entities (blank nodes), which increases the amount of information accessible through the integration system. In particular, they allow one to palliate missing data values, by stating the existence of data whose values are not known in the sources. We devised, implemented and experimentally compared several query answering techniques in this setting.

- *ESWC 2019 [23], technical report [36] basis of a paper accepted to EDBT 2020. In collaboration with Maxime Buron and Ioana Manolescu (Inria CEDAR), and François Goasdoué (IRISA).*

7.2. Reasoning with conflicts and decision support

Participants: Pierre Bisquert, Patrice Buche, Michel Chein, Madalina Croitoru, Jérôme Fortin, Alain Gutierrez, Abdelraouf Hecham, Martin Jedwabny, Michel Leclère, Rallou Thomopoulos, Bruno Yun.

The work carried out during this year can be structured into two main research directions: *structured logic-based argumentation* and *collective decision making*.

7.2.1. Structured argumentation

To solve real-world problems we sometimes need to consider features that cannot be expressed purely (or naturally) in classical logic. Indeed, real world information is often "imperfect": it can be partially contradictory, vague or uncertain, etc. During the evaluation period, we mostly considered reasoning in presence of conflicts. To handle this issue, as a reasoning method robust to contradiction, we have used structured argumentation, where arguments have an internal logical structure representing an inference step (i.e. some premises inducing a conclusion). In this context, arguments and their interaction are typically generated from an inconsistent knowledge base. Such arguments are in contrast to those employed in abstract argumentation where they are considered a black box (usually provided as input to a problem and not computed).

More precisely, this year, we mainly worked on two issues: the first one concerns the question of scrutinizing a structured argument, i.e. checking both the validity ("is the conclusion induced by the premisses?") and its soundness ("is the argument valid and are its premisses true?"). This is interesting in the context of collective decision making, where participants utter arguments that can be assessed. The second one relates to the computational complexity of generating arguments from a knowledge base. Indeed, it can potentially produce a huge number of arguments, which impedes the usability of argumentation for big knowledge bases.

7.2.1.1. Formalizing argument schemes and fallacies

More precisely, we have presented a logical framework allowing us to express assessment of facts and arguments together with a proof system to answer these questions. Our motivation was to clarify the notion of validity in the context of logic-based arguments along different aspects (such as the formulas used and the inference scheme). Originality lies in the possibility for the user to design their own argument schemes, i.e. specific inference patterns (e.g. expert argument, analogy argument). We showed that classical inference obtains when arguments are based on classical schemes (e.g. Hilbert axioms). We went beyond classical logic by distinguishing "proven" formulas from "uncontroversial" ones (whose negation is not proven) and provided a definition of a fallacious argument in this context.

- *LPNMR 2019 [20]. In collaboration with Florence Dupin de Saint-Cyr and Philippe Besnard (IRIT).*

7.2.1.2. Optimising argumentation frameworks

Another problem addressed was the large number of logical arguments that can be potentially constructed from a knowledge base. To address this problem we have proposed a compact representation of the structured argumentation system under the form of hypergraphs and implemented it in the NAKED prototype. The tool allows to import a knowledge base (expressed in the existential rule framework), generate, visualise and export the corresponding argumentation hypergraph. These functions, paired with the aim of improving the extension computation efficiency, make this software an interesting tool for non-computer science experts, such as people working in the agronomy domain.

- *AAMAS 2019 [33]. In collaboration with Srdjan Vesic (CRIL).*

7.2.2. Collective decision making

In this setting we have focused towards the deliberation and voting techniques. We have investigated how deliberation can help generate or impact the structure of preferences underlying the voting process. We have implemented the PAPOW prototype [27] that allows for filtering of voters depending on their individual characteristics.

7.2.2.1. Argumentation as a tool to generate new preferences

We have investigated how argumentation can solve the Condorcet paradox by using the notion of extension (maxi-consistent sets of arguments) in order to compute new preferences. Our research hypothesis is that a decision made by a group of participants understanding the qualitative rationale (expressed by arguments) behind each other's preferences has better chances to be accepted and used in practice. Accordingly, we proposed a novel qualitative procedure which combines argumentation with computational social choice for modeling the collective decision-making problem. We showed that this qualitative approach produces structured preferences that can overcome major deficiencies that were exhibited in the social choice literature and affect most of the major voting rules. More precisely, we have dealt with the Condorcet Paradox and the properties of monotonicity and homogeneity, which are unsatisfiable by many voting rules.

- *PRAI 2019 [14]. In collaboration with Christos Kaklamanis and Nikos Karanikolas (CTI, Greece).*

7.2.2.2. Argumentation as a tool to modify individual preferences

The previous approach implies that voters are replaced by the extensions which, while it allows to circumvent the Condorcet Paradox, might prove difficult to implement as it disregards the notion of (voters') majority. Hence, we proposed a decision-making procedure based on argumentation and preference aggregation which permits us to explore the effect of reasoning and deliberation along with voting for the decision process. We represented the deliberation phase by defining a new voting argumentation framework, that uses vote and generic arguments, and its acceptability semantics based on the notion of pairwise comparisons between alternatives. We proved for these semantics some theoretical results regarding well-known properties from argumentation and social choice theory.

Moreover, we also studied the notion of unshared features (i.e., alternatives' criteria that constitute justifications of preferences for some agents but not for others) and showed under which conditions it is possible to reach a Condorcet consensus. We provided a deliberation protocol that ensures that, after its completion, the number of unshared features of the decision problem can only be reduced, which would tend to show that deliberation allows to lower the risk of Condorcet Paradox.

- *ICAART 2019 [28]. In collaboration with Christos Kaklamanis and Nikos Karanikolas (CTI, Greece). PRIMA 2019 [21].*

7.2.3. Discovering and qualifying authority links

We finalized this year the description of the engine SudoQual, devoted to the evaluation of link quality in document bases, developed in collaboration with ABES, the French National Agency for Academic Libraries (http://www.abes.fr), in the context of ANR Qualinca research project (2012-2016) (https://www.lirmm.fr/qualinca/). We presented the methodology and general algorithms used to discover and qualify so-called authority links (which are coreference links between entities mentioned in descriptions of documents and entities described in referential bases). Moreover, ABES has put in production this year a professional tool for documentalists, called Paprika (https://paprika.idref.fr/), whose kernel is the SudoQual engine.

- *KCAP 2019 [25].*

7.3. Miscellaneous: Automated design of biological devices

Participants: Michel Leclère, Guillaume Perution Kihli, Federico Ulliana.

We mention here results obtained in a collaboration with a team of biologists from the Center for Structural Biochemistry (CBS, Montpellier) on the logical computing capabilities of living organisms. More precisely, this joint work focuses on the development of a framework dedicated to the design of so-called Recombinase-based devices, whose behavior is specified as Boolean functions. We looked at the case of single-cell devices, whose expressivity limits, that is, the Boolean functions they can implement without distributing the Boolean function in several parts, are still unknown. While it is easy to determine which Boolean function is implemented by a device, the converse problem of automatically designing a device implementing a given Boolean function is a difficult task for which no automatic method exists. To tackle this problem, we experimented in the past years a combinatorial approach consisting in exhaustively generating all devices up to a given size, then determining the Boolean function they implement. A generating program and a database for these devices were developed. This year, we achieved the first formal study of this problem, which we believe can serve as foundations for the development of new biological design solutions. A set of minimality properties naturally emerged from our study, which led us to define the notion of canonical and representative devices, by which infinitely large classes of design solutions can be finitely expressed. These results strengthen the reliability of the approach and show that our program generates all representative canonical devices. Finally, our results also indicate some interesting expressivity limits for single-cell devices. Indeed, the generation process showed that 8% among all 4-input Boolean functions cannot be implemented. We also formally proved that single-cell devices cannot implement some n-input Boolean functions, for every $n \geq 7$.

- *TPNC 2019 [30]. In collaboration with Jérôme Bonnet and Sarah Guiziou (CBS).*

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. CQFD (ANR PRC, Jan. 2019-Dec. 2022)

Participants: Jean-François Baget, Michel Leclère, Marie-Laure Mugnier, Federico Ulliana.

CQFD (Complex ontological Queries over Federated heterogeneous Data), coordinated by Federico Ulliana (GraphIK), involves participants from Inria Saclay (CEDAR team), Inria Paris (VALDA team), Inria Nord

Europe (SPIRALS team), IRISA, LIG, LTCI, and LaBRI. The aim of this project is tackle two crucial challenges in OMQA (Ontology Mediated Query Answering), namely, heterogeneity, that is, the possibility to deal with multiple types of data-sources and database management systems, and federation, that is, the possibility of cross-querying a collection of heterogeneous datasources. By featuring 8 different partners in France, this project aims at consolidating a national community of researchers around the OMQA issue.

8.1.2. ICODA (Inria Project Lab, 2017-2021)

Participants: Jean-François Baget, Michel Chein, Marie-Laure Mugnier.

The iCODA project (Knowledge-mediated Content and Data Interactive Analytics—The case of data journalism), coordinated by Guillaume Gravier and Laurent Amsaleg (LINKMEDIA), takes together four Inria teams: LINKMEDIA, CEDAR, ILDA and GraphIK, as well as three press partners: Ouest France, Le Monde (les décodeurs) and AFP.

Taking data journalism as an emblematic use-case, the goal of the project is to develop the scientific and technological foundations for knowledge-mediated user-in-the-loop big data analytics jointly exploiting data and content, and to demonstrate the effectiveness of the approach in realistic, high-visibility use-cases.
https://project.inria.fr/icoda/

8.1.3. Docamex (CASDAR project, 2017-2020)

Participants: Patrice Buche, Madalina Croitoru, Jérôme Fortin, Clément Sipieter.

DOCaMEx (Développement de prOgiciels de Capitalisation et de Mobilisation du savoir-faire et de l'Expérience fromagers en filière valorisant leur terroir), let by CFTC (centre technique des fromages de Franche-Comté) involves 7 research units (including IATE and LIRMM), 8 technical centers and 3 dairy product schools. It represents five cheese-making chains (Comté, Reblochon, Emmental de Savoie, Salers, Cantal).

Traditional cheese making requires a lot of knowledge, expertise, and experience, which are usually acquired over a long time. This know-how is today mainly transmitted by apprenticeship and a concrete risk of knowledge forgetting is raised by the evolution of practices in the sector. The main goal of the project is to develop a new approach for expert knowledge elicitation and capitalization, and a dedicated software for decision making. The novel part of the decision making tool consists in the representation power and reasoning efficiency in the context of the logic used to describe the domain knowledge.
http://www.rmtfromagesdeterroirs.com/projets-de-r-et-d/docamex/

8.1.4. Convergence Institute #DigitAg (2017-2023)

Participants: Patrice Buche, Madalina Croitoru, Marie-Laure Mugnier, Rallou Thomopoulos, Federico Ulliana.

Located in Montpellier, #DigitAg (for Digital Agriculture) gathers 17 founding members: research institutes, including Inria, the University of Montpellier and higher-education institutes in agronomy, transfer structures and companies. Its objective is to support the development of digital agriculture. GraphIK is involved in this project on the issues of designing data and knowledge management systems adapted to agricultural information systems, and of developing methods for integrating different types of information and knowledge (generated from data, experts, models). A starting PhD thesis (Elie Najm) will investigate knowledge representation and reasoning for agro-ecological systems, in collaboration with the research laboratory UMR SYSTEM (Tropical and mediterranean cropping system functioning and management).
https://www.hdigitag.fr/en/

8.1.5. Vitamin (Méta-programme Did'It 2017-2018)

Participant: Rallou Thomopoulos.

The goal is to get a better understanding of factors influencing individuals in their transition to stop or reduce their animal product consumption. We use comprehensive individual interviews, questionnaires as well as diverse modelling techniques (mainly multi-agents & argumentation systems) to collect and analyse this topic. We develop agent-based models integrating argumentation systems about vegetarian transitions, at the long and short term. We have proposed a generic framework implemented in the GAMA platform allowing to explicitly represent exchanges of arguments between actors in the context of an opinion dynamic model. More precisely, we propose to formalize the inner attitude towards an opinion of each agent as an argumentation graph and give them the possibility to share arguments with other agents. The application to food choices allows studying the possible evolution of the vegetarian diet.
https://www.researchgate.net/project/VITAMIN-VegetarIan-Transition-Argument-ModellINg

8.1.6. Informal National Partners

We continue to work informally with the following partners:

- Pierre Bourhis (SPIRALS Inria team) and Sophie Tison (LINKS Inria team) Ontology-Mediated Query Answering [22].
- Michael Thomazo (VALDA Inria team) on Ontology-Mediated Query Answering [29].
- Jérôme Bonnet and Sarah Guiziou, from the Center for Structural Biochemistry of Montpellier (CBS), on the encoding of Boolean functions in biological systems [30]
- Srdjan Vesic (CRIL) on logical argumentation systems. In particular, Srdjan Vesic was a co-supervisor of Bruno Yun's PhD thesis, defended in July 2019 [33].
- Jean-Claude Léon (IMAGINE Inria team) on the development of an ontology-mediated query answering system applied to the field of CAD (Computer Aided Design).
- Slawek Staworko (LINKS Inria team) on data cleaning and argumentation techniques for repairing.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. NoAW (H2020, Oct. 2016-Sept. 2020)

Participants: Patrice Buche, Pierre Bisquert, Madalina Croitoru, Rallou Thomopoulos.

NoAW (No Agricultural Waste) is led by INRA-IATE. Driven by a "near zero-waste" society requirement, the goal of NoAW project is to generate innovative efficient approaches to convert growing agricultural waste issues into eco-efficient bio-based products opportunities with direct benefits for both environment, economy and EU consumer. To achieve this goal, the NoAW concept relies on developing holistic life cycle thinking able to support environmentally responsible R&D innovations on agro-waste conversion at different TRLs, in the light of regional and seasonal specificities, not forgetting risks emerging from circular management of agro-wastes (e.g. contaminants accumulation). GraphIK contributes on two aspects. On the one hand we participate in the annotation effort of knowledge bases (using the @Web tool). On the other hand we further investigate the interplay of argumentation with logically instantiated frameworks and its relation with social choice in the context of decision making.
http://cordis.europa.eu/project/rcn/203384_en.html

8.2.1.2. GLOPACK (H2020, June. 2018- July. 2022)

Participants: Patrice Buche, Pierre Bisquert, Madalina Croitoru.

GLOPACK is also led by INRA-IATE. It proposes a cutting-edge strategy addressing the technical and societal barriers to spread in our social system, innovative eco-efficient packaging able to reduce food environmental footprint. Focusing on accelerating the transition to a circular economy concept, GLOPACK aims to support users and consumers' access to innovative packaging solutions enabling the reduction and circular management of agro-food, including packaging, wastes. Validation of the solutions including compliance with legal requirements, economic feasibility and environmental impact will push forward the technologies tested and the related decision-making tool to TRL 7 for a rapid and easy market uptake contributing therefore to strengthen European companies' competitiveness in an always more globalised and connected world.
https://glopack2020.eu/

8.2.2. Collaborations in European Programs, Except FP7 & H2020

8.2.2.1. FoodMC (European COST action, 2016-2020)

Participants: Patrice Buche, Madalina Croitoru, Rallou Thomopoulos.

COST actions aim to develop European cooperation in science and technology. FoodMC (CA 15118) is a cost action on Mathematical and Computer Science Methods for Food Science and Industry. Rallou Thomopoulos is co-leader of this action for France, and member of the action Management Committee, and other members of GraphIK (Patrice Buche, Madalina Croitoru) are participants. The action is organised in four working groups, dealing respectively with the modelling of food products and food processes, modelling for eco-design of food processes, software tools for the food industry, and dissemination and knowledge transfer. http://www6.inra.fr/foodmc

8.3. International Research Visitors

8.3.1. Visits of International Scientists

Carlos Saez, postdoctoral researcher at the Biomedical Data Science Lab of the ITACA Institute of the Universitat Politècnica de València (UPV, Spain) stayed one week (from 10/12/2019 to 14/12/2019) to work on data quality issues for machine learning techniques and how OBDA and argumentation could help improve the quality of data.

8.3.2. Visits to International Teams

8.3.2.1. Research Stays Abroad

Madalina Croitoru obtained a SICSA Distinguished Visitor Program Funding and stayed at the University of Aberdeen from the 1st of April 2019 to the 31st of May 2019. She worked with Professor Nir Oren on ethical decision making in a multi-agent setting.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events: Organisation

- Marie-Laure Mugnier is co-responsible for a national group (2017-2020), named **Reasoning on Data** (Rod), common to two GDRs (CNRS research groups), namely Artificial Intelligence (formal and algorithmic aspects of Artificial Intelligence) and MaDICS (Big Data, Data Science). The aim of this action is to gather researchers from different domains on the development of knowledge representation and reasoning techniques devoted to data exploitation. http://www.lirmm.fr/rod/

- Rallou Thomopoulos has been co-leader of the trans-unit program **InCom** (Knowledge and Model Integration) of the CEPIA Division of INRA from 2018. She also organised the session on “Digital Issues” in the 2019 annual seminar of INRAE-TRANSFORM research division, and she was co-organizer of a one-day workshop on data-mining for food and bioproduct processing research on the 25th of November 2019.
- Patrice Buche is a coordinator of the **IN-OVIVE** (INtégration de sources/masses de données hétérogènes et Ontologies, dans le domaine des sciences du VIVant et de l’Environnement) network. He also was one of the organisers of the Fifth IN’OVIVE workshop event (https://workshop.inra.fr/in-ovive-2019/), collocated with the IC 2019 conference.

9.1.1.1. General Chair, Scientific Chair

Madalina Croitoru is part of the Steering Committee of ICCS 2020 (25th International Conference of Conceptual Structures).

9.1.2. Scientific Events: Selection

9.1.2.1. Chair of Conference Program Committees

Madalina Croitoru was co-chair of the **Doctoral Consortium at AAMAS 2019** (http://aamas2019.encs.concordia.ca/).

9.1.2.2. Member of the Conference Program Committees

We regularly participate to the program committees of the top conferences in AI and KR (IJCAI, AAAI, ECAI, KR, AAMAS), as PC members or senior PC members. We also regularly participate to the program committees of more focused international conferences and workshops as well as national events.

International

- IJCAI / PRICAI 2020 (29th International Joint Conference on Artificial Intelligence): senior PC and PC
- IJCAI / ECAI 2019 (28th International Joint Conference on Artificial Intelligence): senior PC
- ECAI 2020 (24th European Conference on Artificial Intelligence): senior PC
- AAAI 2019 (33rd AAAI Conference on Artificial Intelligence): PC
- Datalog 2.0 2019: PC
- ISWC 2019 (18th International Semantic Web Conference): PC

National

- CNAI 2019 (Conférence Nationale en Intelligence Artificielle): PC
- IC 2019 (Ingénierie des Connaissances): PC
- EGC 2019 (Extraction et Gestion des Connaissances): PC

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- International Journal of Metadata, Semantics and Ontologies (IJSMO)
- Revue africaine de la recherche en informatique et mathématiques appliquées (ARIMA)

9.1.3.2. Reviewer - Reviewing Activities

- Artificial Intelligence Journal (AIJ)
- Theory and Practice of Logic Programming (TPLP)
- International Journal of Approximate Reasoning (IJAR)

9.1.4. Invited Talks

- Marie-Laure Mugnier, *Existential Rules: a Study Through Chase Termination, FO-Rewritability and Boundedness*, keynote talk, 3rd International Joint Conference on Rules and Reasoning (RuleML+RR 2019), 2019 http://2019.ruleml-rr.org
- Marie-Laure Mugnier, *Reasoning on Data: Ontology-Based Data Access*, keynote talk, Journées d'Intelligence Artificielle Fondamentale (JIAF 2019), associated with PFIA 2019, 2019 https://www.irit.fr/pfia2019/jiaf/
- Marie-Laure Mugnier, *An introduction to Ontology-Based Data Access*, invited tutorial, Winter School of the 19th Conférence Francophone sur l'Extraction et la Gestion de Connaissances (EGC 2019), 2019 https://egc2019.sciencesconf.org/
- Patrice Buche, *Semantic to the rescue of food industry needs*, invited talk, SEmantic web SeminAr MontpEllier (SESAME), 2019 (https://informatique-mia.inra.fr/sesame)
- Pierre Bisquert, *Argumentation and decision in agronomical problems*, invited talk, Journée Robustesse en traitement de données et en recommandation: méthodes et applications, 2019 https://lfa2019.wp.imt.fr/files/2019/10/Programme13nov2019.pdf

9.1.5. Research Administration

- Marie-Laure Mugnier was the *scientific coordinator* for the evaluation of Inria theme "Data and Knowledge Representation and Processing" and its twelve project-teams (evaluation period: 2016-2019).
- From September 2019 onwards, Madalina Croitoru is *deputy member* of the CNU section 27 (Computer Science).
- Rallou Thomopoulos is an *elected member* of the Scientific Committee of the INRA-CEPIA research division (2016-2020).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

The six faculty members teach at all university levels (IUT, Licence, Master). All of them do an average of 200 teaching hours per year. The main courses they are in charge of are: Logics (L), Databases (M, IUT), Web Technologies (IUT), Artificial Intelligence (M), Knowledge Representation and Reasoning (M), Social and Semantic Web (M), Software Engineering (IUT), Human Computer Interaction (IUT). Concerning full-time researchers in 2019, Jean-François Baget and Pierre Bisquert gave Master courses (40h and 1h30 respectively).

Moreover, some faculty members have specific teaching responsibilities:

- At IUT, Madalina Croitoru was the head of Special Conversion Year (2014-2019) and the head of international relations for the computer science department (2018-mid-2019). In 2019, she was promoted professor and moved to the Science Faculty. From September 2019, she has been in charge of international relations for the Computer Science department at the Science Faculty as well as of the management of industrial master internships (about 100 students each year).
- Federico Ulliana is the head of the curriculum "Data, Knowledge and Natural Language Processing" (DECOL, about 30 students), part of the Master of Computer Science, since 2017.

9.2.2. Involvement in University Structures

- Michel Leclère has been deputy head of the Computer Science department of the Science Faculty (July 2015 - July 2019). He was also in charge of the Information Systems of the faculty (April 2017 - October 2019)
- Marie-Laure Mugnier is member of the Council of the Scientific Department MIPS (Mathematics Informatics Physics and Systems) of the University of Montpellier (since 2016).

9.2.3. Supervision

PhD defended: Stathis Delivorias, “Chase variants & boundedness”. Supervisors: Federico Ulliana, Michel Leclère and Marie-Laure Mugnier. University of Montpellier, September 2019.

PhD defended: Bruno Yun, “Argumentation techniques for existential rules”. Supervisors: Madalina Croitoru, Rallou Thomopolous and Srdjan Vesic (CRIL). University of Montpellier, July 2019.

PhD in progress: Elie Najm, “Knowledge Representation and Reasoning for innovating agroecological systems”. Supervisors: Marie-Laure Mugnier and Christian Gary (INRA, UMR SYSTEM). Started October 2019.

PhD in progress: Olivier Rodriguez, “Querying key-value store under semantic constraints”. Supervisors: Federico Ulliana and Marie-Laure Mugnier. Started February 2019.

PhD in progress: Martin Jedwabny, “Argumentation and ethical decision making”. Supervisors: Madalina Croitoru and Pierre Bisquert. Started October 2019.

PhD in progress: Maxime Buron (CEDAR Inria team), “Efficient reasoning on large heterogeneous graphs”. Supervisors: François Gaosdoué (IRISA/CEDAR), Ioana Manolescu (CEDAR) and Marie-Laure Mugnier. Started October 2017.

9.2.4. Juries

- Jury member for the HDR of Ivan Varzinczak (Nov. 2019, U. Artois) - Marie-Laure Mugnier
- Jury member for the HDR of Meghyn Bienvenu (Dec. 2019, U. Bordeaux) - Marie-Laure Mugnier
- Jury reviewer for the PhD defense of Gerald Berger (June 2019, TU Vienna, Austria) - Marie-Laure Mugnier
- Jury member for the PhD defense of Frederic Verdier (Dec. 2019, U. Montpellier) - Marie-Laure Mugnier
- Jury member for the PhD defense of Lily Galois (Dec. 2019, U. Lille) - Marie-Laure Mugnier

We do not not mention here participations to juries as supervisors of GraphIK PhD students.

9.3. Popularization

Michel Chein gave two talks on Artificial Intelligence: a public conference in the context of the Academy of the Sciences and Humanities of Montpellier and a radio interview (RCF) - both in March 2019.

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Project-Team HEPHAISTOS

HExapode, PHysiology, AssISTance and RobOtics

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Robotics and Smart environments

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Project-Team HEPHAISTOS

Creation of the Team: 2014 January 01, updated into Project-Team: 2015 July 01

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A5.6. - Virtual reality, augmented reality
A5.10. - Robotics
A5.11. - Smart spaces
A6.1. - Methods in mathematical modeling
A6.2. - Scientific computing, Numerical Analysis & Optimization
A6.4. - Automatic control
A8.4. - Computer Algebra
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A9.5. - Robotics

Other Research Topics and Application Domains:

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B2.5. - Handicap and personal assistances
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B2.8. - Sports, performance, motor skills
B3.1. - Sustainable development
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B5.2. - Design and manufacturing
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B5.7. - 3D printing
B8.1. - Smart building/home
B8.4. - Security and personal assistance
B9.1. - Education
B9.2. - Art
B9.9. - Ethics

1. Team, Visitors, External Collaborators

Research Scientists

Jean-Pierre Merlet [Team leader, Inria, Senior Researcher, HDR]
Yves Papegay [Inria, Researcher, HDR]
Odile Pourtallier [Inria, Researcher]
Eric Wajnberg [INRA, Senior Researcher]

External Collaborator

Ting Wang [ESIEE]

Technical Staff

Sylvain Guénon [Univ Côte d'Azur, Engineer, from Nov 2019]

PhD Student
Jaafar Moussaid [Inria, PhD Student, from Apr 2019]

Visiting Scientists
Wesley Godoy [Univ Sao Paolo, from Dec 2019]
Hiparco Lins Vieira [Univ Sao Paolo, until Aug 2019]
Maysa Tome [Univ Sao Paolo, from Dec 2019]
Midori Tuda [Univ Sao Paolo, from Jun 2019 until July 2019]
Igor Daniel Weber [Univ Sao Paolo, from Dec 2019]

Administrative Assistant
Laurie Vermeersch [Inria, Administrative Assistant]

2. Overall Objectives

2.1. Overall Objectives

HEPHAISTOS has been created as a team on January 1st, 2013 and as a project team in 2015.

The goal of the project is to set up a generic methodology for the design and evaluation of an adaptable and interactive assistive ecosystem for the elderly and the vulnerable persons that provides furthermore assistance to the helpers, on-demand medical data and may manage emergency situations. More precisely our goals are to develop devices with the following properties:

- they can be adapted to the end-user and to its everyday environment
- they should be affordable and minimally intrusive
- they may be controlled through a large variety of simple interfaces
- they may eventually be used to monitor the health status of the end-user in order to detect emerging pathology

Assistance will be provided through a network of communicating devices that may be either specifically designed for this task or be just adaptation/instrumentation of daily life objects.

The targeted population is limited to frail people [0] and the assistive devices will have to support the individual autonomy (at home and outdoor) by providing complementary resources in relation with the existing capacities of the person. Personalization and adaptability are key factor of success and acceptance. Our long term goal will be to provide robotized devices for assistance, including smart objects, that may help disabled, elderly and handicapped people in their personal life.

Assistance is a very large field and a single project-team cannot address all the related issues. Hence HEPHAISTOS will focus on the following main **societal challenges**:

- **mobility**: previous interviews and observations in the HEPHAISTOS team have shown that this was a major concern for all the players in the ecosystem. Mobility is a key factor to improve personal autonomy and reinforce privacy, perceived autonomy and self-esteem.
- **managing emergency situations**: emergency situations (e.g. fall) may have dramatic consequences for elderly. Assistive devices should ideally be able to prevent such situation and at least should detect them with the purposes of sending an alarm and to minimize the effects on the health of the elderly.

[0] for the sake of simplicity this population will be denoted by *elderly* in the remaining of this document although our work deal also with a variety of people (e.g. handicapped or injured people, ...)

- **medical monitoring**: elderly may have a fast changing trajectory of life and the medical community is lacking timely synthetic information on this evolution, while available technologies enable to get raw information in a non intrusive and low cost manner. We intend to provide synthetic health indicators, that take measurement uncertainties into account, obtained through a network of assistive devices. However respect of the privacy of life, protection of the elderly and ethical considerations impose to ensure the confidentiality of the data and a strict control of such a service by the medical community.
- **rehabilitation and biomechanics**: our goals in rehabilitation are 1) to provide more objective and robust indicators, that take measurement uncertainties into account to assess the progress of a rehabilitation process 2) to provide processes and devices (including the use of virtual reality) that facilitate a rehabilitation process and are more flexible and easier to use both for users and doctors. Biomechanics is an essential tool to evaluate the pertinence of these indicators, to gain access to physiological parameters that are difficult to measure directly and to prepare efficiently real-life experiments.

Addressing these societal focus induces the following **scientific objectives**:

- **design and control of a network of connected assistive devices**: existing assistance devices suffer from a lack of essential functions (communication, monitoring, localization,...) and their acceptance and efficiency may largely be improved. Furthermore essential functions (such as fall detection, knowledge sharing, learning, adaptation to the user and helpers) are missing. We intend to develop new devices, either by adapting existing systems or developing brand-new one to cover these gaps. Their performances, robustness and adaptability will be obtained through an original design process, called *appropriate design*, that takes uncertainties into account to determine almost all the nominal values of the design parameters that guarantee to obtain the required performances. The development of these devices covers our robotics works (therefore including robot analysis, kinematics, control, ...) but is not limited to them. These devices will be present in the three elements of the ecosystem (user, technological helps and environment) and will be integrated in a common network. The study of this robotic network and of its element is therefore a major focus point of the HEPHAISTOS project. In this field our objectives are:
  - to develop methods for the analysis of existing robots, taking into account uncertainties in their modeling that are inherent to such mechatronic devices
  - to propose innovative robotic systems
- **evaluation, modeling and programming of assistive ecosystem**: design of such an ecosystem is an iterative process which relies on different types of evaluation. A large difference with other robotized environments is that effectiveness is not only based on technological performances but also on subjectively perceived dimensions such as acceptance or improvement of self-esteem. We will develop methodologies that cover both evaluation dimensions. Technological performances are still important and modeling (especially with symbolic computation) of the ecosystem will play a major role for the design process, the safety and the efficiency, which will be improved by a programming/communication framework than encompass all the assistance devices. Evaluation will be realized with the help of clinical partners in real-life or by using our experimental platforms.
- **uncertainty management**: uncertainties are especially present in all of our activities (sensor, control, physiological parameters, user behavior, ...). We intend to systematically take them into account especially using interval analysis, statistics, game theory or a mix of these tools.
- **economy of assistance**: interviews by the HEPHAISTOS team and market analysis have shown that cost is a major issue for the elderly and their family. At the opposite of other industrial sectors manufacturing costs play a very minor role when fixing the price of assistance devices: indeed prices result more from the relations between the players and from regulations. We intend to model these relations in order to analyze the influence of regulations on the final cost.

The societal challenges and the scientific objectives will be supported by experimentation and simulation using our development platforms or external resources.

In terms of methodologies the project will focus on the use and mathematical developments of **symbolic tools**(for modeling, design, interval analysis), on **interval analysis** (for design, uncertainties management, evaluation), on **game theory** (for control, localization, economy of assistance) and on **control theory**. Implementation of the algorithms will be performed within the framework of general purpose software such as `Scilab`, `Maple`, `Mathematica` and the interval analysis part will be based on the existing library `ALIAS`, that is still being developed mostly for internal use.

Experimental work and the development of our own prototypes are strategic for the project as they allow us to validate our theoretical work and to discover new problems that will feed in the long term the theoretical analysis developed by the team members.

Dissemination is also an essential goal of our activity as its background both on the assistance side and on the theoretical activities as our approaches are not sufficiently known in the medical, engineering and academic communities.

In summary HEPHAISTOS has as major research axes assistance robotics, modeling (see section 7.1.1), game theory, interval analysis and robotics (see section 6.1). The coherence of these axis is that interval analysis is a major tool to manage the uncertainties that are inherent to a robotized device, while assistance robotics provides realistic problems which allow us to develop, test and improve our algorithms. Our overall objectives are presented in http://www-sop.inria.fr/hephaistos/texte_fondateur_hephaistos.pdf and in a specific page on assistance http://www-sop.inria.fr/hephaistos/applications/assistance_eng.html.

3. Research Program

3.1. Interval analysis

We are interested in real-valued system solving ($f(X)=0$, $f(X)\leq 0$), in optimization problems, and in the proof of the existence of properties (for example, it exists X such that $f(X)=0$ or it exist two values X_1, X_2 such that $f(X_1)>0$ and $f(X_2)<0$). There are few restrictions on the function f as we are able to manage explicit functions using classical mathematical operators (e.g. $\sin(x+y)+\log(\cos(e^x)+y^2)$ as well as implicit functions (e.g. determining if there are parameter values of a parametrized matrix such that the determinant of the matrix is negative, without calculating the analytical form of the determinant).

Solutions are searched within a finite domain (called a *box*) which may be either continuous or mixed (i.e. for which some variables must belong to a continuous range while other variables may only have values within a discrete set). An important point is that we aim at finding all the solutions within the domain whenever the computer arithmetic will allow it: in other words we are looking for *certified* solutions. For example, for 0-dimensional system solving, we will provide a box that contains one, and only one, solution together with a numerical approximation of this solution. This solution may further be refined at will using multi-precision.

The core of our methods is the use of *interval analysis* that allows one to manipulate mathematical expressions whose unknowns have interval values. A basic component of interval analysis is the *interval evaluation* of an expression. Given an analytical expression F in the unknowns $\{x_1,x_2,...,x_n\}$ and ranges $\{X_1,X_2,...,X_n\}$ for these unknowns we are able to compute a range $[A,B]$, called the interval evaluation, such that

$$\forall\{x_1,x_2,...,x_n\}\in\{X_1,X_2,...,X_n\}, A\leq F(x_1,x_2,...,x_n)\leq B \tag{7}$$

In other words the interval evaluation provides a lower bound of the minimum of F and an upper bound of its maximum over the box.

For example if $F=x\ sin(x+x^2)$ and $x\in[0.5,1.6]$, then $F([0.5,1.6])=[-1.362037441,1.6]$, meaning that for any x in [0.5,1.6] we guarantee that $-1.362037441\leq f(x)\leq 1.6$.

The interval evaluation of an expression has interesting properties:

- it can be implemented in such a way that the results are guaranteed with respect to round-off errors i.e. property 1 is still valid in spite of numerical errors induced by the use of floating point numbers
- if $A > 0$ or $B < 0$, then no values of the unknowns in their respective ranges can cancel F
- if $A > 0$ ($B < 0$), then F is positive (negative) for any value of the unknowns in their respective ranges

A major drawback of the interval evaluation is that $A(B)$ may be overestimated i.e. values of $x_1, x_2, ..., x_n$ such that $F(x_1, x_2, ..., x_n) = A(B)$ may not exist. This overestimation occurs because in our calculation each occurrence of a variable is considered as an independent variable. Hence if a variable has multiple occurrences, then an overestimation may occur. Such phenomena can be observed in the previous example where $B = 1.6$ while the real maximum of F is approximately 0.9144. The value of B is obtained because we are using in our calculation the formula $F = xsin(y + z^2)$ with y, z having the same interval value as x.

Fortunately there are methods that allow one to reduce the overestimation and the overestimation amount decreases with the width of the ranges. The latter remark leads to the use of a branch-and-bound strategy in which for a given box a variable range will be bisected, thereby creating two new boxes that are stored in a list and processed later on. The algorithm is complete if all boxes in the list have been processed, or if during the process a box generates an answer to the problem at hand (e.g. if we want to prove that $F(X) < 0$, then the algorithm stops as soon as $F(\mathcal{B}) \geq 0$ for a certain box $\mathcal{B}$).

A generic interval analysis algorithm involves the following steps on the current box [8], [4]:

1. *exclusion operators*: these operators determine that there is no solution to the problem within a given box. An important issue here is the extensive and smart use of the monotonicity of the functions
2. *filters*: these operators may reduce the size of the box i.e. decrease the width of the allowed ranges for the variables
3. *existence operators*: they allow one to determine the existence of a unique solution within a given box and are usually associated with a numerical scheme that allows for the computation of this solution in a safe way
4. *bisection*: choose one of the variable and bisect its range for creating two new boxes
5. *storage*: store the new boxes in the list

The scope of the HEPHAISTOS project is to address all these steps in order to find the most efficient procedures. Our efforts focus on mathematical developments (adapting classical theorems to interval analysis, proving interval analysis theorems), the use of symbolic computation and formal proofs (a symbolic pre-processing allows one to automatically adapt the solver to the structure of the problem), software implementation and experimental tests (for validation purposes).

Important note: We have insisted on interval analysis because this is a **major component** or our robotics activity. Our theoretical work in robotics is an analysis of the robotic environment in order to exhibit proofs on the behavior of the system that may be qualitative (e.g. the proof that a cable-driven parallel robot with more than 6 non-deformable cables will have at most 6 cables under tension simultaneously) or quantitative. In the quantitative case as we are dealing with realistic and not toy examples (including our own prototypes that are developed whenever no equivalent hardware is available or to very our assumptions) we have to manage problems that are so complex that analytical solutions are probably out of reach (e.g. the direct kinematics of parallel robots) and we have to resort to algorithms and numerical analysis. We are aware of different approaches in numerical analysis (e.g. some team members were previously involved in teams devoted to computational geometry and algebraic geometry) but interval analysis provides us another approach with high flexibility, the possibility of managing non algebraic problems (e.g. the kinematics of cable-driven parallel robots with sagging cables, that involves inverse hyperbolic functions) and to address various types of issues (system solving, optimization, proof of existence ...). However whenever needed we will rely as well on continuation, algebraic geometry, geometry or learning.

3.2. Robotics

HEPHAISTOS, as a follow-up of COPRIN, has a long-standing tradition of robotics studies, especially for closed-loop robots [3], especially cable-driven parallel robots. We address theoretical issues with the purpose of obtaining analytical and theoretical solutions, but in many cases only numerical solutions can be obtained due to the complexity of the problem. This approach has motivated the use of interval analysis for two reasons:

1. the versatility of interval analysis allows us to address issues (e.g. singularity analysis) that cannot be tackled by any other method due to the size of the problem
2. uncertainties (which are inherent to a robotic device) have to be taken into account so that the *real* robot is guaranteed to have the same properties as the *theoretical* one, even in the worst case. This is a crucial issue for many applications in robotics (e.g. medical or assistance robot)

Our field of study in robotics focuses on *kinematic* issues such as workspace and singularity analysis, positioning accuracy, trajectory planning, reliability, calibration, modularity management and, prominently, *appropriate design*, i.e. determining the dimensioning of a robot mechanical architecture that guarantees that the real robot satisfies a given set of requirements. The methods that we develop can be used for other robotic problems, see for example the management of uncertainties in aircraft design [6].

Our theoretical work must be validated through experiments that are essential for the sake of credibility. A contrario, experiments will feed theoretical work. Hence HEPHAISTOS works with partners on the development of real robots but also develops its own prototypes. In the last years we have developed a large number of prototypes and we have extended our development to devices that are not strictly robots but are part of an overall environment for assistance. We benefit here from the development of new miniature, low energy computers with an interface for analog and logical sensors such as the Arduino or the Phidgets. The web pages http://www-sop.inria.fr/hephaistos/mediatheque/index.html presents all of our prototypes and experimental work.

4. Highlights of the Year

4.1. Highlights of the Year

4.1.1. Science

- strong advances on the analysis of cable-driven parallel robots (section 6.1.1)
- first results the daily activities monitoring in a day hospital (section 6.2)

4.1.2. Experimentation

- Two months experimentation of a very large cable-driven parallel robot for an artistic exhibition (section 6.1.2)
- Completion of the second version of our immersive environment for rehabilitation (section 5.3.2.1)

5. New Software and Platforms

5.1. ALIAS

Algorithms Library of Interval Analysis for Systems

FUNCTIONAL DESCRIPTION: The ALIAS library whose development started in 1998, is a collection of procedures based on interval analysis for systems solving and optimization.

ALIAS is made of two parts:

ALIAS-C++ : the C++ library (87 000 code lines) which is the core of the algorithms

ALIAS-Maple : the Maple interface for ALIAS-C++ (55 000 code lines). This interface allows one to specify a solving problem within Maple and get the results within the same Maple session. The role of this interface is not only to generate the C++ code automatically, but also to perform an analysis of the problem in order to improve the efficiency of the solver. Furthermore, a distributed implementation of the algorithms is available directly within the interface.

- Participants: Jean-Pierre Merlet and Odile Pourtallier
- Contact: Jean-Pierre Merlet

5.2. PALGate

KEYWORDS: Health - Home care - Handicap

- Contact: David Daney

5.3. Platforms

5.3.1. ALIAS, Algorithms Library of Interval Analysis for Systems

Participants: Hiparco Lins Vieira, Jean-Pierre Merlet [correspondant], Yves Papegay.

URL: http://www-sop.inria.fr/hephaistos/developpements/main.html

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ALIAS is a core element for solving the usually complex equations we have to manage our robotics problems. We may mention as example our work on cable-driven parallel robot (see section 6.1.1) involves non-algebraic models whose exact solving is required while the unknowns of our system are physical entities that may usually be bounded (meaning that we are not interested in all solutions of the system but only in the one that make physical sense) and therefore interval analysis is appropriate (and quite often the only one that may manage to get exactly all solutions). This year we have also used ALIAS to provide certified solutions of the kinematics of a flexible parallel robots [17]. We have confirmed the solutions that has been provided by a computer intensive iterative methods and have shown that the interval analysis method was able to manage a more complex case for which the iterative method cannot be reasonably used. In a third example we combine interval analysis and Monte-Carlo method for developing a reliable motion planning for parallel manipulators [15] while interval analysis has been used for the design of parallel robot [14].

5.3.2. Hardware platforms

We describe here only the new platforms that have been developed or improved in 2019 while we maintain a very large number of platforms (e.g. the cable-driven parallel robots of the MARIONET family, the ANG family of walking aids,r our experimental flat and the activities detection platform implemented in the day hospital Institut Claude Pompidou and EHPAD Valrose, Nice). Among the MARIONET family we have reactivated and adapted the MARIONET-CRANE prototype for the experiment described in section 6.1.2. We have also updated our parallel $6-\underline{P}US$ prototype for the medical application mentioned in section 6.3.

5.3.2.1. REVMED: virtual reality and rehabilitation

Inria and Université Côte d'Azur have agreed to fund us for developing the platform REVMED whose purpose is to introduce end-user motion and their analysis in a virtual reality environment in order to make rehabilitation exercises more attractive and more appropriate for the rehabilitation process. The main idea is to have a modular rehabilitation station allowing to manage various exercise devices with a very low set-up time (typically 10 mn), that will be actuated in order to allow ergotherapists to favor the work of various muscles groups and the difficulty of the exercise, while monitoring the rehabilitation process with various external sensors, providing an objectification of the evaluation. Version 2 has been completed this year and we will proceed in 2020 to the first trials. These trials will consist in establishing walking patterns for non-pathological people in various conditions that will be created by a walk in a mountainous environment.

6. New Results

6.1. Robotics

6.1.1. Analysis of Cable-driven parallel robots

Participants: Jean-Pierre Merlet [correspondant], Yves Papegay.

We have continued the analysis of suspended CDPRs for control and design purposes. This analysis is heavily dependent on the behavior of the cable. Three main models can be used: *ideal* (no deformation of the cable due to the tension, the cable shape is a straight line between the attachments points), *elastic* (cable length changes according to the tension to which it is submitted, straight line cable shape) and *sagging* (cable shape is not a line as the cable is submitted to its own mass). The different models leads to very different analysis with a complexity increasing from ideal to sagging. All cables exhibit sagging but the sagging effect is often neglected if the CDPR is relatively small while it definitively cannot be neglected for large CDPRs. The most used sagging model is the Irvine model [24]. This is a non algebraic planar model with the upper attachment point of the cable is supposed to be grounded: it provides the coordinates of the lowest attachment point B of the cable if the cable length L_0 at rest and the force applied at this point are known. It takes into account both the elasticity and deformation of the cable due to its own mass. A drawback of this model is that we will be more interested in a closed-form of the L_0 for a given pose of B (for the inverse kinematics of CDPR) and in alternate form of the model that will provide constraint on the force components (for the direct kinematics). We have proposed new original formulations of the Irvine model in [13] and have shown that their use drastically improve the solving time for both the inverse and direct kinematics (i.e finding all possible solutions for both problems) that are required for CDPRs control. Still the solving time of the direct kinematics is too large for the real-time direct kinematics and in that case only the current pose of the platform is of interest.

The direct kinematics relies on an accurate estimation of the cable lengths that is usually based on the measurement of the winch drum rotation. We have evaluated the influence of uncertainties in the cable length measurement on the result of the FK [19] and have shown that for a poor robot geometry (which was for example the case for the prototype described in section 6.1.2 for which the geometry was imposed) this influence may be quite large . An usual strategy to decrease this uncertainty for small to medium-sized CDPR is to use a drum with a cable spiral guide for the coiling which impose a coiling path for the cable. However this strategy is unfeasible for large and very large CDPR (that we called *Ultrabot*) for which the large length of the cables impose to have several layers on the drum and therefore leads to a more erratic coiling process that leads to possibly large errors of the cable lengths estimation. To get a better estimation of the cable lengths we have proposed an original method, based on the Vernier principle [21]. The idea is to have several small colored marks on the cable at known distances from the end-point of the cable and to have several color sensors in the mast of the CDPR. We have first shown that if 3 colors (e.g. RGB) were used, then an appropriate disposition of the marks on the cable allows to have up to 29 marks on the cable so that the sequence of 3 successive colors is always unique. Hence by coiling the cable and detecting the 3 successive color detected by a sensor allows to determine exactly the distance between the sensor and the cable end-point, i.e. to *calibrate* the cable length. Calibration is always an issue for CDPR which uses usually incremental encoders for measuring the drum rotation (which explain why we have also proposed another approach [18]. Then we have considered the sequence of color detection when coiling the cable, starting from its largest length. We have looked at the distribution of cable length changes $\Delta\rho$ between two successive detection and have proposed a strategy that provide the distance between the marks so that this distribution is quasi-uniform with a mean value that is minimal. For example we have shown that for a 60 meters length cable having 29 marks we were able to have an almost constant $\Delta\rho$ of 40 cm, meaning that when the cable length changes by this value, then we get an exact evaluation of the cable length at each detection. In between such detection we rely on the drum rotation measurement to estimate the cable length. Furthermore we have shown that the difference between the expected detection time and the real one allows one to update the estimate of the drum radius, thus enabling to manage an erratic coiling process. We have initially installed this system on the prototype presented in section 6.1.2. The few initial tests were really promising but on-site we have had problems for ensuring a constant positioning of the marks on the synthetic cables. Being given the very short deployment time we have not been able to fix this problem. Consequently we have decided to use another approach based on direct measurement of the load pose with lidars, this approach being described in section 6.1.2.

We have also continued to investigate the calculation of planar cross-sections of the workspace for CDPR with sagging cables. We have shown in a previous paper that the border of this workspace was either determined by cable length limits but also by the singularity of the kinematics equations. Hence these singularities play an important role for the design of a CDPR. We have started a preliminary investigation on this topic [20]. We have shown that these singularities may be classified in two categories:

- *classical singularity* which corresponds to the singularity of parallel robots with rigid legs which basically implies that the mechanical equilibrium of the system cannot be obtained, leading to a motion of the platform even if the actuators are locked
- *full singularity* which are singularity of the kinematics equations but are not classical singularity. In this case mechanical equilibrium is obtained but the CDPR is unable to move in a given direction

We have also developed an algorithm that check if a full singularity exists in the neighborhood of a given pose and to locate it with an arbitrary accuracy.

6.1.2. Cable-Driven Parallel Robots for large scale additive manufacturing

Participants: Jean-Pierre Merlet, Yves Papegay [correspondant].

Easy to deploy and to reconfigure, dynamically efficient in large workspaces even with payloads, cable-driven parallel robots are very attractive for solving displacement and positioning problems in architectural building at large scale seems to be a good alternative to crane and industrial manipulators in the area of additive manufacturing. We have co-founded in 2015 years ago the XtreeE (www.xtreee.eu) start-up company that is currently one of the leading international actors in large-scale 3D concrete printing.

We have been contacted in 2018 by the artist Anne-Valérie Gasc that is interested in mimicking the 3D additive manufacturing process on large scale for a live art performance. She was interested in a mean for widespreading glass micro-beads on a given trajectory over a 21 $\times$ 9m large platform located at the contemporary art center *Les Tanneries* (figure 1), located close to Montargis. She was especially interested in using a CDPR for that purpose because of the low visual intrusivity of the cables and its ability to move large load. After a few month of discussions we agree to recycle our old MARIONET-CRANE prototype (2009) for this exhibition although the place was not the most appropriate for the CDPR as the height of the location was only 3 meters. We design as load a 80 liters drum of weight 55 kg with 40 kg of powder that was sufficient for printing one trajectory (figure 1). An on-board computer connected through wifi to a master computer was managing the lidar measurement and the opening/closing of the servo-valve controlling the powder flow. The drum was supported by 4 Dyneema cables of diameter 3mm whose output points were located at the corners of the platform and whose lengths were varying between 3 and 26 meters. The master computer was controlling the CDPR and the parameters of the system were recorded every second in log files. The development was very fast and we were not able to test a full scale installation in our laboratory for lack of the appropriate space. The on-site deployment was difficult because it has to be done in a record time, far away from our home base. The lack of height has especially a strong influence on the positioning errors of the drum that drastically increase if the cables are close to the horizontal. We solve on-site this problem by adding 3 low-cost lidars that were providing partial measurement on the drum pose. The system was fully operational a few days after the official opening of the exhibition and was at the heart of the artistic exhibition "Les Larmes du Prince - Vitrifications" (http://www.lestanneries.fr/exposition/larmes-prince-vitrifications), that was run during July and August under the control of a local student. The exhibition was scheduled to run 5 days per week until the end of August. During this period the CDPR has worked 174 hours (4h15mn/day), has traveled 4757 meters and has dispersed about 1.5 tons of powder. We get two failures: one of the cables has broken but without any consequence because of the redundancy of the robot and a failure of the reduction gear of one of the winch on the exhibition closing day, which has been immediately repaired. From a scientific viewpoint we have been able to test, in this quasi-industrial context, the efficiency of a control law using external measurements of the pose and the logs, still being processed has allowed us to identify possible improvements and scientific issues regarding the modeling of the system. An unexpected benefit of using the lidars was to allow to record a profile of the powder wall at each trajectory, showing its life over time as it was always evolving because of the powder particle motion after a printing.

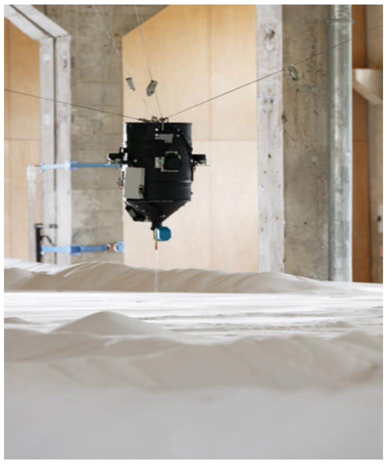

Figure 1. The exhibition place and the drum. Photos copyrighted Anne-Valérie Gasc, "Vitrifications", Photograph: Aurélien Mole

6.1.3. *Killing robots*

Participant: Jean-Pierre Merlet [correspondant].

The director, Linda Blanchet, of a theater company has contacted us for helping organizing a theater event, *Killing Robots*, centered on the story of *Hitchbot*, a passive 70cm high mannequin designed by Canadian colleagues, that was put on the side-way of roads in Canada so that people may transport it, the purpose being to study the human interaction with people during a travel from the east to the west cost of Canada. The mannequin was located through a GPS and has taken a picture of its surrounding every 20 minutes while it was active. This mannequin indeed performs this travel in 15 days and a similar experiment was then scheduled in the US, the purpose being to go from Boston to San Francisco. Unfortunately after 5 days of travel the mannequin was discovered completely dismantled in Philadelphia. The idea of Linda Blanchet's performance was to propose a thriller based on the robot data for discovering who has dismantled the robot and in parallel to have the robot interacts with the actors to describe its feeling. For that purpose it was necessary that the robot becomes actuated while keeping its appearance identical to the original model. We have therefore retrieved a clone of the original Hitchbot and we have actuated the arms and head, so that the robot was able to move them, adding a lidar on top of the head so that it was able to locate the actors on stage (figure 2).

Figure 2. The transformed Hitchbot robot

The Canadian colleague have also provided a conversational agent so that the robot was able to speak with a learning process. The opening of the performance was done on November 6 at the National theater of Nice and it is now performing in various places in France. We have been present at several of them to interact with the public at the end of the performance. From a scientific viewpoint our interest in this exhibition was to better understand why adding motion to a mannequin modify drastically the perception of the robot by the public. These understanding will help to work on the factors that increase the acceptance of a technological object by the public, which is clearly a major factor for the efficiency of our assistance devices.

6.2. Smart Environment for Human Behaviour Recognition

Participants: Jean-Pierre Merlet, Yves Papegay, Odile Pourtallier [correspondant], Eric Wajnberg.

The general aim of this research activity focuses on long term indoor monitoring of frail persons. In particular we are interested in early detection of daily routine and activity modifications. These modifications may indicate health condition alteration of the person and may require further medical or family care. Note that t our work does not aim at detecting brutal modifications such as faintness or fall.

In our research we envisage both individual and collective housing such as rehabilitation center or retirement home.

Our work relies on the following leading ideas :

- We do not base our monitoring system on wearable devices since it appears that they may not be well accepted and worn regularly,
- Privacy advocates adequacy between the monitoring level needed by a person and the detail level of the data collected. We therefore strive to design a system fitted to the need of monitoring of the person.
- In addition to privacy concern, intrusive feature of video led us not to use it.

The main aspect that grounds this work is the ability to locate a person or a group in their indoor environment. We focus our attention to the case where several persons are present in the environment. As a matter of fact the single person case is less difficult.

6.2.1. Tools and data analysis for experimental systems

Two experimental systems are installed in two areas (a consultation center (Institut Claude Pompidou, ICP, Nice), and a retirement home (EHPAD Valrose, Nice)) were several types of persons (residents, visitors, staff) evolve. They are made up of virtual barriers (constituted of distance and motion sensors) displayed in the environment and connected to a PC that collects and stores the measurements of the barriers. Each crossing of a barriers hence corresponds to a specific signal of a set of sensors. We develop a set of codes that aim to analyze the data collected to construct information on the moves of the persons in the experiment areas [23].

This year we have improved the code that yields the barrier events (time and direction of crossing of barriers) from the raw data. This allowed us to use this first step to reconstruct the individual trajectories of the users.

Although the filtering technics do not use external information (such as specific use of a zone bounded by barriers, habit of users according to time....) we can determine most of the individual trajectories of the users, even when several users evolve simultaneously in the area. Although some uncertainties remain (and could probably be improved using external knowledge), we can use the results obtained to perform a statistical analysis.

The aim on the main scientific efforts this year was to develop a detailed statistical treatment chain to extract and to visualize the events information coming from the set of movement activity detectors installed at ICP. All the (statistical and graphical) development were performed in the R software environment. Globally, two sets of information were collected, for the recorded data. The first provides a kinematic view of the presence of individuals on the mass plan of ICP during a chosen time interval. The following graph gives a static example of the kinematic graph obtained. Such a dynamic information points, for example, to specific movement activities in the medical center, at given time intervals. Figure 3 shows the presence of individuals in the corridors and consultation rooms at ICP at different times.

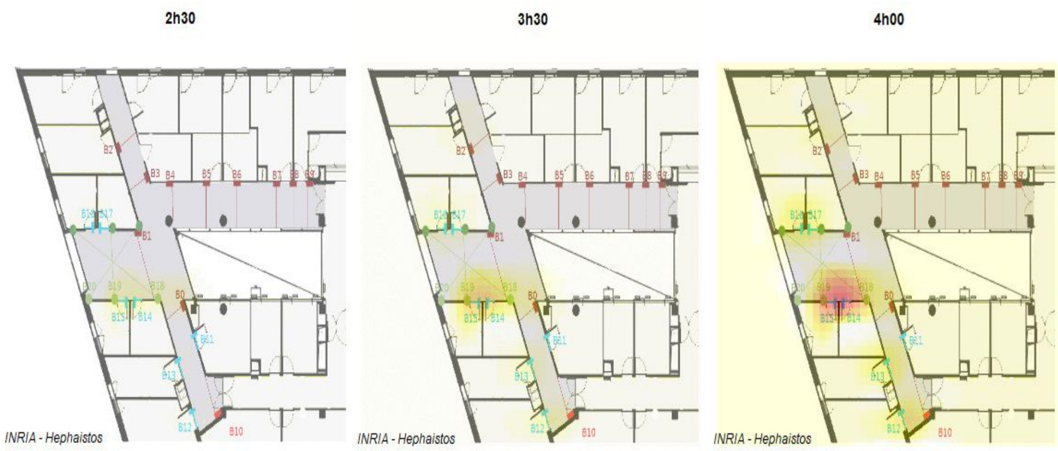

Figure 3. Three photograms on a kinematic view of the presence of individuals on the mass plan of ICP

Such a graph is only descriptive. Hence, it does not provide a functional analysis of the displacements of individuals in the medical center. In order to understand this better, the chronological movement patterns were functionally described by building, for every time interval, the transition matrix between all zones present in the analyzed medical center. After proper algebraic manipulation, the obtained transition matrices were analyzed using a factorial correspondence analysis, a multivariate method that - in this case and among other features – built graphs describing the functional movement patterns between zones. The graph presented in figure 4 gives an example of the obtained results.

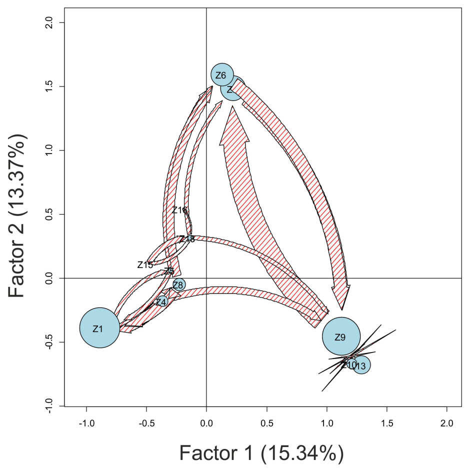

Figure 4. Example of the best factorial plan (explaining almost 30% of all the information contained in the data) obtained from a factorial correspondence analysis used to describe the functional movement patterns of individual between zones in the followed medical center during a full day of activity. Each blue circle represents a zone, with a radius proportional of its frequentation frequency. Arrows between zones (in red) are proportional to the observed flux of individual movements between zones. Only the most important arrows are presented.

The next step will be to statistically compare such results, e.g., between morning or afternoon activity, between days with or without medical consultation, etc. Results obtained might lead to a better organization of the medical activities at ICP.

6.3. Other medical activities

Participants: Jean-Pierre Merlet [correspondant], Sylvain Guénon.

Eric Sejor, a surgeon at Nice hospital, has contacted us about developing a robotized system for realizing sutures in an autonomous way. Suturing is a lengthy process while in many cases this is not a complex operation. Eric Sejor mentions that developing an autonomous system allowing to manage standard wounds may be extremely interesting, especially for emergency service that are under-staffed. Instead of developing a new robot dedicated to this purpose we have proposed to Eric Sejor to build a system based on the existing manual tools that require to put the instrument in place and then simply squeezing a trigger. The placement will be realized by one of our small parallel robot, with the help of vision system to locate the edge of the wound, while the trigger squeezing will be performed by an actuator. We have obtained an Idex funding (one year for an engineer) to develop a proof-of-concept prototype that will perform the operation on silicone mockups that are used for the surgeon training.

We have had also a contact with the ergotherapist Nicolas Ciai from Nice hospital for the evaluation of patient motricity before an operation. For this evaluation the ergotherapist performs muscular testing before the operation, right after the operation and 6 months later. The exercise consists in opposing the ergotherapist palm against the musculo group that has to be tested until a force equilibrium is reached. Then the ergotherapist ranks the tonicity of the muscles on a discrete scale between 0 and 6 according to his muscular feeling. As numerous muscles have to be tested, the process is quite lengthy. Clearly this process is quite subjective and we have proposed an objectification of the process by developing a glove prototype that includes pression sensors for measuring accurately the pressure exerted by the patient. These sensors are used by a micro-computer the size of a large watch located on the wrist of the ergotherapist. This computer determines when the pressure becomes stable, in which case this pressure is displayed and recorded. A companion software will then exploit the recorded data to provide an evaluation report. Beside the objectification of the ranking, the purpose is also to speed-up the tests. Although this project is quite advanced, we are lacking of manpower to complete it so that we have presented a project to Nice hospital for funding an engineer that may complete the second version of the glove.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Grants with Industry

7.1.1. Symbolic tools for modeling and simulation

Participant: Yves Papegay.

This activity is the main part of a long-term ongoing collaboration with Airbus whose goal is to directly translate the conceptual work of aeronautics engineers into digital simulators to accelerate aircraft design.

An extensive modeling and simulation platform - MOSELA - has been designed which includes a dedicated modeling language for the description of aircraft dynamics models in term of formulae and algorithms, and a symbolic compiler producing as target an efficient numerical simulation code ready to be plugged into a flight simulator, as well as a formatted documentation compliant with industrial requirements of corporate memory.

Technology demonstrated by our prototype has been transferred : final version of our modeling and simulation environment has been delivered to Airbus in November 2012 and developer level know-how has been transferred in 2013 to a software company in charge of its industrialization and maintenance.

Since 2014, we are working on several enhancements and extension of functionalities, namely to enhance the performances and the numerical quality of the generated C simulation code, ease the integration of our environment into the airbus toolbox, help improving the robustness of the environment and the documentation.

8. Partnerships and Cooperations

8.1. National Initiatives

- the project **Craft** on collaborative cable-driven parallel robot has been funded by ANR. It involves LS2N (Nantes) and the Cetim. This project will start in 2019

8.1.1. FHU

- the team has been involved for the FHU *INOVPAIN : Innovative Solutions in Refractory Chronic Pain* that has been labeled in December 2016

8.2. International Initiatives

8.2.1. Inria International Partners

8.2.1.1. Informal International Partners

We have numerous international collaborations but we mention here only the one with activities that go beyond joint theoretical or experimental works:

- University of Bologna, Italy: 2 joint PhD student, publications

- University Innsbruck, Austria: joint conference organization
- Fraunhofer IPA, Stuttgar, Germany: joint conference organization
- Duisburg-Essen University, Germany: joint conference organization
- University of New-Brunswick, Canada: 1 joint PhD student
- University Laval, Québeç Canada: joint book
- University of Tokyo, Japan: joint conference organization
- Tianjin University, China: joint book

8.3. International Research Visitors

8.3.1. Visits of International Scientists

- W. Godoy, Pr. Univ Sao Paolo, from Dec 2019
- M. Tome, PhD student, Univ Sao Paolo, from Dec 2019
- I.D. Weber, Master student, Univ Sao Paolo, from Dec 2019
- M. Tuda, PhD student, Univ Sao Paolo, from Jun 2019 until July 2019
- H. Lins Vieira, PhD student, Univ Sao Paolo, from January until Aug 2019

8.4. Transfert

- J-P. Merlet is scientific advisor of the startup *Farmboy Labs* that is currently being created by our former PhD student L. Blanchet. The purpose of this startup is to propose cable-driven parallel robots for agriculture (monitoring, maintenance, weeding, ...). .

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events: Organisation

- J-P. Merlet is a permanent member of the International Steering Committee of the IROS conference, of the CableCon conference and chairman of the scientific Committee of the Computational Kinematics workshop. He is also an advisor for ICRA 2020,
- Y. Papegay is a permanent member of the International Steering Committee of the International Mathematica Symposium conferences series. He is a member of the OpenMath Society, building an extensible standard for representing the semantics of mathematical objects.

9.1.1.1. Reviewer - Reviewing Activities

- The members of the team reviewed numerous papers for numerous international conferences and journals

9.1.2. Journal

9.1.2.1. Member of the Editorial Boards

- E. Wajnberg is Editor-in-Chief of the journal BioControl (published by Springer).
- E. Wajnberg is a board member of the journals Entomologia Experimentalis et Applicata (published by Wiley), Neotropical Entomology (published by Springer), Applied Entomology and Zoology (published by Springer), and Journal of Economical Entomology (Publish by Oxford University Press).

9.1.3. Invited Talks

- E. Wajnberg has been invited for talks by the University of Beer Shava at Sde Boqer (Israel, March), the University of La Plata (Argentina, April), the University of Buenos Aires (Argentina, April), the University of São Paulo at Piracicaba (Brazil, October)

9.1.4. Leadership within the Scientific Community

- J-P. Merlet is Inria representative to the PPP Eurobotics aisbl. He is a member of the IFToMM (International Federation for the Promotion of Mechanism and Machine Science) Technical Committees on History and on Computational Kinematics and is one of the 10 elected members of IFToMM Executive Council, the board of this federation. He is a member of the scientific committee of the CNRS GDR robotique and a chair of 3IA Côte d'Azur.

9.1.5. Scientific Expertise

- J-P. Merlet was involved in project evaluations for several foreign funding agencies (Israel, Austria, ERC). He was also appointed as *Nominator* for the Japan's Prize.
- E. Wajnberg is involved in project evaluation for several foreign funding agencies (Belgium, Italy).
- E. Wajnberg was invited to be a committee number for recruiting an Institute Director by the CNR (Rome, Italy)

9.1.6. Research Administration

- J-P. Merlet was an elected member of the Academic Council of UCA COMUE (until July 2019), is a corresponding member of Inria ethical committee (COERLE) and member of the Research, Ethical Committees of UCA. He is an elected member of Inria Scientific Committee and of the "Commission Administrative Paritaire" of Inria
- Y. Papegay is a member of the CUMI (the committee managing the interaction between researchers and the computer support staff)
- O. Pourtallier is responsible of the NICE committee (long term invited scientists and post-doctoral student selection).
- O. Pourtallier is a board member of the Scientific and Pedagogical Council of DS4H graduate school of UCA.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

J-P. Merlet has taught 6 hours on parallel robots to Master ISC (M2) at University of Toulon. He has also been invited at ESIEE Paris for a talk about assistance robotics

J-P. Merlet, P. Martinet (CHORALE) and G. Allibert (I3S) have organized the first GDR robotics winter school, *Foundation of robotics*. During 5 days 35 students, mostly 1st year PhD students, have followed courses taught by international experts. Slides and additional materials have been regrouped in a HAL collection, *Robotics principia*, that has been organized in such a way that the next occurrences of this school will also be able to deposit additional documents. The idea of this collection is to be able to address all topics in robotics with various viewpoints.

In February, Y. Papegay has been visiting lecturer of University of French Polynesia, where he gave an object oriented programming course.

Y. Papegay has taught 3 hours on parallel robots to Master ISC (M2) at University of Toulon

P. Pourtallier lectured 6 hours on game theory to Master OSE (M2), at École des Mines de Paris, Sophia Antipolis, France

E. Wajnberg lectured One week course (about 30 h) about the use of the R program and statistics for PhD students and senior scientists in Rehovot (Israel, February)

9.2.2. Supervision

J. Moussaid. Analyse de robots parallèles à câbles (2019-), Supervisor: J-P. Merlet

W. Plouvier. Improving pest control efficiency: a modelling approach (2015-2019). Supervisor: E. Wajnberg.

E. Thomine. Agencement cultural pour promouvoir le transfert des services écosystémiques de biocontrôle au sein des paysages agricoles (2016 à 2019). Supervisors : N. Desneux & E. Wajnberg.

9.2.3. Juries

- J-P. Merlet was a jury member for the Best PhD Awards of the robotics GDR and has been president of 2 PhD juries.

9.3. Popularization

- J-P. Merlet gives 3 talks in the Alpes-Maritimes in the framework of the *Science pour Tous* association. He has also participated in a seminar on *robotics and media* involving 6 robotics experts and 6 journalists for a reflexion on the bias of the presentation of robotics to a general audience. He was also a member of the scientific committee for the permanent exhibition *Robot* at the Cité des Sciences, Paris
- Y. Papegay is actively participating to the Math.en.Jeans initiative for Mathematics teaching for undergraduate students.
- Y. Papegay is developing several pedagogical resources based on small robotics devices at high-school level.
- Y. Papegay organized and animated summer schools in experimental mathematics and computer sciences. Several one week sessions have been held in Oxford in June, July, August and November gathering more than 70 high-school students - most of them were awardees in Mathematics Olympiads.
- O. Pourtallier is corresponding researcher for two MATh.en.JEANS workshops, an initiative for Mathematics teaching for undergraduate students.
- E. Wajnberg gives 5 talks in the Alpes-Maritimes in the framework of the *Science pour Tous* association

9.3.1. Interventions

- the HEPHAISTOS project has on average about 100 visitors per year, either young students or teachers, to which we present our robotics and assistance activities

9.3.2. Internal action

- the HEPHAISTOS project has developed a set of cable-driven parallel robots, the MARIONET-SCHOOL series, that is used to illustrate visually scientific concepts in various domains

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Project-Team INDES

Secure Diffuse Programming

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Distributed programming and Software engineering

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Project-Team INDES

Creation of the Team: 2009 January 01, updated into Project-Team: 2010 July 01

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Computer Science and Digital Science:

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A2.1.1. - Semantics of programming languages
A2.1.3. - Object-oriented programming
A2.1.4. - Functional programming
A2.1.7. - Distributed programming
A2.1.9. - Synchronous languages
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Other Research Topics and Application Domains:

B6.3.1. - Web
B6.4. - Internet of things
B9.5.1. - Computer science
B9.10. - Privacy

1. Team, Visitors, External Collaborators

Research Scientists

Manuel Serrano [Team leader, Inria, Senior Researcher, HDR]
Nataliia Bielova [Inria, Researcher]
Ilaria Castellani [Inria, Researcher]
Tamara Rezk [Inria, Researcher, HDR]
Gérard Berry [Collège de France, Senior Researcher, HDR]

External Collaborator

Marc Feeley [Université de Montréal]

PhD Students

Feras Al Kassar [Inria, PhD Student, until Sep 2019]
Lesly Ann Daniel [CEA, PhD Student]
Imane Fouad [Inria, PhD Student]
Jayanth Krishnamurthy [Inria, PhD Student]
Héloïse Maurel [Inria, PhD Student]

Bertrand Petit [Pôle Emploi, PhD Student]
Michael Toth [Inria, PhD Student, from Dec 2019]

Post-Doctoral Fellows

Yoon Seok Ko [Inria, Post-Doctoral Fellow]
Celestin Matte [Inria, Post-Doctoral Fellow, from Mar 2019]
Doliere Some [Inria, Post-Doctoral Fellow, until Apr 2019]

Visiting Scientists

Andrei Sabelfeld [Chalmers, Jul 2019]
Cristiana Santos [University of Toulouse, Feb 2019 and May 2019]

Administrative Assistant

Nathalie Bellesso [Inria, Administrative Assistant]

2. Overall Objectives

2.1. Overall Objectives

The goal of the Indes team is to study models for diffuse computing and develop languages for secure diffuse applications. Diffuse applications, of which Web 2.0 applications are a notable example, are the new applications emerging from the convergence of broad network accessibility, rich personal digital environment, and vast sources of information. Strong security guarantees are required for these applications, which intrinsically rely on sharing private information over networks of mutually distrustful nodes connected by unreliable media.

Diffuse computing requires an original combination of nearly all previous computing paradigms, ranging from classical sequential computing to parallel and concurrent computing in both their synchronous / reactive and asynchronous variants. It also benefits from the recent advances in mobile computing, since devices involved in diffuse applications are often mobile or portable.

The Indes team contributes to the whole chain of research on models and languages for diffuse computing, going from the study of foundational models and formal semantics to the design and implementation of new languages to be put to work on concrete applications. Emphasis is placed on correct-by-construction mechanisms to guarantee correct, efficient and secure implementation of high-level programs. The research is partly inspired by and built around *Hop*, the web programming model proposed by the former Mimosa team, which takes the web as its execution platform and targets interactive and multimedia applications.

3. Research Program

3.1. Parallelism, concurrency, and distribution

Concurrency management is at the heart of diffuse programming. Since the execution platforms are highly heterogeneous, many different concurrency principles and models may be involved. Asynchronous concurrency is the basis of shared-memory process handling within multiprocessor or multicore computers, of direct or fifo-based message passing in distributed networks, and of fifo- or interrupt-based event handling in web-based human-machine interaction or sensor handling. Synchronous or quasi-synchronous concurrency is the basis of signal processing, of real-time control, and of safety-critical information acquisition and display. Interfacing existing devices based on these different concurrency principles within *Hop* or other diffuse programming languages will require better understanding of the underlying concurrency models and of the way they can nicely cooperate, a currently ill-resolved problem.

3.2. Web, functional, and reactive programming

We are studying new paradigms for programming Web applications that rely on multi-tier functional programming. We have created a Web programming environment named *Hop*. It relies on a single formalism for programming the server-side and the client-side of the applications as well as for configuring the execution engine.

Hop is a functional language based on the SCHEME programming language. That is, it is a strict functional language, fully polymorphic, supporting side effects, and dynamically type-checked. *Hop* is implemented as an extension of the BIGLOO compiler that we develop. In the past, we have extensively studied static analyses (type systems and inference, abstract interpretations, as well as classical compiler optimizations) to improve the efficiency of compilation in both space and time.

As a *Hop* DSL, we have created *HipHop*, a synchronous orchestration language for web and IoT applications. *HipHop* facilitates the design and programming of complex web/IoT applications by smoothly integrating three computation models and programming styles that have been historically developed in different communities and for different purposes: *i) Transformational programs* that simply compute output values from input values, with comparatively simple interaction with their environment; *ii)* asynchronous concurrent programs that perform interactions between their components or with their environment with uncontrollable timing, using typically network-based communication; and *iii)* synchronous reactive programs that react to external events in a conceptually instantaneous and deterministic way.

3.3. Security of diffuse programs

The main goal of our security research is to provide scalable and rigorous language-based techniques that can be integrated into multi-tier compilers to enforce the security of diffuse programs. Research on language-based security has been carried on before in former Inria teams. In particular previous research has focused on controlling information flow to ensure confidentiality.

Typical language-based solutions to these problems are founded on static analysis, logics, provable cryptography, and compilers that generate correct code by construction. Relying on the multi-tier programming language *Hop* that tames the complexity of writing and analysing secure diffuse applications, we are studying language-based solutions to prominent web security problems such as code injection and cross-site scripting, to name a few.

4. Application Domains

4.1. Web

The Web is the natural application domain of the team. We are designing and implementing multitier languages for helping the development of Web applications. We are creating static and dynamic analyses for Web security. We are conducting empirical studies about privacy preservation on the Web.

4.2. Internet of Things

More recently, we have started focusing on *Internet of Things* (IoT) applications. They share many similarities with Web applications so most of the methodologies and expertises we have developed for the Web apply to IoT but the restricted hardware resources made available by many IoT devices demand new developments and new research explorations.

5. New Software and Platforms

5.1. Bigloo

KEYWORD: Compilers

FUNCTIONAL DESCRIPTION: Bigloo is a Scheme implementation devoted to one goal: enabling Scheme based programming style where C(++) is usually required. Bigloo attempts to make Scheme practical by offering features usually presented by traditional programming languages but not offered by Scheme and functional programming. Bigloo compiles Scheme modules. It delivers small and fast stand alone binary executables. Bigloo enables full connections between Scheme and C programs, between Scheme and Java programs.

RELEASE FUNCTIONAL DESCRIPTION: modification of the object system (language design and implementation), new APIs (alsa, flac, mpg123, avahi, csv parsing), new library functions (UDP support), new regular expressions support, new garbage collector (Boehm's collection 7.3alpha1).

- Participant: Manuel Serrano
- Contact: Manuel Serrano
- URL: http://www-sop.inria.fr/teams/indes/fp/Bigloo/

5.2. Hop

KEYWORDS: Programming language - Multimedia - Iot - Web 2.0 - Functional programming

SCIENTIFIC DESCRIPTION: The Hop programming environment consists in a web broker that intuitively combines in a single architecture a web server and a web proxy. The broker embeds a Hop interpreter for executing server-side code and a Hop client-side compiler for generating the code that will get executed by the client.

An important effort is devoted to providing Hop with a realistic and efficient implementation. The Hop implementation is validated against web applications that are used on a daily-basis. In particular, we have developed Hop applications for authoring and projecting slides, editing calendars, reading RSS streams, or managing blogs.

FUNCTIONAL DESCRIPTION: Multitier web programming language and runtime environment.

- Participant: Manuel Serrano
- Contact: Manuel Serrano
- URL: http://hop.inria.fr

5.3. IFJS

Infomation Flow monitor inlining for JavaScript

KEYWORD: Cybersecurity

FUNCTIONAL DESCRIPTION: The IFJS compiler is applied to JavaScript code. The compiler generates JavaScript code instrumented with checks to secure code. The compiler takes into account special features of JavaScript such as implicit type coercions and programs that actively try to bypass the inlined enforcement mechanisms. The compiler guarantees that third-party programs cannot (1) access the compiler internal state by randomizing the names of the resources through which it is accessed and (2) change the behaviour of native functions that are used by the enforcement mechanisms inlined in the compiled code.

- Contact: Tamara Rezk
- URL: http://www-sop.inria.fr/indes/ifJS/

5.4. Hiphop.js

KEYWORDS: Web 2.0 - Synchronous Language - Programming language

FUNCTIONAL DESCRIPTION: HipHop.js is an Hop.js DLS for orchestrating web applications. HipHop.js helps programming and maintaining Web applications where the orchestration of asynchronous tasks is complex.

- Contact: Manuel Serrano
- URL: http://hop-dev.inria.fr/hiphop

5.5. Server-Side Protection against Third Party Web Tracking

KEYWORDS: Privacy - Web Application - Web - Architecture - Security by design - Program rewriting techniques

FUNCTIONAL DESCRIPTION: We present a new web application architecture that allows web developers to gain control over certain types of third party content. In the traditional web application architecture, a web application developer has no control over third party content. This allows the exchange of tracking information between the browser and the third party content provider.

To prevent this, our solution is based on the automatic rewriting of the web application in such a way that the third party requests are redirected to a trusted third party server, called the Middle Party Server. It may be either controlled by a trusted party, or by a main site owner and automatically eliminates third-party tracking cookies and other technologies that may be exchanged by the browser and third party server

- Contact: Francis Doliére Some
- URL: http://www-sop.inria.fr/members/Doliere.Some/essos/

5.6. webstats

Webstats

KEYWORDS: Web Usage Mining - Statistic analysis - Security

FUNCTIONAL DESCRIPTION: The goal of this tool is to perform a large-scale monthly crawl of the top Alexa sites, collecting both inline scripts (written by web developers) and remote scripts, and establishing the popularity of remote scripts (such as Google Analytics and jQuery). With this data, we establish whether the collected scripts are actually written in a subset of JavaScript by analyzing the different constructs used in those scripts. Finally, we collect and analyze the HTTP headers of the different sites visited, and provide statistics about the usage of HTTPOnly and Secure cookies, and the Content Security Policy in top sites.

- Contact: Francis Doliére Some
- URL: https://webstats.inria.fr

5.7. Skini

Platform for creation and execution for audience participative music

KEYWORDS: Music - Interaction - Web Application - Synchronous Language

FUNCTIONAL DESCRIPTION: Skini is a platform form designing et performing collaborative music. It is based on two musical concept: pattern and orchestration. The orchestration is design using HipHop.js.

RELEASE FUNCTIONAL DESCRIPTION: Can be use for performance and création.

- Contact: Bertrand Petit

5.8. Platforms

5.8.1. BehaviorTrack

Keyword: Web tracking detection, Large-scale measurement
Description: In our study, we propose a tracking detection method inspired by analyzing behavior of invisible pixels. By crawling 84,658 webpages from 8,744 domains, we detect that third-party invisible pixels are widely deployed: they are present on more than 94.51% of domains and constitute 35.66% of all third-party images. We propose a fine-grained behavioral classification of tracking based on the analysis of invisible pixels. BehaviorTrack uses this classification to detect new categories of tracking and uncover new collaborations between domains on the full dataset of 4,216,454 third-party requests.

- Contact: Imane Fouad
- URL: http://www-sop.inria.fr/members/Imane.Fouad/pixeltrack

6. New Results

6.1. JavaScript Implementation and Browser Security

We have pursued the development of *Hop* and our study on efficient and secure JavaScript implementations.

6.1.1. JavaScript Property Caches

JavaScript objects are dynamic. At any moment of their lifetime, properties can be added or deleted. In principle a property access requires a lookup in the object itself, and, possibly, in all the objects forming its prototype chain. All fast JavaScript implementations deploy strategies to implement this lookup operation in nearly constant time. They generally rely on two ingredients: *hidden classes* and *property caches*. Hidden classes describe object memory layouts. Property caches use these descriptions to access objects directly, avoiding the normal name lookup operations. Hidden classes and property caches make property accesses comparable in speed to field accesses of traditional languages like C and Java.

Hidden classes and property caches are not new. They were invented for Self, the first dynamically typed prototype-based languages, following Smalltalk's idea that already used caches at that time for optimizing method calls. For the past ten years they have enjoyed a revival of interest after it was shown how effective they are at improving Object-Oriented languages performance in general and specially JavaScript. Today most JavaScript implementations such as V8, JavaScriptCode, and SpiderMonkey use them. Hidden classes and property caches apply in specific situations, which unfortunately means that some accesses are unoptimized or not treated very efficiently.

1. **Property addition problem**: hidden classes support the accesses of existing properties but they do not handle efficiently property addition commonly found in object constructors.
2. **Prototype properties problem**: hidden classes and property caches optimize accesses of properties directly stored in the object. They do not optimize accesses of properties stored in one of the objects composing the prototype chain.
3. **Polymorphic properties problem**, as property caches require strict hidden class equivalence for optimizing accesses, polymorphic data structures and polymorphic method invocations need special treatment to not be left unoptimized. This has been addressed by the *Polymorphic Inline Cache* technique proposed by Holzle *et al.* in previous studies, which resorts to a dynamic search in the cache history. As a linear or binary search is involved, it is not as efficient as plain property caches.

Problem 1 is critical for all existing JavaScript programs as it impacts the performance of object construction. Problems 2 and 3 will become prominent with the advent of ECMAScript 6 class-like programming style that is backed up by object prototypes. We propose solutions to these problems. At the cost of one extra test inserted at each property access, we optimize prototype property accesses. Resorting to a static analysis, we propose a technique that we call *speculative caches* for optimizing object construction.

Trading memory space for speed, we propose *cache property tables* that enable accessing polymorphic objects in constant time. For the analogy with C++ virtual tables we call these cache tables *vtables*.

We have implemented these techniques in *Hopc*, the *Hop* static JavaScript compiler and we have presented them in a conference publication [17]. We have shown how the complement and enhance property caches used for accessing object properties of JavaScript like languages. We have shown that they take over classical caches when the searched property is either stored in an object of the prototype chain or defined using accessors. They also support efficiently polymorphic and megamorphic property accesses. Finally, they also support efficient object extensions. These techniques do not apply as frequently as simple property caches that cover a vast majority of accesses. However, since they impose no overhead when not used, they can be integrated in any existing system at no run time cost. We have validated the approach with an experimental report based that shown that the presented techniques improve performance in situations where simple cache miss.

6.1.2. Secure JavaScript

Whereas the dynamic nature of JavaScript plays an essential role in the advantages it offers for easy and fast development, a malicious JavaScript program can easily break the integrity and confidentiality of a web or IoT application. JavaScript dynamic semantics and sharing are deeply intricated and attacker code can trivially exploit these.

We have developed a compiler, called SecureJS to offer security guarantees for JavaScript on clients, servers, and IoT devices. Our compiler is applicable to ECMAScript 5th legacy code, which in particular means that we allow for built-in JavaScript functions. Moreover, we go beyond the JavaScript language and handle a common web API, XMLHttpRequest module. The challenge is to cover most of the JavaScript language efficiently while providing strong security guarantees. For the latter, we formally define and prove the compiler's security guarantees by means of a new security property, coined as *dynamic delimited release*, for JavaScript integrity and confidentiality.

Compiled programs can be effortlessly deployed in client, server, and IoT JavaScript environments and do not require an external isolation mechanism to preserve integrity and confidentiality.

We have validated SecureJS experimentally using ECMAScript Test262 test suits. First, we have shown that SecureJS preserves the correct SecureJS semantics. Second, we have shown that it successfully implements the memory isolation needed to enforce the security property.

The current SecureJS implementation as been architectured to support low-power platforms that only supports ECMAScript 5. In the future we plan to accommodate more recent version of JavaScript for the platforms that supports it. This will extend the possibility of communications between trusted and untrusted codes and this will enable more efficient implementation techniques. A paper describing this work is currently under submission.

6.1.3. Empowering Web Applications with Browser Extensions

Browser extensions are third party programs, tightly integrated to browsers, where they execute with elevated privileges in order to provide users with additional functionalities. Unlike web applications, extensions are not subject to the Same Origin Policy (SOP) and therefore can read and write user data on any web application. They also have access to sensitive user information including browsing history, bookmarks, credentials (cookies) and list of installed extensions. They have access to a permanent storage in which they can store data as long as they are installed in the user's browser. They can trigger the download of arbitrary files and save them on the user's device. For security reasons, browser extensions and web applications are executed in separate contexts. Nonetheless, in all major browsers, extensions and web applications can interact by exchanging messages. Through these communication channels, a web application can exploit extension privileged capabilities and thereby access and exfiltrate sensitive user information.

We have analyzed the communication interfaces exposed to web applications by Chrome, Firefox and Opera browser extensions [18]. As a result, we identified many extensions that web applications can exploit to access privileged capabilities. Through extensions' APIS, web applications can bypass SOP and access user data on any other web application, access user credentials (cookies), browsing history, bookmarks, list of installed extensions, extensions storage, and download and save arbitrary files in the user's device. Our results demonstrate that the communications between browser extensions and web applications pose serious security and privacy threats to browsers, web applications and more importantly to users. We discuss countermeasures and proposals, and believe that our study and in particular the tool we used to detect and exploit these threats, can be used as part of extensions review process by browser vendors to help them identify and fix the aforementioned problems in extensions.

6.2. Timing-side channels attacks

We have pursued our studies on foundations of language-based security following two axes on timing-side channels research:

6.2.1. Speculative constant time

The most robust way to deal with timing side-channels in software is via *constant-time* programming—the paradigm used to implement almost all modern cryptography. Constant-time programs can neither branch on secrets nor access memory based on secret data. These restrictions ensure that programs do not leak secret information via timing side channels, at least on hardware *without* microarchitectural features. However, microarchitectural features are a major source of timing side channels as the growing list of attacks (Spectre, Meltdown, etc) is showing. Moreover code deemed to be constant-time in the usual sense may in fact leak information on processors with microarchitectural features. Thus the decade-old constant-time recipes are no longer enough. We lay the foundations for constant-time in the presence of micro-architectural features that have been exploited in recent attacks: out-of-order and speculative execution. We focus on constant-time for two key reasons. First, *impact*: constant-time programming is largely used in narrow, high-assurance code—mostly cryptographic implementations—where developers already go to great lengths to eliminate leaks via side-channels. Second, *foundations:* constant-time programming is already rooted in foundations, with well-defined semantics. These semantics consider very powerful attackers have control over the cache and the scheduler. A nice effect of considering powerful attackers is that the semantics can already overlook many hardware details—e.g., since the cache is adversarially controlled there is no point in modeling it precisely—making constant-time amenable to automated verification and enforcement.

We have first defined a semantics for an abstract, three-stage (fetch, execute, and retire) machine. This machine supports out-of-order and speculative execution by modeling *reorder buffers* and *transient instructions*, respectively. Our semantics assumes that attackers have complete control over microarchitectural features (e.g., the branch target predictor), and uses adversarial execution *directives* to model adversary's control over predictors. We have then defined *speculative constant-time*, the counterpart of *constant-time* for machines with out-of-order and speculative execution. This definition has allowed us to discover microarchitectural side channels in a principled way—all four classes of Spectre attacks as classified by Canella et al., for example, manifest as violation of our constant-time property. Our semantics even revealed a new Spectre variant, that exploits the aliasing predictor. The variant can be disabled by unsetting a flag, by illusttrates the usefulness of our semantics. This study is described in a paper currently submitted.

6.2.2. Remote timing attacks

A common approach to deal with timing attacks is based on preventing secrets from affecting the execution time, thus achieving security with respect to a strong, *local* attacker who can measure the timing of program runs. Another approach is to allow branching on secrets but prohibit any subsequent attacker-visible side effects of the program. It is sometimes used to handle *internal timing* leaks, i.e., when the timing behavior of threads affects the interleaving of attacker-visible events via the scheduler.

While these approaches are compatible with strong attackers, they are highly restrictive for program runs as soon as they branch on a secret. It is commonly accepted that "adhering to constant-time programming is hard" and "doing so requires the use of low-level programming languages or compiler knowledge, and forces developers to deviate from conventional programming practices".

This restrictiveness stems from the fact that there are many ways to set up timing leaks in a program. For example, after branching on a secret the program might take different time in the branches because of: (i) more time-consuming operations in one of the branches, (ii) cache effects, when in one of the branches data or instructions are cached but not in the other branch, (iii) garbage collection (GC) when in one of the branches GC is triggered but not in the other branch, and (iv) just-in-time (JIT) compilation, when in one of the branches a JIT-compiled function is called but not in the other branch. Researchers have been painstakingly addressing these types of leaks, often by creating mechanisms that are specific to some of these types. Because of the intricacies of each type, addressing their combination poses a major challenge, which these approaches have largely yet to address.

This motivates a general mechanism to tackle timing leaks independently of their type. However, rather than combining enforcement for the different types of timing leaks for strong local attackers, is there a setting where the capabilities of attackers are perhaps not as strong, enabling us to design a general and less restrictive mechanism for a variety of timing attacks with respect to a weaker attacker?

We focus on timing leaks under *remote* execution. A key difference is that the remote attacker does not generally have a reference point of when a program run has started or finished, which significantly restricts attacker capabilities.

We illustrate remote timing attacks by two settings: a server-side setting of IoT apps where apps that manipulate private information run on a server and a client-side setting where e-voting code runs in a browser.

IFTTT (If This Then That), Zapier, and Microsoft Flow are popular IoT platforms driven by enduser programming. App makers publish their apps on these platforms. Upon installation apps manipulate sensitive information, connecting cyberphysical "things" (e.g., smart homes, cars, and fitness armbands) to online services (e.g., Google and Dropbox) and social networks (e.g., Facebook and Twitter). An important security goal is to prevent a malicious app from leaking private information of a user to the attacker.

Recent research identifies ways to leak private information by IoT apps and suggests tracking information flows in IoT apps to control these leaks. The suggested mechanisms perform data-flow (*explicit*) and control-flow (*implicit*) tracking. Unfortunately, they do not address timing leaks, implying that a malicious app maker can still exfiltrate private information, even if the app is subject to the security restrictions imposed by the proposed mechanisms.

In addition, Verificatum, an advanced client-side cryptographic library for e-voting motivates the question of remote timing leaks with respect to attackers who can observe the presence of encrypted messages on the network.

This leads us to the following general research questions:

1. What is the right model for remote timing attacks?
2. How do we rule out remote timing leaks without rejecting useful secure programs?
3. How do we generalize enforcement to multiple security levels?
4. How do we harden existing information flow tools to track remote timing leaks?
5. Are there case studies to give evidence for the feasibility of the approach?

To help answering these questions, we propose an extensional knowledge-based security characterization that captures the essence of remote timing attacks. In contrast to the local attacker that counts execution steps/time since the beginning of the execution, our model of the remote attacker is only allowed to observe inputs and outputs on attacker-visible channels, along with their timestamps. At the same time, the attacker is in charge of the potentially malicious code with capabilities to access the clock, in line with assumptions about remote execution on IoT app platforms and e-voting clients.

A timing leak is typically enabled by branching on a secret and taking different time or exhibiting different cache behavior in the branches. However, as discussed earlier, it is desirable to avoid restrictive options like forcing the execution to take constant time, prohibiting attacker-visible output any time after the branching, or prohibiting branching on a secret in the first place.

Our key observation is that for a remote attacker to successfully set up and exploit a timing leak, program behavior must follow the following pattern: (i) branching on a secret takes place in a program run, and either (ii-a) the branching is followed by more than one attacker-visible I/O event, or (ii-b) the branching is followed by one attacker-visible I/O event, and prior to the branching there is either an attacker-visible I/O event or a reading to the clock.

Based on this pattern, we design Clockwork, a monitor that rules out timing leaks. Our mechanism pushes for permissiveness. For example, runs (free of explicit and implicit flows) that do not access the clock and only have one attacker-visible I/O event are accepted.

Runs that do not perform attacker-visible I/O after branching on a secret are accepted as well. As we will see, these kinds of runs are frequently encountered in secure IoT and e-voting apps.

We implement our monitor for JavaScript, leveraging JSFlow, a state-of-the-art information flow tracker for JavaScript. We demonstrate the feasibility of the approach on a case study with IFTTT, showing how to prevent malicious app makers from exfiltrating users' private information via timing, and a case study with Verificatum, showing how to track remote timing attacks with respect to network attackers. Our case studies demonstrate both the security and permissiveness. While apps with timing leaks are rejected, benign apps that use clock and I/O operations in a non-trivial fashion are accepted.

6.3. Security analysis of ElGamal implementations

Throughout the last century, especially with the beginning of public key cryptography due to Diffie-Hellman, many cryptographic schemes have been proposed. Their security depends on mathematically complex problems such as integer factorization and discrete logarithm. In fact, it is thought that a cryptographic scheme is secure if it resists cryptographic attacks over a long period of time. On one hand, since certain schemes may take several years before being widely studied in depth, they become vulnerable as time passes. On the other hand, a cryptographic scheme is a provable one, if it resists cryptographic attacks relying on mathematical hypothesis.

Being easily adaptable to many kinds of cryptographic groups, the ElGamal encryption scheme enjoys homomorphic properties while remaining semantically secure , provided that the Decisional Diffie-Hellman (DDH) assumption holds on the chosen group. While the homomorphic property forbids resistance against chosen ciphertext attacks, it is very convenient for voting systems. The ElGamal encryption scheme is the most extensively used alternative to RSA, and it is the homomorphic encryption scheme almost exclusively used for voting systems. Moreover, ElGamal is the only homomorphic encryption scheme implemented by default in many hardware security modules.

In order to be provable secure, ElGamal encryption needs to be implemented on top of a group verifying the Decisional Diffie-Hellman (DDH) assumption. Since this assumption does not hold for all groups, one may have to wrap an encoding and a decoding phase to ElGamal to be able to have a generic encryption scheme.

We have submitted a paper that studies ElGamal encryption scheme libraries in order to identify which implementations respect the DDH assumption. The paper presents an analysis of 25 libraries that implement ElGamal encryption scheme in the wild. We focus our analysis on understanding whether the DDH assumption is respected in these implementations, ensuring a secure scheme in which no information about the original message could be leaked. The DDH assumption is crucial for the security of ElGamal because it ensures indistinguishability under chosen-plaintext attacks (IND-CPA). Without the DDH assumption, encryption mechanisms may leak one bit of information about the plaintext and endager the security of the electoral system as one bit has the ability to completely invalidate privacy in an election. One way to comply with the DDH assumption is by using groups of prime order. In particular, when adopting safe primes, one can ensure the existence of a *large* prime order subgroup and restrict messages to belong to this subgroup. Mapping plaintexts into subgroups is called message encoding. Such encoding necessitates to be efficient and precisely invertible to allow decoding after the decryption.

Our results show that out of 25 analyzed libraries, 20 are wrongly implemented because they do not respect the conditions to achieve IND-CPA security under the DDH assumption. This means that encryptions using ElGamal from any of these 20 libraries leak one bit of information.

From the 5 libraries which respect the DDH assumption, we also study and compare various encoding and decoding techniques. We identify four different message encoding and decoding techniques and discuss the different designs and conclude which implementation is more efficient for voting systems.

6.4. Measurement and Detection of Web Tracking

6.4.1. Missed by Filter Lists: Detecting Unknown Third-Party Trackers with Invisible Pixels

The Web has become an essential part of our lives: billions are using Web applications on a daily basis and while doing so, are placing *digital traces* on millions of websites. Such traces allow advertising companies, as well as data brokers to continuously profit from collecting a vast amount of data associated to the users.

Web tracking has been extensively studied over the last decade. To detect tracking, most of the research studies and user tools rely on *consumer protection lists*. EasyList [0] and EasyPrivacy [0] (EL&EP) are the most popular publicly maintained blacklist of know advertising and tracking domains, used by the popular browser extensions AdBlock Plus [0] and uBlockOrigin [0]. Disconnect [0] is another very popular list for detecting domains known for tracking, used in Disconnect browser extension [0] and in integrated tracking protection of Firefox browser. Relying on EL&EP or Disconnect became the *de facto* approach to detect third-party tracking requests in privacy and measurement community. However it is well-known that these lists detect only known tracking and ad-related requests, and a tracker can easily avoid this detection by registering a new domain or changing the parameters of the request.

Our contributions: To evaluate the effectiveness of filter lists, we propose a new, fine-grained behavior-based tracking detection. Our results are based on a stateful dataset of 8K domains with a total of 800K pages generating 4M third-party requests. We make the following contributions:

- *We analyse all the requests and responses that lead to invisible pixels (by "invisible pixels" we mean* 1×1 *pixel images or images without content).* Pixels are routinely used by trackers to send information or third-party cookies back to their servers: the simplest way to do it is to create a URL containing useful information, and to dynamically add an image tag into a webpage. This makes invisible pixels *the perfect suspects for tracking* and propose a new classification of tracking behaviors. Our results show that pixels are still widely deployed: they are present on more than 94% of domains and constitute 35.66% of all third-party images. We found out that pixels are responsible only for 23.34% of tracking requests, and the most popular tracking content are scripts: a mere loading of scripts is responsible for 34.36% of tracking requests.
- *We uncover hidden collaborations between third parties.* We applied our classification on more than 4M third-party requests collected in our crawl. We have detected new categories of tracking and collaborations between domains. We show that domains sync first party cookies through a *first to third party cookie syncing*. This tracking appears on 67.96% of websites.
- *We show that filter lists miss a significant number of cookie-based tracking.* Our evaluation of the effectiveness of EasyList&EasyPrivacy and Disconnect lists shows that they respectively miss 25.22% and 30.34% of the trackers that we detect. Moreover, we find that if we combine all three lists, 379,245 requests originating from 8,744 domains still track users on 68.70% of websites.
- *We show that privacy browser extensions miss a significant number of cookie-based tracking.* By evaluating the popular privacy protection extensions: Adblock, Ghostery, Disconnect, and Privacy Badger, we show that Ghostery is the most efficient among them and that all extensions fail to block at least 24% of tracking requests.

This paper [15] has been accepted for publication at the Privacy Enhancing Technologies Symposium (PETs) 2020.

6.4.2. A survey on Browser Fingerprinting

This year, we have conducted a survey on the research performed in the domain of browser fingerprinting, while providing an accessible entry point to newcomers in the field. We explain how this technique works and where it stems from. We analyze the related work in detail to understand the composition of modern fingerprints and see how this technique is currently used online. We systematize existing defense solutions into different categories and detail the current challenges yet to overcome.

[0]https://easylist.to/
[0]https://easylist.to/easylist/easyprivacy.txt
[0]https://adblockplus.org/
[0]https://github.com/gorhill/uBlock
[0]https://disconnect.me/trackerprotection/blocked
[0]https://disconnect.me/

A *browser fingerprint* is a set of information related to a user's device from the hardware to the operating system to the browser and its configuration. *Browser fingerprinting* refers to the process of collecting information through a web browser to build a fingerprint of a device. Via a script running inside a browser, a server can collect a wide variety of information from public interfaces called Application Programming Interface (API) and HTTP headers. An API is an interface that provides an entry point to specific objects and functions. While some APIs require a permission to be accessed like the microphone or the camera, most of them are freely accessible from any JavaScript script rendering the information collection trivial. Contrarily to other identification techniques like cookies that rely on a unique identifier (ID) directly stored inside the browser, browser fingerprinting is qualified as completely *stateless*. It does not leave any trace as it does not require the storage of information inside the browser.

The goal of this work is twofold: first, to provide an accessible entry point for newcomers by systematizing existing work, and second, to form the foundations for future research in the domain by eliciting the current challenges yet to overcome. We accomplish these goals with the following contributions:

- A thorough survey of the research conducted in the domain of browser fingerprinting with a summary of the framework used to evaluate the uniqueness of browser fingerprints and their adoption on the web.
- An overview of how this technique is currently used in both research and industry.
- A taxonomy that classifies existing defense mechanisms into different categories, providing a high-level view of the benefits and drawbacks of each of these techniques.
- A discussion about the current state of browser fingerprinting and the challenges it is currently facing on the science, technological, business, and legislative aspects.

This work has been submitted for publication at an international journal.

6.5. Security Analysis of GDPR Subject Access Request Procedures

With the GDPR in place since May 2018, the rights of the European users have been strengthened. The GDPR defines users' rights and aims at protecting their personal data. Every European Data Protection Authority (DPA) provides advices, explanations and recommendations on the use of these rights. However, the GDPR does not provide any prescriptive requirements on how to authenticate a data subject request. This lack of concrete description undermines the practical effect of the GDPR: it hampers the way to exercise the subject access right, to check the lawfulness of the processing and to enforce the derived legal rights therefrom (erasure, rectification, restriction, etc).

Every data subject would like to benefit from the rights specified in GDPR, but still wonders: *How do I exercise my access right?How do I prove my identity to the controller?* These questions are critical to build trust between the data subject and the controller. The data subject is concerned with threats like *impersonation* and *abusive identity check*. Impersonation is the case of a malicious party who attempts to abuse the subject access request (SAR) by impersonating a subject to a controller. Abusive identity check occurs when a data controller is too curious and verifies the identity of a subject by asking irrelevant and unnecessary information like an electricity bill or government issued documents.

Symmetrically, every data controller needs to know how to proceed when they receive an access request: *Is the request legitimate? What is necessary to identify the subject's data?* These concerns aggravate when controllers deal with indirectly-linked identifiers, such as IP addresses, or when they have no prior contact with data subjects, as in *Google Spain* [0]. Most of all, data controllers want to avoid data breaches, as it can result in legal proceedings and heavy fines. Such consequence occurs in two cases: *(i)* the data controller releases data to an illegitimate subject, or *(ii)* he releases data of a subject A to a legitimate subject B.

[0] Google Spain SL and Google Inc. v Agencia Española de Protección de Datos (AEPD) and Mario Costeja González, Case C-131/12, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:62012CJ0131&from=EN

All these questions concern the authentication procedure between the data subject and the controller. They both share a common interest in holding a strong authentication procedure to prevent impersonation and data breaches. The subject must be careful during the authentication procedure, as for providing too much personal information could compromise her right of privacy. Additionally, the controller needs to ask the appropriate information to identify the subject's data without ambiguity. There is clearly a tension during this authentication act between the controller, who tries to get as much information as possible, and the data subject who wants to provide as little as possible. Plausibly, subject access rights can probably increase the incidence of personal records being accidentally or deliberately opened to unauthorised third parties [22].

This work studies *the tension during the authentication between the data subject and the data controller*. We first evaluate the threats to the SAR authentication procedure and then we analyze the recommendations of 28 DPAs of European Union countries. We observe that four of them can potentially lead to abusive identity check. On the positive side, six of them are recommending to enforce the data minimization principle during authentication. This principle, on one hand, protects the right to privacy of data subjects, and on the other hand prevents data controllers to massively collect personal data that is not needed for authentication, thus preventing abusive identity check.

We have then evaluated the authentication procedure when exercising the access right of the 50 most popular websites and 30 third-party tracking services. Several popular websites require to systematically provide a national identity card or government-issued documents to authenticate the data subject. Among third-party tracking services, 9 of them additionally to cookies demand other personal data from the data subjects, like the identity card or the full name. We explain that such demands are not justified because additional information can not prove the ownership of the cookie.

We then provide guidelines to Data Protection Authorities, website owners and third party services on how to authenticate data subjects safely while protecting their identities, and without requesting additional unnecessary information (complying with the data minimization principle). More precisely, we explain how data controllers and data subjects must interact and how digital identifiers can be redesigned to be compliant with the GDPR.

This work has been published at the Annual Privacy Forum (APF) 2019 [13].

6.6. Measuring Legal Compliance of Cookie Banners

6.6.1. Deciphering EU legal requirements on consent and technical means to verify compliance of cookie banners

In this work, we analyze the legal requirements on how cookie banners are supposed to be implemented to be fully compliant with the ePrivacy Directive and the GDPR.

Our contribution resides in the definition of 17 operational and fine-grained requirements on cookie banner design that are legally compliant, and moreover, we define whether and when the verification of compliance of each requirement is technically feasible.

The definition of requirements emerges from a joint interdisciplinary analysis composed of lawyers and computer scientists in the domain of web tracking technologies. As such, while some requirements are provided by explicitly codified legal sources, others result from the domain-expertise of computer scientists. In our work, we match each requirement against existing cookie banners design of websites. For each requirement, we exemplify with compliant and non-compliant cookie banners.

As an outcome of a technical assessment, we verify per requirement if technical (with computer science tools) or manual (with any human operator) verification is needed to assess compliance of consent and we also show which requirements are impossible to verify with certainty in the current architecture of the Web. For example, we explain how the GDPR's requirement for revocable consent could be implemented in practice: when consent is revoked, the publisher should delete the consent cookie and communicate the withdrawal to all third parties who have previously received consent.

With this approach we aim to support practically-minded parties (compliance officers, regulators, privacy NGOs, researchers, and computer scientists) to assess compliance and detect violations in cookie banners' design and implementation, specially under the current revision of the EU ePrivacy framework.

This working paper is submitted for publication.

6.6.2. *Measuring Legal Compliance of Banners from IAB Europe's Transparency and Consent Framework*

As a result of the GDPR and the ePrivacy Directive, (known as “cookie law”), European users encounter cookie banners on almost every website. Many of such banners are implemented by Consent Management Providers (CMPs), who respect the IAB Europe's Transparency and Consent Framework (TCF). Via cookie banners, CMPs collect and disseminate user consent to third parties. In this work, we systematically study IAB Europe's TCF and analyze consent stored behind the user interface of TCF cookie banners. We analyze the GDPR and the ePrivacy Directive to identify legal violations in implementations of cookie banners based on the storage of consent and detect such violations by crawling 22 949 European websites.

With two automatic and semi-automatic crawl campaigns, we detect violations, and we find that: 175 websites register positive consent even if the user has not made their choice; 236 websites nudge the users towards accepting consent by pre-selecting options; and 39 websites store a positive consent even if the user has explicitly opted out. Performing extensive tests on 560 websites, we find at least one violation in 54% of them.

Finally, we provide a browser extension called "Cookie Glasses" to facilitate manual detection of violations for regular users and Data Protection Authorities.

This working paper is submitted for publication at an international conference.

6.7. Session Types

Session types describe communication protocols between two or more parties by specifying the sequence of exchanged messages and their functionality (sender, receiver and type of carried data). They may be viewed as the analogue, for concurrency and distribution, of data types for sequential computation. Originally conceived as a static analysis technique for an enhanced version of the π-calculus, session types have been subsequently embedded into a range of functional, concurrent, and object-oriented programming languages.

While binary sessions can be described by a single session type, multiparty sessions require two kinds of types: a *global type* that describes the whole session protocol, and *local types* that describe the contributions of the various participants to the protocol. The key requirement to achieve safety properties such as the absence of communication errors and deadlock-freedom, is that the local types of the processes implementing the participants be obtained as projections from the same global type (the one describing the session protocol).

We have pursued our work on multiparty session types along four main directions, in collaboration with colleagues from the Universities of Groningen, Luxemburg, Nice Sophia Antipolis, Turin and Eastern Piedmont. One of these directions is described in Section 6.8.3, the others are described below.

6.7.1. *Reversible Sessions with Flexible Choices*

Reversibility has been an active trend of research for the last fifteen years. A reversible computation is a computation that may roll back to a past state. Allowing computations to reverse is a means to improve system flexibility and reliability. In the setting of concurrent process calculi, reversible computations have been first studied for Milner's calculus CCS, then for the π-calculus, and only recently for typed session calculi.

Following up on our previous work on concurrent reversible sessions, we studied a simpler but somewhat more realistic calculus for concurrent reversible multiparty sessions, equipped with a flexible choice operator allowing for different sets of participants in each branch of a choice. This operator was inspired by the notion of *connecting communication* introduced by other authors to describe protocols with optional participants. Our calculus supports a compact representation of the *history* of processes and types, which facilitates the definition of rollback. Moreover, it implements a fine-tuned strategy for backward computation, where only some specific participants, the “choice leaders”, can trigger a rollback. We present a session type system for this calculus and show that it enforces the expected properties of session fidelity, forward progress and backward progress. This work has been published in the journal [11].

6.7.2. Multiparty Sessions with Internal Delegation

We have investigated a new form of *delegation* for multiparty session calculi. Usually, the delegation mechanism allows a session participant to appoint a participant in another session to act on her behalf. This means that delegation is inherently an inter-session mechanism, which requires session interleaving. Hence delegation falls outside the descriptive power of global types, which specify single multiparty sessions. As a consequence, properties such as deadlock-freedom or lock-freedom are difficult to ensure in the presence of delegation. In our work, we adopt a different view of delegation, by allowing participants to delegate tasks to each other within the same multiparty session. This way, delegation occurs within a single session (whence the name "internal delegation") and may be captured by its global type. To increase flexibility in the use of delegation, we use again connecting communications, in order to accommodate optional participants in the branches of choices. By this means, we are also able to express conditional delegation. We present a session type system based on global types with internal delegation, and show that it ensures the usual safety properties of multiparty sessions, together with a progress property.

This work has been published in a special issue of TCS dedicated to Maurice Nivat [12].

6.7.3. Event Structure Semantics for Multiparty Sessions

In the work [14] we investigate the relationship between multiparty session calculi and other concurrency models, by focussing on Event Structures as proposed in the late 80's. We consider a standard multiparty session calculus where sessions are described as networks of sequential processes, and each process implements a participant in the session. We propose an interpretation of such networks as *Flow Event Structures* (FESs) (a subclass of Winskel's Stable Event Structures), which allows concurrency between session communications to be explicitly represented. We then introduce global types for these networks, and define an interpretation of global types as *Prime Event Structures* (PESs). Since the syntax of global types does not allow all the concurrency among communications to be expressed, the events of the associated PES need to be defined as equivalence classes of communication sequences up to *permutation equivalence*. We show that when a network is typable by a global type, the FES semantics of the former is equivalent, in a precise technical sense, to the PES semantics of the latter.

This work has been published in a volume dedicated to Rocco De Nicola on the occasion of his 65th birthday [14]. An extended version is available as Research Report [21].

6.8. Web Reactive Programming

6.8.1. HipHop.js

This year, we have completed the design of the *HipHop* programming language. We have finalized the syntax of core instructions, stabilized the interfacing with JavaScript, added variables that supplement signals in local computation, and we have completed the synchronous/asynchronous connections. A paper describing this final version of the paper is currently under submission.

We have also improved significantly the *HipHop* implementation for speed and for debugging.

- Leveraging on the *Hop* speed improvement and by adding a new *HipHop* compilation stage we have been able to accelerate by a factor of about 10$\times$ the intrinsic execution time of the reactive machine. The optimization removes nets of the virtual electronic circuits that are generated by the *HipHop* compiler by propagating constant and by collapsing identical nodes. This contributions is included in the main development tree (https://github.com/manuel-serrano/hiphop).
- A central difficulty of the synchronous reactive programming is debugging and error messages. The *HipHop* compilation roughly consists in implementing efficiently and compactly a deterministic automata that represents the user source code. If a causality error is detected during that compilation, unless a precise isolation of the user source code fragments that are involved in that error, the error

message reported to the user is so imprecise that fixing the problem is difficult. We have implemented an algorithm based on *strongly connected components* that enables the needed isolation. This experimental feature is currently publicly available via a dedicating development branch under the *HipHop* github repository.

6.8.2. Interactive music composition

The production of a piece of music by school children using the Skini platform as part of SACEM's call for projects "Fabrique à musique" (Music Factory) was initiated in 2019. It ended in 2019 with the realization of a show at the Nice Conservatory in May 2019. The music piece thus created implemented all of Skini's functionalities, from the distributed sequencer that allowed the pupils to design the basic material, to the control of the live orchestration, not by the audience in this case, but by the 24 students who participated in the project. Following the success of this first experiment, the project is being extended for 2020/2021 by Inria, with another class, as part of the "les cordées de la réussite" program.

Beyond the improvement of the system, and in particular of the distributed sequencer, thanks to the significant performance improvements of HipHop.js, it has been possible to enrich the controls on musical orchestrations by driving transformation elements of Skini's basic elements (the patterns) such as transpositions, use of patterns of different durations, music mode conversions, or tempo control. The coupling of these new processes has enriched the range of possibilities for interaction and has opened up new horizons in the field of pattern-based generative music.

In terms of musical creation, we have been able to implement orchestrations using the platform's new technical possibilities in order to reduce musical processes perceived as too automatic. We can note as convincing results: the possibility to break the too big symmetries on the durations of the patterns, and the variations of tempi subjected to various controls. We were able to demonstrate that with the same HipHop.js music orchestration program, we could efficiently generate very different musical pieces.

Skini music composition has been described in a conference paper presented in the NIME 2019 conference [16].

6.8.3. Multiparty Reactive Sessions

Ensuring that communication-centric systems interact according to an intended protocol is a challenging problem, particularly for systems with some reactive or timed components. To rise to this challenge, we have studied the integration of Session-based Concurrency and Synchronous Reactive Programming (SRP).

Synchronous Reactive Programming (SRP) is a well-established programming paradigm whose essential features are logical instants, broadcast events and event-based preemption. This makes it an ideal vehicle for the specification and analysis of timed reactive systems. *Session-based Concurrency* is the model of concurrent computation induced by session types.

In the Research Report [20], we propose a multiparty session calculus enriched with features from SRP. In this calculus, protocol participants may broadcast messages, suspend themselves while waiting for a message, and react to events. Our main contribution is a session type system for this calculus, which enforces session correctness for non-interleaved sessions and additionally ensures *input timeliness*, a time-related property that entails livelock-freedom (while deadlock-freedom holds by construction in our calculus). Our type system departs significantly from existing ones, specifically as it captures the notion of “logical instant” typical of SRP.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Grants with Industry

The ANSWER project (Advanced aNd Secured Web Experience and seaRch) is lead by the QWANT search engine and the Inria Sophia Antipolis Méditerranée research center. This proposal is the winner of the "Grand

Challenges du Numérique" (BPI) and aims to develop the new version of the search engine http://www.qwant.com with radical innovations in terms of search criteria, indexed content and privacy of users. Nataliia Bielova, Manuel Serrano and Tamara Rezk are involved in this project. The project started on January 1, 2018. In the context of this project, we got

- with Arnaud Legout from the DIANA project-team a funding for a 3 years Ph.D. student to work on Web tracking technologies and privacy protection. Imane Fouad was hired to work on this project.
- a funding for 18 months Postdoc to work on Web application security. Yoon Seok Ko has worked on this project as a postdoc.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. Skini

Skini was used for the production of a musical piece as part of SACEM's "Music Factory" program in collaboration with the *CIRM* in Nice and the *Conservatory of Nice*. This piece was designed, and produced in May at the Nice Conservatory, by 12 years old pupils of the Nucéra secondary school in Nice after a dozen working sessions within the school. This production is followed by a similar project with 14 years old pupils as part of the "Cordé de la résussite" programme run by Inria with the objective of a musical production in spring 2020.

8.2. National Initiatives

8.2.1. ANR CISC

The CISC project (Certified IoT Secure Compilation) is funded by the ANR for 42 months, starting in April 2018. The goal of the CISC project is to provide strong security and privacy guarantees for IoT applications by means of a language to orchestrate IoT applicatoins from the microcontroller to the cloud. Tamara Rezk coordinates this project, and Manuel Serrano, Ilaria Castellani and Nataliia Bielova participate in the project. The partners of this project are Inria teams Celtique, Indes and Privatics, and Collège de France.

8.2.2. ANR PrivaWeb

The PrivaWeb project (Privacy Protection and ePrivacy Compliance for Web Users) is funded by the ANR JCJC program for 48 months, started in December 2018. PrivaWeb aims at developing new methods for detection of new Web tracking technologies and new tools to integrate in existing Web applications that seamlessly protect privacy of users.

Nataliia Bielova coordinates this project.

8.2.3. PIA ANSWER

The ANSWER project (Advanced aNd Secured Web Experience and seaRch) is funded by PIA program for 36 months, starting January 1, 2018. The aim of the ANSWER project is to develop the new version of the http://www.qwant.com search engine by introducing radical innovations in terms of search criteria as well as indexed content and users' privacy. The partners of this project include QWANT and Inria teams Wimmics, Indes, Neo and Diana.

8.3. Inria Internal Funding

8.3.1. IPL SPAI

SPAI (Security Program Analyses for the IoT) is an IPL (Inria Project Lab), with a duration of 4 years, started on April 2018. Members of the Antique, Celtique, Indes, Kairos, and Privatics Inria teams are involved in the SPAI IPL.

SPAI is concerned with the design of program analyses for a multitier language for the Internet of Things (IoT). The programming abstractions will allow us to reason about IoT systems from microcontrollers to the cloud. Relying on the Inria multitier language Hop.js semantics and the current Coq formalizations of JavaScript semantics, we plan to certify these analyses in order to guarantee the impossibility of security properties violations and implement security properties' enforcements by compilation.

8.3.2. AEx DATA4US

DATA4US is a joint project between two teams in Inria Sophia Antipolis and Inria Grenoble - Rhône-Alpes that tackles these interdisciplinary challenges by establishing collaborations with researchers in Law. Members are Nataliia Bielova (INDES) and Cedric Lauradoux (Privatics).

DATA4US will propose a new architecture for exercising access rights that will explain the users whether their data has been legally collected and eventually help contact DPAs for further investigations.

8.3.3. ADT FingerKit

In the context of the Inria ADT call, we are involved in a *FingerKit: a Cloud Platform to Study Browser Fingerprints at Large*, lead by Walter Rudametkin from the Spirals project-team. The funding for a two year engineering position for the 2018-2020 period was obtained and an engineer is hired in Spirals project-team. Nataliia Bielova is part of this project.

8.4. European Initiatives

8.4.1. H2020 Sparta

SPARTA (Strategic Programs for Advanced Research and Technology in Europe) is a novel cybersecurity competence network, with the objective to collaboratively develop and implement top-tier research and innovation actions. Strongly guided by concrete challenges forming an ambitious Cybersecurity Research & Innovation Roadmap, SPARTA will tackle hard innovation challenges, leading the way in building transformative capabilities and forming a world-leading cybersecurity competence network across the EU. Four initial research and innovation programs will push the boundaries to deliver advanced solutions to cover emerging issues, with applications from basic human needs to economic activities, technologies, and sovereignty.

See also: https://www.sparta.eu/

8.4.2. Collaborations in European Programs, Except FP7 & H2020

8.4.2.1. ICT Cost Action IC1405 on Reversible Computation

Program: ICT COST Action IC1405

Project title: Reversible computation - extending horizons of computing

Duration: November 2014 - April 2019

Coordinator: Irek Ulidowski, University of Leicester

Other partners: several research groups, belonging to 23 European countries.

Abstract: Reversible computation is an emerging paradigm that extends the standard mode of computation with the ability to execute in reverse. It aims to deliver novel computing devices and software, and to enhance traditional systems. The potential benefits include the design of reversible logic gates and circuits - leading to low-power computing and innovative hardware for green ICT, new conceptual frameworks and language abstractions, and software tools for reliable and recovery-oriented distributed systems. This was the first European network of excellence aimed at coordinating research on reversible computation.

See also: http://www.revcomp.eu

8.4.2.2. Bilateral PICS project SuCCeSS

Program: CNRS Bilaterial PICS project

Project acronym: SuCCeSS

Project title: Security, Adaptability and time in Communication Centric Software Systems

Duration: June 2016 - June 2019

Coordinator: Cinzia Di Giusto, I3S, Sophia Antipolis

Partners: I3S, Inria, University of Groningen

Abstract: The project SuCCeSS was a CNRS-funded "Projet coopératif" (PICS 07313), involving two French teams in Sophia Antipolis (the MDSC team at the laboratory I3S, acting as coordinator, and the INDES team) and one Dutch team at the University of Groningen. The objective of the project was to study formal models for reliable distributed communication-centric software systems. The project focussed on analysis and validation techniques based on behavioural types, aimed at enforcing various properties (safety, liveness, security) of structured communications.

8.5. International Initiatives

8.5.1. Inria International Partners

8.5.1.1. Informal International Partners

- We are collaborating with Professor of Law, Frederik Zuiderveen Borgesius from the Radbound University Nijmegen and Amsterdam Law School (double affiliation). We are studying General Data Protection Regulation (GDPR) and ePrivacy Regulation and their application to Web tracking technologies.
- We have been collaborating with Prof. Benoit Baudry from KTH Royal Institute of Technology, Sweden and with Pierre Laperdrix from Stony Brook University on the survey of browser fingerprinting technologies.
- We are setting a new collaboration with Dr. Zinaida Benenson from University of Erlangen-Nuremberg, Germany, to study Human Factors in Privacy: in particular, to set up user studies to evaluate their perception and understanding of the cookie banners design and measure the influence of dark patterns on user decisions.
- We are setting a new collaboration with Prof. Martin Johns from TU Braunschweig, Germany, to work on cryptographic primitives to include proof of ownership in browser cookies that would facilitate the exercise of GDRP subject access rights. The is a joint collaboration with Cedric Lauradoux from Privatics.
- We are pursuing our collaboration on session types with Prof. Mariangiola Dezani Ciancaglini from the University of Torino and Prof. Paola Giannini from the University of Piemonte Orientale. This year, this collaboration was extended to Dr. Ross Horne from the University of Luxemburg. We also continue to collaborate with Dr. Jorge Pérez and his PhD student Mauricio Cano, from the University of Groningen, on the integration of session types with synchronous reactive programming.
- We are pursuing our collaboration on reactive programming and on higher contracts for security with Prof. Robby Findler from Northwestern University in Chicago.
- We are pursuing our collaboration with Prof. Marc Feeley from Univerisity of Montréal on the compilation of dynamic languages.

8.5.2. Participation in Other International Programs

8.5.2.1. International Initiatives

DAJA

Title: Detection strategies based on Software Metrics for Multitier JavaScript

International Partners (Institution - Laboratory - Researcher):

Universidad de Chile (Chile), Intelligent Software Construction laboratory (ISCLab) - Alexandre Bergel

Universidad Nacional del Centro de la Provincia de Buenos Aires (Argentina) Computer Science Departement - Santiago Vidal

Duration: 2018 - 2019

Start year: 2018

See also: https://daja-sticamsud.github.io/

JavaScript is the most popular object scripting programming language. It is extensively used conceived only for scripting, it is frequently used in large applications. The rapid adoption of JavaScript has outpaced the Software Engineering community to propose solutions to ensure a satisfactory code quality production. This situation has favored the production of poor quality JavaScript applications: we have found across JavaScript applications a large presence of dead-code (i.e., source code portion that is never used) and code duplications. These symptoms are known to lead to maintenance and performance degradation. Moreover, we have previously analyzed potential security threats to JavaScript applications produced by bad coding practices. The DAJA project will provide methodologies, techniques, and tools to ease the maintenance of software applications written in JavaScript while improving its security.

8.6. International Research Visitors

8.6.1. Visits of International Scientists

- We are collaborating with Cristiana Teixeira Santos from University Toulouse 1-Capitole. Cristiana is a postdoc in Data Protection Law with whom we have been analyzing legal requirements for GDPR consent, and cookie banners in particular. Cristiana has visited us two times in 2019 and will be hired as a postdoc for Inria AEx project DATA4US in 2020.
- As part of our ongoing collaboration on GDPR Subject Access Rights, Cedric Lauradoux has visited us several times in 2019, to expand our existing work [13] and establish new research directions. Cedris is a co-PI for Inria AEx project DATA4US.
- We are collaborating with Prof. Marc Feeley from University of Montréal. For the third consecutive year, M. Feeley has visited us for studying implementation of dynamic languages, and in particular we started a study of the efficient compilation of the Python programming language.
- We are collaborating with Prof. Andrei Sabelfeld from Chalmers University of Technology. A.Sabelfeld has visited us for one month in July 2019 for studying remote timing attackers in the context of IoT frameworks.
- Prof. Robby Findler and his PhD student Spencer Florence visited us in July, where we have organized a mini-workshop during a week, working with Prof. G. Berry and J. Krishnamurthy on the semantics and implementation of reactive languages.

8.6.1.1. Internships

- Nataliia Bielova has co-supervised Hicham Lesfari for 3 months together with Frederic Giroire from Inria Coati team.
- Nataliia Bielova has supervised the intern Michael Toth as a "relai-de-these" for 2 months.
- Ilaria Castellani and Tamara Rezk supervised the intern Carlo Prato for 6 months.
- Tamara Rezk supervised the ENS L3 internship of Maxime Legoupil for 7 weeks in June and July 2019.
- Tamara Rezk has co-supervised the ENS L3 internship of Clément Ogier in July 2019.
- Tamara Rezk supervised the internship of Adam Khayam for 6 months.

- Tamara Rezk supevised -as tutor- the internship of Ayoub Ider Aghbal in a company.

8.6.2. Visits to International Teams

For the third consecutive year, Manuel Serrano and Gérard Berry visited Prof. Robby Findler at University of Northeastern in Chicago. This time, Tamara Rezk joined the delegation that also visited Prof. Christos Dimoulas also working at Northeastern University. The Indes team and Findler's team have applied for the second time to the Inria Associated Team program.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events: Organisation

9.1.1.1. General Chair, Scientific Chair

- Ilaria Castellani was the co-chair (together with Mohammad Reza Mousavi, Antonio Ravara and Alexandra Silva) of the workshop "Open Problems in Concurrency Theory 2019" (OPCT 2019), which was held in affiliation with the POPL 2019 conference in Lisbon, on January 14-15, 2019. https://popl19.sigplan.org/track/opct-2019-papers
- Ilaria Castellani was the co-chair (together with Mohammad Reza Mousavi) of the workshop TRENDS 2019, the annual event of the IFIP WG1.8 on Concurrency Theory, which took place in Amsterdam on August 31, 2019, in association with the CONCUR 2019 conference. https://concurrency-theory.org/events/workshops/trends
- Nataliia Bielova was the co-chair (together with François Pellegrini) of the CNIL-Inria Privacy Award 2019. The award ceremony will take place at the CPDP 2020 conference in Brussels. https://www.cnil.fr/en/launch-4th-edition-cnil-inria-privacy-award

9.1.1.2. Member of the Organizing Committees

Manuel Serrano organized the IFIP 2.16 (working group on Language Design) workshop in Nice from November 11th to November 15th http://program-transformation.org/WGLD/NiceMeeting2019.

9.1.2. Scientific Events: Selection

9.1.2.1. Member of the Conference Program Committees

- Ilaria Castellani served in the Program Committees of the conference CONCUR 2019 and the workshop EXPRESS/SOS 2019.
- Nataliia Bielova served in the Program Committees of the workshop MADWeb 2019, and the conferences PETs 2019, IEEE SecDev 2019, and IEEE EuroS&P 2019.
- Manuel Serrano served in the Program Committee of ProWeb'19 workshop. He was member of the ACM Software award https://www.sigplan.org/Awards/Software/.
- Tamara Rezk served in the Program Committees of the workshops MADWeb 2019, SSIoT 2019, PriSC 2019, and the conferences IEEE SecDev 2019, and NDSS 2019, and Programming.

9.1.2.2. Reviewer

- The team members have been reviewers for the following conferences and workshops: CONCUR'19, EXPRESS/SOS'19, PETs 2019, IEEE SecDev 2019, IEEE EuroS&P 2019, OOPSLA'19, ...

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- Ilaria Castellani was a member of the editorial board of *Technique et Science Informatiques*, a French journal ended in June 2019.

- Ilaria Castellani (together with Mohammad Reza Mousavi) was guest editor for the JLAMP special issue on Trends in Concurrency Theory (Selected invited contributions from the workshops TRENDS 2015 and TRENDS 2016), J. Log. Algebr. Meth. Program., vol. 107, 2019 [19]. https://doi.org/10.1016/j.jlamp.2019.07.001.

9.1.3.2. Reviewer - Reviewing Activities

- The team members have been reviewers for the following journal: The Computer Journal.

9.1.4. Invited Talks

- Nataliia Bielova has been a keynote at the the Francophone workshop on Privacy Protection " l'Atelier sur la Protection de la Vie Privée" (APVP), which took place in Cap Hornu (France) from 9 to 11 July 2019. https://project.inria.fr/apvp2019/. Nataliia gave invited talks at SAP Labs (France), NOYB and TU Wien (Austria) in July/August 2019. She was an invited speaker at the Mozilla Security Summit on November 8, 2019, Vienna (Austria). https://events.mozilla.org/mozillasecurityresearchsummit2019 presenting the joint work with Imane Fouad and Arnaud Legout.
- Celestin Matte presented an ongoing work at the CNIL on October 1, 2019. Title of the talk: "Détection des violations du RGPD et de la directive e-Privacy dans les bannières de consentement aux cookies du Transparency and Consent Framework d'IAB Europe".
- Manuel Serrano has been a invited to be a keynote at the *Huawei European Research Symposium* in January 2019. He presented his work on *Hop* and *HipHop*. He has been invited by RainCode, a Belgium company located in Brussels, specialized in language compilation, to give a talk on the static compilation of dynamic languages.

9.1.5. Leadership within the Scientific Community

- Ilaria Castellani is the chair of the IFIP TC1 WG 1.8 on Concurrency Theory since June 2014 (reelected for a second term in March 2018).
- Ilaria Castellani was a member of the Management Committee of the COST Action IC1405 on Reversible Computation (until April 2019).
- Nataliia Bielova is a member of the Steering Committee of ACM PLAS.
- Tamara Rezk was a member of the Steering Committee of the POST conference during 2019 and is a member of the Steering Committee of the PriSC workshop.

9.1.6. Research Administration

- Ilaria Castellani is a member of Inria's "Comité Parité et Égalité des Chances". In the Centre of Inria Sophia Antipolis, she is a member of the "Comité d'Animation et Médiation Scientifique" and of the "Comité Scientifique du Colloquium". Within UCA, she is a member of the "Réseau Égalité" and of the organising committee of the seminar series "Forum Numerica".
- Ilaria Castellani was the chair of the "jury d'admissibilité" of the CRCN competition (for junior researcher permanent positions) in the Inria Centre of Grenoble Rhône Alpes.
- Nataliia Bielova was a member of the hiring committee for an Inria chair position "enseignement et recherche dans le domaine de la cyberse´curité" of Supelec in February 2019.
- Nataliia Bielova is a member of "Comité du Suivi Doctoral (CSD)" (Supervision of PhD students) of the Inria Sophia Antipolis Mediterranée research center.
- Since summer 2019, Manuel Serrano is vice-chair of the Inria evaluation committee (EC). The charge for this duty amounts to about 50% of his professional activities. He co-chaired the three research promotion juries of 2019. He chaired the Inria *Algorithmics, Computer Algebra and Cryptology* theme EC evaluation. He prepared the evaluation seminar of the Inria theme *Embedded systems, Architecture, and Compilation*.

- Tamara Rezk was a member of " Commission de Développement Technologique (CDT)" of the Inria Sophia Antipolis Mediterranée research center.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master : Tamara Rezk, Security of Web Applications, 28ETD, niveau M2, University of Nice Sophia Antipolis, France

Master : Tamara Rezk, Preuves en Cryptographie, 28ETD, niveau M2, University of Nice Sophia Antipolis, France

IUT : Héloïse Maurel, Introduction aux technologies du Web, 20ETD, niveau DUT1, University of Nice Sophia Antipolis, France

DIU-EIL : Héloïse Maurel, Introduction aux langages de description et programmation du Web , 20ETD, University of Nice Sophia Antipolis, France

Master: Nataliia Bielova, Privacy on the Internet, 15ETD, M2, SKEMA Business school, France.

Master : Nataliia Bielova, Security and Ethical aspect of Data, 27ETD, niveau M1, Université Côte d'Azur, France

Doctorat : Nataliia Bielova, Ecole de Cybersécurité, 3ETD, UCA, France

9.2.2. E-learning

E-learning

Mooc: Nataliia Bielova with C. Lauradoux and V. Roca, 1 session (2 months), FUN-MOOC, Inria, public targeted: around 30,000 for all the sessions since 2018, https://www.fun-mooc.fr/courses/course-v1:inria+41015+session03/about.

9.2.3. Supervision

PhD in progress: Imane Fouad, Web tracking detection and measurement, 1/01/2018, Nataliia Bielova and Arnaud Legout.

PhD in progress: Michael Toth, Privacy Policies and Cookie Banners as a GDPR consent, 1/12/2019, Nataliia Bielova and Vincent Roca.

Postdoc, Celestin Matte, Large-scale measurement of Cookie Banners, 1/03/2019-, Nataliia Bielova.

Postdoc: Yoon Seok Ko, Subsets of secure JavaScript, 1/10/2018-, Tamara Rezk, Manuel Serrano.

PhD in progress: Jayanth Krishnamurthy, Secure Reactive Web Programming, 12/09/2018, Manuel Serrano.

PhD in progress: Bertrand Petit, Musique Massivement Interactive, 12/09/2017, Manuel Serrano.

PhD in progress : Héloïse Maurel, Secure compilation of IoT applications, 1/10/2018, Tamara Rezk

PhD in progress : Mohamad Ellaz, Encodings of ElGammal, 1/12/2017, Benjamin Gregoire and Tamara Rezk

PhD in progress : Lesly-Ann Daniel, Security analysis of binary code, 1/10/2018, Sébastien Bardin and Tamara Rezk

PhD in progress : Adam Khayam, Semantics of Multitier Languages, 1/07/2019, Alan Schmitt and Tamara Rezk

Postdoc: Francis Somé, IoT secure broadcasting, 1/11/2018-1/04/2019, Tamara Rezk

9.2.4. Juries

- Nataliia Bielova was a member of the PhD jury of Antoine Vastel, University of Lille.

- Nataliia Bielova was a member of the jury "soutenance de stage" of the UBINET master of the University of Nice Sophia Antipolis.
- Tamara Rezk was a member of the HdR jury of Catalin Hritcu, ENS.
- Tamara Rezk was a reporter and jury member of the PhD jury of Alexandre Dang, University of Bretagne Loire.
- Tamara Rezk was a member of the jury “soutenance de stage” of the CASPAR master of the University of Nice Sophia Antipolis.
- Manuel Serrano was a reporter and jury member of N. Oostvogels’s PhD, Vrije University, Brussels.

9.3. Popularization

9.3.1. Internal or external Inria responsibilities

Tamara Rezk was member of the editorial board of Interstices (https://interstices.info/) and Blog Binaire Le Monde (https://www.lemonde.fr/blog/binaire/).

9.3.2. Articles and contents

- Nataliia Bielova has been interviewed by the Usine Digitale on 22 November 2019, title "Fuite massive de données à AccorHotels : ce que risque l’entreprise", https://www.usine-digitale.fr/article/fuite-massive-de-donnees-a-accorhotels-que-risque-l-entreprise.N906279.
- Nataliia Bielova has been interviewed by the L’OBS on 29 November 2019, title "Entre réalité augmentée et reconnaissance faciale, on a parcouru le supermarché de demain", https://www.nouvelobs.com/economie/20191129.OBS21725/entre-realite-augmentee-et-reconnaissance-faciale-on-a-parcouru-le-supermarche-de-demain.html.
- Nataliia Bielova and Tamara Rezk have contributed to the Inria white book on CyberSecurity, published in January 2019: https://hal.inria.fr/hal-01993308.
- The browser extension "Cookie Glasses" developed by Celestin Matte and Nataliia Bielova has been extensively discussed on the general public media due to a complaint made by NOYB to the CNIL on the GDPR and ePrivacy violations of several e-commerce websites: https://noyb.eu/say-no-to-cookies-yet-see-your-privacy-crumble/.

9.3.3. Education

- Nataliia Bielova: *Moderation and Animation of the MOOC Protection de la vie privée dans le monde numérique*, 05/2019-06/2019.

9.3.4. Interventions

- Nataliia Bielova made an intervention with high school students during Semaine De La Science with Cinesciences at the cinémathèque of Nice on 4 October 2019.
- Celestin Matte presented his work on "Tracage Wifi et Bluetooth" at the public event called "Pas Sage en Seine" in June 2019, https://programme.passageenseine.fr/.
- Nataliia Bielova made a presentation with BSc and MSc students during the ACM-W Ukrainian Chapter celebration on December 5, 2019, https://women.acm.org/2019-2020-celebrations/.
- Imane Fouad presented her work on "detection of third-party trackers" at Inria PhD Seminars in December 2019.

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[1] N. Bielova, T. Rezk.*A Taxonomy of Information Flow Monitors*, in "International Conference on Principles of Security and Trust (POST 2016)", Eindhoven, Netherlands, F. Piessens, L. Viganò (editors), LNCS - Lecture Notes in Computer Science, Springer, April 2016, vol. 9635, p. 46–67 [*DOI :* 10.1007/978-3-662-49635-0_3], https://hal.inria.fr/hal-01348188

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[5] I. CASTELLANI, M. DEZANI-CIANCAGLINI, P. GIANNINI.*Concurrent Reversible Sessions*, in "CONCUR 2017 - 28th International Conference on Concurrency Theory ", Berlin, Germany, CONCUR 2017, Roland Meyer and Uwe Nestmann, September 2017, vol. 85, p. 1-17 [*DOI :* 10.4230/LIPICS.CONCUR.2017.30], https://hal.inria.fr/hal-01639845

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[10] D. F. SOMÉ, N. BIELOVA, T. REZK.*On the Content Security Policy Violations due to the Same-Origin Policy*, in " 26th International World Wide Web Conference, 2017 (WWW 2017)", April 2017 [*DOI :* 10.1145/3038912.3052634], https://hal.inria.fr/hal-01649526

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Articles in International Peer-Reviewed Journal

[11] I. CASTELLANI, M. DEZANI-CIANCAGLINI, P. GIANNINI.*Reversible sessions with flexible choices*, in "Acta Informatica", November 2019, vol. 56, n^o^ 7-8, p. 553-583 [*DOI :* 10.1007/S00236-019-00332-Y], https://hal.inria.fr/hal-02420508

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[13] C. BONIFACE, I. FOUAD, N. BIELOVA, C. LAURADOUX, C. SANTOS.*Security Analysis of Subject Access Request Procedures How to authenticate data subjects safely when they request for their data*, in "APF 2019 - Annual Privacy Forum", Rome, Italy, June 2019, p. 1-20, https://hal.inria.fr/hal-02072302

[14] I. CASTELLANI, M. DEZANI-CIANCAGLINI, P. GIANNINI.*Event Structure Semantics for Multiparty Sessions*, in "Models, Languages, and Tools for Concurrent and Distributed Programming - Hommage to Rocco De Nicola on the Occasion of His 65th Birthday", Lucca, Italy, Lecture Notes in Computer Science, Michele Boreale and Flavio Corradini and Michele Loreti and Rosario Pugliese, July 2019, vol. 11665, p. 340-363 [*DOI :* 10.1007/978-3-030-21485-2_19], https://hal.inria.fr/hal-02420485

[15] I. FOUAD, N. BIELOVA, A. LEGOUT, N. SARAFIJANOVIC-DJUKIC.*Missed by Filter Lists: Detecting Unknown Third-Party Trackers with Invisible Pixels*, in "PETS 2020 - 20th Privacy Enhancing Technologies Symposium", Montréal, Canada, PETs (Privacy Enhancing Technologies Symposium), July 2020, https://hal.inria.fr/hal-01943496

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[19] I. CASTELLANI, M. R. MOUSAVI.*Special Issue on Trends in Concurrency Theory (selected invited contributions from the workshops TRENDS 2015 and 2016)*, Elsevier, October 2019, vol. 107, p. 175-176 [*DOI :* 10.1016/J.JLAMP.2019.07.001], https://hal.inria.fr/hal-02422352

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[20] M. CANO, I. CASTELLANI, C. DI GIUSTO, J. A. PÉREZ.*Multiparty Reactive Sessions*, Inria, April 2019, n° 9270, 65, https://hal.archives-ouvertes.fr/hal-02106742

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Project-Team Kairos

Multiform Logical Time for Formal Cyber-Physical System Design

IN COLLABORATION WITH: Laboratoire informatique, signaux systèmes de Sophia Antipolis (I3S)

IN PARTNERSHIP WITH:
CNRS

Université Nice - Sophia Antipolis

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Embedded and Real-time Systems

Table of contents

Project-Team Kairos

Creation of the Project-Team: 2019 July 01

Keywords:

Computer Science and Digital Science:

A1.1.1. - Multicore, Manycore
A1.1.2. - Hardware accelerators (GPGPU, FPGA, etc.)
A1.2.5. - Internet of things
A1.2.7. - Cyber-physical systems
A1.5.2. - Communicating systems
A2.2. - Compilation
A2.3. - Embedded and cyber-physical systems
A2.4. - Formal method for verification, reliability, certification
A2.5.1. - Software Architecture & Design

Other Research Topics and Application Domains:

B5.1. - Factory of the future
B5.4. - Microelectronics
B6.1. - Software industry
B6.4. - Internet of things
B6.6. - Embedded systems
B6.7. - Computer Industry (harware, equipments...)
B7.2. - Smart travel
B8.1. - Smart building/home
B8.2. - Connected city
B9.5.1. - Computer science

1. Team, Visitors, External Collaborators

Research Scientists

Robert de Simone [Team leader, Inria, Senior Researcher, HDR]
Luigi Liquori [Inria, Senior Researcher, HDR]
Eric Madelaine [Inria, Researcher, HDR]
Dumitru Potop Butucaru [Inria, Researcher, from Jul 2019, HDR]

Faculty Members

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Marie-Agnès Peraldi Frati [Univ de Nice - Sophia Antipolis, Associate Professor]
Sid Touati [Univ de Nice - Sophia Antipolis, Professor, HDR]

Technical Staff

Paul Bouche [IRT Saint Exupéry, Engineer]
Luc Hogie [CNRS, Engineer]
Amin Oueslati [IRT Saint Exupéry, Engineer, until Aug 2019]

PhD Students

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Carsten Bruns [Univ Côte d'Azur, PhD Student]
Giovanni Liboni [Safran, PhD Student, granted by CIFRE]
Hugo Pompougnac [Inria, PhD Student, from Oct 2019]
Claude Stolze [Univ de Nice - Sophia Antipolis, PhD Student]
Hui Zhao [Inria, PhD Student, until Jan 2019]

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Stéphanie Challita [Inria, Post-Doctoral Fellow, from Apr 2019]
Jad Khatib [Inria, Post-Doctoral Fellow, from Oct 2019]

Visiting Scientists

Xiaohong Chen [East China Normal University (Shanghai), from Nov 2019]
Grygoriy Zholtkevych [V.N. Karazin Kharkiv National University (Ukrain), from Oct 2019 until Nov 2019]
Matteo Sereno [University of Turin (It), Professor, Juin 2019]
Thomas Ehrhard [CNRS, University of Paris, Research Director, Sept 2019]

Administrative Assistant

Patricia Riveill [Inria]

2. Overall Objectives

2.1. Overall Objectives

The Kairos proposal ambitions to deal with the Design of Cyber-Physical Systems (CPS), at various stages, using Model-Based techniques and Formal Methods. Design here stands for co-modeling, co-simulation, formal verification and analysis activities, with connections both ways from models to code (synthesis and instrumentation for optimization). Formal analysis, in turn, concerns both functional and extra-functional correctness properties. Our goal is to link these design stages together, both vertically along the development cycle, and horizontally by considering the interactions between cyber/digital and physical models. These physical aspects comprise both physical environments and physical execution platform representations, which may become rather heterogeneous as in the cases of the Internet of Things (IoT) and computing at the edges of the gateways. The global resulting methodology can be tagged as Model-Based, Platform-Based CPS Design (Fig.1).

CPS design must take into account all 3 aspects of application requirements, execution platform guarantees and contextual physical environment to establish both functional and temporal correctness. The general objective of Kairos is thus to contribute in the definition of a corresponding design methodology, based on formal Models of Computation for joint modeling of cyber and physical aspects, and using the important central concept of Logical Time for expressing the requirements and guarantees that define CPS constraints.

Logical Multiform Time. It may be useful to provide an introduction and motivation for the notion of Logical Multiform Time (and Logical Clocks), as they play a central role in our approach to Design. We call Logical Clock any repetitive sequence of occurrences of an event (disregarding possible values carried by the event). It can be regularly linked to physical time (periodic), but not necessarily so: fancy processors may change speeds, simulation engine change time-integration steps, or much more generally one may react with event-driven triggers of complex logical nature (do this after 3-times that unless this...). It is our belief that user specifications are generally expressed using such notions, with only partial timing correlations between distinct logical clocks, so that the process of realization (or "model-based compilation") consists for part in establishing (by analysis or abstract simulation) the possible tighter relations between those clocks (unifying them from a partial order of local total orders to a global total order). We have defined in the past a small language of primitives expressing recognized constraints structuring the relations between distinct logical clocks. This language (named CCSL for Clock Constraint Specification Language), borrows from notions of Synchronous Reactive Languages, Real-Time Scheduling Theory, and Concurrent Models of Computations and Communication (MoCCs) in Concurrency Theory altogether. Corresponding extensions of Timed Models

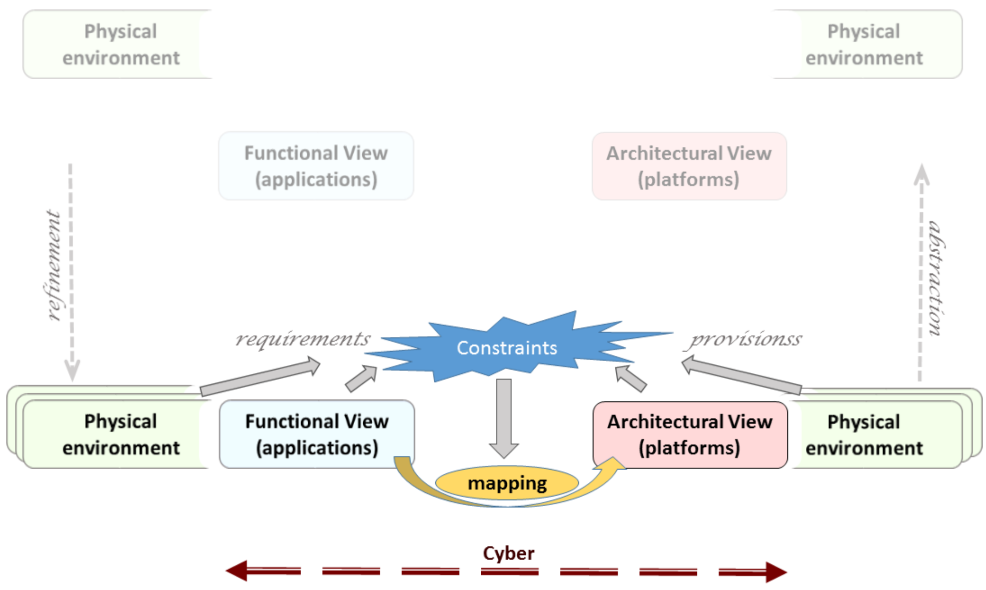

Figure 1. Cyber-Physical generic architectural features

originally based on single (discrete or continuous) time can also be considered. Logical Time is used in our approach to express relation constraints between heterogeneous models, of cyber or physical origin, and to support analysis and co-simulation. Addressing cyber-physical systems demands to revisit logical time to deal with the multi-physical and sometimes uncertain environments.

In the following sections we describe in turn the research agenda of Kairos on co-modeling, co-simulation, co-analysis and verification, and relation from models to code, respectively.

3. Research Program

3.1. Cyber-Physical co-modeling

Cyber-Physical System modeling requires joint representation of digital/cyber controllers and natural physics environments. Heterogeneous modeling must then be articulated to support accurate (co-)simulation, (co-)analysis, and (co-)verification. The picture above sketches the overall design framework. It comprises functional requirements, to be met provided surrounding platform guarantees, in a contract approach. All relevant aspects are modeled with proper Domain Specific Languages (DSL), so that constraints can be gathered globally, then analyzed to build a mapping proposal with both a structural aspect (functions allocated to platform resources), but also a behavioral ones, scheduling activities. Mapping may be computed automatically or not, provably correct or not, obtained by static analytic methods or abstract execution. Physical phenomena (in a very broad acceptance of the term) are usually modeled using continuous-time models and differential equations. Then the "proper" discretization opportunities for numerical simulation form a large spectrum of mathematical engineering practices. This is not at all the domain of expertise of Kairos members, but it should not be a limitation as long as one can assume a number of properties from the discretized version. On the other hand, we do have a strong expertise on modeling of both embedded processing architectures and embedded software (i.e., the kind of usually concurrent, sometimes distributed software that reacts to and control the physical environment). This is important as, unlike in the "physical" areas where modeling is common-place, modeling of software and programs is far from mainstream in the Software Engineering community. These domains are also an area of computer science where modeling, and even formal modeling, of the real objects that are originally of discrete/cyber nature, takes some importance with formal Models of Computation and Communications. It seems therefore quite natural to combine physical and cyber modeling in a more global design approach (even multi-physic domains and systems of systems possibly, but always with software-intensive aspects involved). Our objective is certainly not to become experts in physical modeling and/or simulation process, but to retain from it only the essential and important aspects to include them into System-Level Engineering design, based on Model-Driven approaches allowing formal analysis.

This sets an original research agenda: Model-Based System Engineering environments exist, at various stages of maturity and specificity, in the academic and industrial worlds. Formal Methods and Verification/Certification techniques also exist, but generally in a point-wise fashion. Our approach aims at raising the level of formality describing relevant features of existing individual models, so that formal methods can have a greater general impact on usual, "industrial-level", modeling practices. Meanwhile, the relevance of formal methods is enhanced as it now covers various aspects in a uniform setting (timeliness, energy budget, dependability, safety/security...).

New research directions on formal CPS design should focus on the introduction of uncertainty (stochastic models) in our particular framework, on relations between (logical) real-time and security, on relations between common programming languages paradigms and logical time, on extending logical frameworks with logical time, on the concern with resource discovery also in presence of mobility inherent to connected objects and Internet of Things.

3.2. Cyber-Physical co-simulation

The FMI standard (Functional Mock-Up Interface) has been proposed for "purely physical" (i.e., based on persistent signals) co-simulation, and then adopted in over 100 industrial tools including frameworks such as Matlab/Simulink and Ansys, to mention two famous model editors. With the recent use of co-simulation to cyber-physical systems, dealing with the discrete and transient nature of cyber systems became mandatory. Together with other people from the community, we shown that FMI and other frameworks for co-simulation badly support co-simulation of cyber-physical systems; leading to bad accuracy and performances. More precisely, the way to interact with the different parts of the co-simulation require a specific knowledge about its internal semantics and the kind of data exposed (e.g., continuous, piecewise-constant). Towards a better co-simulation of cyber-physical systems, we are looking for conservative abstractions of the parts and formalisms that aim to describe the functional and temporal constraints that are required to bind several simulation models together.

3.3. Formal analysis and verification

Because the nature of our constraints is specific, we want to adjust verification methods to the goals and expressiveness of our modeling approach. Quantitative (interval) timing conditions on physical models combined with (discrete) cyber modes suggest the use of SMT (Satisfiability Modulo Theories) automatic solvers, but the natural expressiveness requested (as for instance in our CCSL constructs) shows this is not always feasible. Either interactive proofs, or suboptimal solutions (essentially resulting of abstract run-time simulations) should be considered. Complementarily to these approaches, we are experimenting with new variants of symbolic behavioural semantics, allowing to construct finite representations of the behaviour of CPS systems with explicit handling of data, time, or other non-functional aspects.

3.4. Relation between Model and Code

While models considered in Kairos can also be considered as executable specifications (through abstract simulation schemes), they can also lead to code synthesis and deployment. Conversely, code execution of smaller, elementary software components can lead to performance estimation enriching the models before global mapping optimization. CPS introduce new challenging problems for code performance stability. Indeed, two additional factors for performance variability appear, which were not present in classical embedded systems: 1) variable and continuous data input from the physical world and 2) variable underlying hardware platform. For the first factor, CPS software must be analysed in conjunction with its data input coming from the physics, so the variability of the performance may come from the various data. For the second factor, the underlying hardware of the CPS may change during the time (new computing actors appear or disappear, some actors can be reconfigured during execution). The new challenge is to understand how these factors influence performance variability exactly, and how to provide solutions to reduce it or to model it. The modeling of performance variability becomes a new input.

3.5. Code generation and optimization

A significant part CPS design happens at model level, through activities such as model construction, analysis, or verification. However, in most cases the objective of the design process is implementation. We mostly consider the implementation problem in the context of embedded, real-time, or edge computing applications, which are subject to stringent performance, embedding, and safety *non-functional requirements*.

The implementation of such systems usually involves a mix of synthesis—(real-time) scheduling, code generation, compilation—and performance (*e.g.* timing) analysis. One key difficulty here is that synthesis and performance analysis depend on each other. As enumerating the various solutions is not possible for complexity reasons, heuristic implementation methods are needed in all cases. One popular solution here is to build the system first using unsafe performance estimations for its components, and then check system *schedulability* through a global analysis. Another solution is to use safe, over-approximated performance estimations and perform their mapping in a way that ensures by construction the schedulability of the system.

In both cases, the specification of the design space—functional specification, execution platform model, non-functional requirements, implementation model—is a key problem. Another problem is the definition of scalable and efficient mapping methods based on both "exact" approaches (ILP/SMT/CP solving) and compilation-like heuristics.

3.6. Extending logical frameworks with logical time

The Curry-Howard isomorphism (*proposition-as-types and proofs-as-typed-λ-terms*) represent the logical and computational basis to interactive theorem provers: our challenge is to investigate and design time constraints within a Dependent Type Theory (e.g. if event A happened-before event B, then the timestamp/type of A is less (i.e. a subtype) than the timestamp/type of B). We are currently extending the Edinburgh Logical Framework (LF) of Harper-Honsell-Plotkin with relevant constructs expressing logical time and synchronization between processes. Also, union and intersection types with their subtyping constraints theories could capture some constraints expressions *à la* CCSL needed to formalize logical clocks (in particular CCSL expressions like subclock, clock union, intersection and concatenation) and provide opportunities for an *ad hoc* polymorphic timed Type Theory. Logical time constraints seen as property types can beneficially be handled by logical frameworks. The new challenge here is to demonstrate the relevance of Type Theory to work on logical and multiform timing constraint resolution.

3.7. Object-oriented programming and logical time

We formalize in the past object-oriented programming features and safe static type systems featuring delegation-based or trait inheritance: well typed program will never produce into the `message-not-found` infamous run-time error. We view the logical time as a means to enhance the description of timing constraints and properties on top of existing language semantics. When considering general purpose object-oriented languages, like Java, Type Theory is a natural way to provide such properties. Currently, few languages have special types to manage instants, time structures and instant relations like subclocking, precedence, causality, equality, coincidence, exclusion, independence, etc. CCSL provides ad-hoc constructors to specify clock constraints and logical time: enriching object-oriented type theories with CCSL expressions could constitute an interesting research perspective towards a wider usage of CCSL. The new challenge is to consider logical time constraints as behavioral type properties, and the design of programming language constructs and *ad-hoc* type systems. Advances of typed-calculi featuring those static time features will be applied to our extension [42] of the lambda-calculus of objects of Fisher-Honsell-Mitchell.

3.8. Extensions for spatio-temporal modeling and mobile systems

While Time is clearly a primary ingredient in the proper design of CPS systems, in some cases Space, and related notions of local proximity or conversely long distance, play also a key role for correct modeling, often in part because of the constraints this puts on interactions and time for communications. Once space is taken into account, one has to recognize also that many systems will request to consider mobility, originated as change of location through time. Mobile CPS (or mCPS) systems occur casually, e.g., in the case of Intelligent Transportation Systems, or in roaming connected objects of the IoT. Spatio-temporal and mobility modeling may each lead to dynamicity in the representation of constraints, with the creation/deletion/discovering of new components in the system. This opportunity for new expressiveness will certainly cause new needs in handling constraint systems and topological graph locations. The new challenge is to provide an algebraic support with a constraint description language that could be as simple and expressive as possible, and of use in the semantic annotations for mobile CPS design. We also aims to provide fully distributed routing protocols to manage Semantic Resource Discovery in IoT.

4. Application Domains

4.1. Cyber-Physical and Embedded Systems

We have historical contacts with industrial and academic partners in the domains of avionics and embedded electronics (Airbus, Thales, Safran). We have new collaborations in the fields of satellites (Thales Alenia Space) and connected cars (Renault Software Labs). These provide for use case and new issues in CPS co-modeling and co-design (Digital Twins) further described in New Results section.

4.2. Connected Objects in the Internet Of Things

Due to increasing collaborations with local partners, we have recently considered Smart Contracts (as popularized in Blockchain frameworks), as a way to formally established specification of behavioral system traces, applied to connected objects in a IoT environment. The new ANR project SIM is based on this.

5. Highlights of the Year

5.1. Highlights of the Year

- New Collaboration with Renault Software Labs - CIFRE starting in April 2019
- ANR Project on the verification of smart contracts on the use of multi-modalities transportations in the smart city - AAPG 2019 PRCE

5.1.1. Awards

Frederic Mallet is Laureate of the program ‘Jeune Talent France Chine 2019’ from French Embassy in China.

6. New Software and Platforms

6.1. VerCors

VERification of models for distributed communicating COmponants, with safety and Security

KEYWORDS: Software Verification - Specification language - Model Checking

FUNCTIONAL DESCRIPTION: The VerCors tools include front-ends for specifying the architecture and behaviour of components in the form of UML diagrams. We translate these high-level specifications, into behavioural models in various formats, and we also transform these models using abstractions. In a final step, abstract models are translated into the input format for various verification toolsets. Currently we mainly use the various analysis modules of the CADP toolset.

RELEASE FUNCTIONAL DESCRIPTION: It includes integrated graphical editors for GCM component architecture descriptions, UML classes, interfaces, and state-machines. The user diagrams can be checked using the recently published validation rules from, then the corresponding GCM components can be executed using an automatic generation of the application ADL, and skeletons of Java files.

The experimental version (2019) also includes algorithms for computing the symbolic semantics of Open Systems, using symbolic methods based on the Z3 SMT engine.

NEWS OF THE YEAR: The experimental version (2019) also includes: - algorithms for computing the symbolic semantics of Open Systems, using symbolic methods based on the Z3 SMT engine. - a stand alone textual editor for (open) pNet systems, that generates API code to construct their internal representation in the platform.

- Participants: Antonio Cansado, Bartlomiej Szejna, Eric Madelaine, Ludovic Henrio, Marcela Rivera, Nassim Jibai, Oleksandra Kulankhina, Siqi Li, Xudong Qin and Zechen Hou
- Partner: East China Normal University Shanghai (ECNU)
- Contact: Eric Madelaine
- URL: https://team.inria.fr/scale/software/vercors/

6.2. TimeSquare

KEYWORDS: Profil MARTE - Embedded systems - UML - IDM

SCIENTIFIC DESCRIPTION: TimeSquare offers six main functionalities:

* graphical and/or textual interactive specification of logical clocks and relative constraints between them,

* definition and handling of user-defined clock constraint libraries,

* automated simulation of concurrent behavior traces respecting such constraints, using a Boolean solver for consistent trace extraction,

* call-back mechanisms for the traceability of results (animation of models, display and interaction with waveform representations, generation of sequence diagrams...).

* compilation to pure java code to enable embedding in non eclipse applications or to be integrated as a time and concurrency solver within an existing tool.

* a generation of the whole state space of a specification (if finite of course) in order to enable model checking of temporal properties on it

FUNCTIONAL DESCRIPTION: TimeSquare is a software environment for the modeling and analysis of timing constraints in embedded systems. It relies specifically on the Time Model of the Marte UML profile, and more accurately on the associated Clock Constraint Specification Language (CCSL) for the expression of timing constraints.

- Participants: Benoît Ferrero, Charles André, Frédéric Mallet, Julien DeAntoni and Nicolas Chleq
- Contact: Julien DeAntoni
- URL: http://timesquare.inria.fr

6.3. GEMOC Studio

KEYWORDS: DSL - Language workbench - Model debugging

SCIENTIFIC DESCRIPTION: The language workbench put together the following tools seamlessly integrated to the Eclipse Modeling Framework (EMF):

- Melange, a tool-supported meta-language to modularly define executable modeling languages with execution functions and data, and to extend (EMF-based) existing modeling languages.
- MoCCML, a tool-supported meta-language dedicated to the specification of a Model of Concurrency and Communication (MoCC) and its mapping to a specific abstract syntax and associated execution functions of a modeling language.
- GEL, a tool-supported meta-language dedicated to the specification of the protocol between the execution functions and the MoCC to support the feedback of the data as well as the callback of other expected execution functions.
- BCOoL, a tool-supported meta-language dedicated to the specification of language coordination patterns to automatically coordinates the execution of, possibly heterogeneous, models.
- Sirius Animator, an extension to the model editor designer Sirius to create graphical animators for executable modeling languages.

FUNCTIONAL DESCRIPTION: The GEMOC Studio is an eclipse package that contains components supporting the GEMOC methodology for building and composing executable Domain-Specific Modeling Languages (DSMLs). It includes the two workbenches: The GEMOC Language Workbench: intended to be used by language designers (aka domain experts), it allows to build and compose new executable DSMLs. The GEMOC Modeling Workbench: intended to be used by domain designersto create, execute and coordinate models conforming to executable DSMLs. The different concerns of a DSML, as defined with the tools of the language workbench, are automatically deployed into the modeling workbench. They parametrize a generic execution framework that provide various generic services such as graphical animation, debugging tools, trace and event managers, timeline, etc.

- Participants: Didier Vojtisek, Dorian Leroy, Erwan Bousse, Fabien Coulon and Julien DeAntoni
- Partners: IRIT - ENSTA - I3S - OBEO - Thales TRT
- Contact: Benoît Combemale
- URL: http://gemoc.org/studio.html

6.4. BCOol

BCOoL

KEYWORDS: DSL - Language workbench - Behavior modeling - Model debugging - Model animation

FUNCTIONAL DESCRIPTION: BCOoL is a tool-supported meta-language dedicated to the specification of language coordination patterns to automatically coordinates the execution of, possibly heterogeneous, models.

- Participants: Julien DeAntoni, Matias Vara Larsen, Benoît Combemale and Didier Vojtisek
- Contact: Julien DeAntoni
- URL: http://www.gemoc.org

6.5. myMed

A geo-localised Framework for building Publish-Subscribe applications in a fixed and mobile environment

KEYWORDS: Framework - Peer-to-peer. - NoSQL - Mobile application - Social network - Publish-subscribe - Iot - Peer-to-peer

SCIENTIFIC DESCRIPTION: myMed : an ad-hoc framework to design, develop, host, and execute Publish-Subscribe based fully distributed applications running in a static or mobile network. Application examples can be found in Online Social Networks or in Resource Discovery for the IoT. In a nutshell myMed is composed by:

• A myMed Software Development Kit (SDK) to develop fixed and mobile web applications, but also to build native applications on Smartphones equipped with Android or iOS. Every module can be freely used without interfering with other applications, in a true Lego fashion.

• A myMed cloud to execute the mobile applications: the cloud is composed of a backbone of 50PCs, distributed through the "AlpMed" EuroRegion and following some precise network criteria (4G, optical Fiber, ..). The operating system running on those PC is a customised and partitioned version of Ubuntu to allow to use the PC as a myMed server as well as a ordinary desktops. As in Peer-to-Peer technology, we do not require that all machines belonging to the backbone are constantly running.

• A myMed backbone, based on a well-tested noSQL database, Cassandra, which can accommodate any number of users without any code changes. Machines can be classically concentrated on a data-center or – more interestingly – fully decentralized (modulo a decent internet connection). Failures of one or many machines do not affect the running of the system, thanks to replication of the data on several servers. A little collection of proof of concept applications to validate, experiment, and testing the development kit and the execution cloud have been implemented.

FUNCTIONAL DESCRIPTION: myMed is an experimental framework for implementing, hosting and deploying, on the top of a built-in cloud platform, many applications using intensively the Publish-Subscribe (PUB/SUB) paradigm, like e.g. Open Social Networks or Resource Discovery in a distributed data-base. Those applications could take advantage of sharing common software modules, hardware resources, making inter-communication and inter-interaction simpler and improving rapid development and deployement.

- Participants: Luigi Liquori, Claudio Casetti, Mariangiola Dezani and Mino Anglano
- Partners: Politecnico di Torino - Université de Nice Sophia Antipolis (UNS) - Università di Torino - Università del Piemonte Orientale
- Contact: Luigi Liquori
- URL: http://www.mymed.fr

6.6. JMaxGraph

KEYWORDS: Java - HPC - Graph algorithmics

FUNCTIONAL DESCRIPTION: JMaxGraph is a collection of techniques for the computation of large graphs on one single computer. The motivation for such a centralized computing platform originates in the constantly increasing efficiency of computers which now come with hundred gigabytes of RAM, tens of cores and fast drives. JMaxGraph implements a compact adjacency-table for the representation of the graph in memory. This data structure is designed to 1) be fed page by page, à-la GraphChi, 2) enable fast iteration, avoiding memory jumps as much as possible in order to benefit from hardware caches, 3) be tackled in parallel by multiple-threads. Also, JMaxGraph comes with a flexible and resilient batch-oriented middleware, which is suited to executing long computations on shared clusters. The first use-case of JMaxGraph allowed F. Giroire, T. Trolliet and S. Pérennes to count K2,2s, and various types of directed triangles in the Twitter graph of users (23G arcs, 400M vertices). The computation campaign took 4 days, using up to 400 cores in the NEF Inria cluster.

- Contact: Luc Hogie
- URL: http://www.i3s.unice.fr/~hogie/software/?name=jmaxgraph

6.7. Lopht

Logical to Physical Time Compiler

KEYWORDS: Real time - Compilation

SCIENTIFIC DESCRIPTION: The Lopht (Logical to Physical Time Compiler) has been designed as an implementation of the AAA methodology. Like SynDEx, Lopht relies on off-line allocation and scheduling techniques to allow real-time implementation of dataflow synchronous specifications onto multiprocessor systems. But there are several originality points: a stronger focus on efficiency, which results in the use of a compilation-like approach, a focus on novel target architectures (many-core chips and time-triggered embedded systems), and the possibility to handle multiple, complex non-functional requirements covering real-time (release dates and deadlines possibly different from period, major time frame, end-to-end flow constraints), ARINC 653 partitioning, the possibility to preempt or not each task, and finally SynDEx-like allocation.

FUNCTIONAL DESCRIPTION: Compilation of high-level embedded systems specifications into executable code for IMA/ARINC 653 avionics platforms. It ensures the functional and non-functional correctness of the generated code.

- Participants: Dumitru Potop-Butucaru, Manel Djemal, Thomas Carle and Zhen Zhang
- Contact: Dumitru Potop-Butucaru

6.8. LoPhT-manycore

Logical to Physical Time compiler for many cores

KEYWORDS: Real time - Compilation - Task scheduling - Automatic parallelization

SCIENTIFIC DESCRIPTION: Lopht is a system-level compiler for embedded systems, whose objective is to fully automate the implementation process for certain classes of embedded systems. Like in a classical compiler (e.g. gcc), its input is formed of two objects. The first is a program providing a platform-indepedent description of the functionality to implement and of the non-functional requirements it must satisfy (e.g. real-time, partitioning). This is provided under the form of a data-flow synchronous program annotated with non-functional requirements. The second is a description of the implementation platform, defining the topology of the platform, the capacity of its elements, and possibly platform-dependent requirements (e.g. allocation).

From these inputs, Lopht produces all the C code and configuration information needed to allow compilation and execution on the physical target platform. Implementations are correct by construction Resulting implementations are functionally correct and satisfy the non-functional requirements. Lopht-manycore is a version of Lopht targeting shared-memory many-core architectures.

The algorithmic core of Lopht-manycore is formed of timing analysis, allocation, scheduling, and code generation heuristics which rely on four fundamental choices. 1) A static (off-line) real-time scheduling approach where allocation and scheduling are represented using time tables (also known as scheduling or reservation tables). 2) Scalability, attained through the use of low-complexity heuristics for all synthesis and associated analysis steps. 3) Efficiency (of generated implementations) is attained through the use of precise representations of both functionality and the platform, which allow for fine-grain allocation of resources such as CPU, memory, and communication devices such as network-on-chip multiplexers. 4) Full automation, including that of the timing analysis phase.

The last point is characteristic to Lopht-manycore. Existing methods for schedulability analysis and real-time software synthesis assume the existence of a high-level timing characterization that hides much of the hardware complexity. For instance, a common hypothesis is that synchronization and interference costs are accounted for in the duration of computations. However, the high-level timing characterization is seldom (if ever) soundly derived from the properties of the platform and the program. In practice, large margins (e.g. 100%) with little formal justification are added to computation durations to account for hidden hardware complexity. Lopht-manycore overcomes this limitation. Starting from the worst-case execution time (WCET) estimations of computation operations and from a precise and safe timing model of the platform, it maintains a precise timing accounting throughout the mapping process. To do this, timing accounting must take into account all details of allocation, scheduling, and code generation, which in turn must satisfy specific hypotheses.

FUNCTIONAL DESCRIPTION: Accepted input languages for functional specifications include dialects of Lustre such as Heptagon and Scade v4. To ensure the respect of real-time requirements, Lopht-manycore pilots the use of the worst-case execution time (WCET) analysis tool (ait from AbsInt). By doing this, and by using a precise timing model for the platform, Lopht-manycore eliminates the need to adjust the WCET values through the addition of margins to the WCET values that are usually both large and without formal safety guarantees. The output of Lopht-manycore is formed of all the multi-threaded C code and configuration information needed to allow compilation, linking/loading, and real-time execution on the target platform.

NEWS OF THE YEAR: In the framework of the ITEA3 ASSUME project we have extended the Lopht-manycore to allow multiple cores to access the same memory bank at the same time. To do this, the timing accounting of Lopht has been extended to take into account memory access interferences during the allocation and scheduling process. Lopht now also pilots the aiT static WCET analysis tool from AbsInt by generating the analysis scripts, thus ensuring the consistency between the hypotheses made by Lopht and the way timing analysis is performed by aiT. As a result, we are now able to synthesize code for the computing clusters of the Kalray MPPA256 platform. Lopht-manycore is evaluated on avionics case studies in the perspective of increasing its technology readiness level for this application class.

- Participants: Dumitru Potop-Butucaru and Keryan Didier
- Contact: Dumitru Potop-Butucaru

7. New Results

7.1. Spatio-temporal constraints for mobile systems, with automotive driving assistance illustrations

Participants: Frédéric Mallet, Joëlle Abou Faysal, Robert de Simone, Xiaohong Chen.

The objective here is to extend constraint specifications to encompass spatial aspects in addition to logical multiform time. Spatio-temporal logics and requirement formalisms are thus an inspiration here. But mobility requests additionally that these spatio-temporal relations evolve in time. We are investigating in several directions:

- a target methodological approach is to consider these spatio-temporal relations to express safe driving rules as requirements or guarantees, meant to (in)validate trajectory proposals computed by a lower-level algorithmic system (itself operating on more direct neighborhood information). A realistic size case study is handled in collaboration with Renault Software Labs, as part of the CIFRE PhD contract of Joëlle Abou-Faysal, to define the precise needs in expressiveness and formal validation.
- Preliminary definitions of a spatio-temporal requirement specification languages, borrowing ideas from spatio-temporal logics and formal mobile process modeling (none of which being sufficient to our aim), is being progressed in collaboration with fellow researchers from ECNU Shanghai [20].

7.2. System Engineering for Performance and Availability in satellite embedded COTS

Participants: Robert de Simone, Julien Deantoni, Amin Oueslati, Paul Bouche.

In the context of the IRT ATIPPIC project, which provided engineer position funding for Paul Bouche and Amin Oueslati, we investigated the application of a realistic formal design methodology applied on a real case study under construction by the ATIPPIC partners, in this case a prototype satellite based on general-purpose electronic Components-on-the-Shelf (COTS), not radiation-hardened. We focused on the one hand on the Model-Based Design of local interconnects, to provide analysis techniques regarding bandwidth and possible congestion of inter-process communications; on the other hand, we considered formal analysis of availability in case of fault (solar radiations), to study impact of alternative mitigation techniques for fault tolerance. Results were delivered in the form of Capella viewpoints and analysis tools to the IRT Saint-Exupéry, as free software. They were also published in [18], [23].

7.3. Efficient solvers and provers for CCSL

Participants: Frédéric Mallet, Xiaohong Chen.

One of the goal of the team is to promote the use of logical time in various application domains. This requires to have efficient solvers for CCSL. We have made considerable progresses on this part along two lines. One by relying on SMT solvers (like Z3), the other by building a dynamic logic amenable to building semi-automatic proofs for logical time properties of reactive systems. Then for some classes of problems we can efficient solving tools.

- The first step is to have an efficient Z3 library for solving CCSL specifications. We have improved a lot the performances over last year by getting rid of some of the existential quantifiers in our properties [35].
- Second, we use this solver to help requirement engineers elicite the requirements. We use execution traces to help generate valid satisfied CCSL specifications [28].
- Third, we have built a dynamic logics based on CCSL, where the formulae are derived from CCSL relational operators and programs include some of CCSL expressions and some imperative reactive constructs akin to Esterel programs. Then we have an interactive proof system, that helps prove that some reactive program satisfies a set of formulas at all time. As we use only a subset of CCSL then, we can restrict to a decidable subset of the logics and the SMT solver is always efficient. The SMT helps guide the semi-automatic proof [34] by identifying the next proof rules that can be used (or not).

7.4. Formal temporal Smart Contracts

Participants: Frédéric Mallet, Marie-Agnès Peraldi Frati, Robert de Simone.

"Smart Contracts", as a way to define legal ledger evolution in Blockchain environments, can be seen as rule constraints to be satisfied by the set of their participants. Such contracts are often reflecting requirements or guarantees extracted from a legal or financial corpus of rules, while this can be carried to other technical fields of expertise. Our view is that Smart Contracts are often relying on logically timed events, thus welcoming the specification style of our formalisms (such as CCSL). The specialization of multiform logical time constraints to this domain is under study, in collaboration with local academic partners at UCA UMR LEAT and Gredeg, and industrial partners, such as Symag and Renault Software Labs. Local funding was obtained from UCA DS4H EUR Academy 1, which allowed preparation of the ANR project SIM that was accepted in 2019. One goal is to get acceptance from the lawyers while still preserving strong semantics for verification. This builds on our previous expertise [16].

7.5. CCSL extension to Stochastic logical time

Participants: Frédéric Mallet, Robert de Simone.

CCSL specifications allows distinct clocks with unfixed inter-relations. In settings such as cyber-physical modeling, probabilistic rates of relative occurrences may be provided as bounds. The objective is to provide construct to introduce such relations for the inclusion and precedence partial orders, but also to consider also constructs that associate them. Preliminary results have been obtained by Frédéric Mallet in collaboration with fellow researchers from ECNU Shanghai.

7.6. Semantic Resource Discovery in Internet

Participant: Luigi Liquori.

Results [30] are obtained in close collaboration with professors Matteo Sereno and Rossano Gaeta from the University of Turin. Internet in recent years has become a huge set of channels for content distribution highlighting limits and inefficiencies of the current protocol suite originally designed for host-to-host communication. We propose a Content Name System Service (CNS) that provides a new network aware Content

Discovery Service. The CNS behavior and architecture uses the BGP inter-domain routing information. In particular, the service registers and discovers resource names in each Internet Autonomous System (AS): contents are discovered by searching through the augmented AS graph representation classifying ASes into customer, provider, and peering, as the BGP protocol does. An interesting extension of this Internet Service could be to scale up to Internet of Things and to Cyber Physical Systems inter-networked with networks different than Internet.

7.7. Raising Semantic Resource Discovery in IoT

Participants: Luigi Liquori, Marie-Agnès Peraldi Frati.

Within the standards for M2M and the Internet of Things, managed by ETSI, oneM2M, we are looking for suitable mechanisms and protocols to perform a Semantic Resource Discovery as described in the previous Subsection. More precisely, we are extending the (actually weak) Semantic Discovery mechanism of the IoT oneM2M standard. The goal is to enable an easy and efficient discovery of information and a proper inter-networking with external source/consumers of information (e.g. a data bases in a smart city or in a firm), or to directly search information in the oneM2M system for big data purposes. oneM2M ETSI standard has currently a rather weak native discovery capabilities that work properly only if the search is related to specific known sources of information (e.g. searching for the values of a known set of containers) or if the discovery is very well scoped and designed (e.g. the lights in a house). We submitted our vision in ETSI project submission "Semantic Discovery and Query in oneM2M" (currently under evaluation by ETSI) for extending oneM2M with a powerful Semantic Resource Discovery Service, taking into account additional constraints, such as topology, mobility (in space), intermittence (in time), scoping, routing ...

7.8. Empirical study of Amdahl's law on multicore processors

Participants: Carsten Bruns, Sid Touati.

Since many years, we observe a shift from classical multiprocessor systems to multicores, which tightly integrate multiple CPU cores on a single die or package. This shift does not modify the fundamentals of parallel programming, but makes harder the understanding and the tuning of the performances of parallel applications. Multicores technology leads to sharing of microarchitectural resources between the individual cores, which Abel et al. classified in storage and bandwidth resources. In this research report [39], we empirically analyze the effects of such sharing on program performance, through repeatable experiments. We show that they can dominate scaling behavior, besides the effects described by Amdahl's law and synchronization or communication considerations. In addition to the classification of Abel et al., we view the physical temperature and power budget also as a shared resource. It is a very important factor for performance nowadays, since DVFS over a wide range is needed to meet these constraints in multicores. Furthermore, we demonstrate that resource sharing not just leads a flat speedup curve with increasing thread count but can even cause slowdowns. Last, we propose a formal modeling of the performances to allow deeper analysis. Our work aims to gain a better understanding of performance limiting factors in high performance multicores, it shall serve as basis to avoid them and to find solutions to tune the parallel applications.

7.9. Communicating Networks of Data-Flow (sub)networks with limited memory

Participant: Robert de Simone.

Process Networks have been proposed a long time ago as models of concurrent, embedded streaming computations and communications, both amenable to formal analysis as models and executable as parallel program abstractions. As part of a larger effort at identifying precise connections between these models, programming models, and embedded parallel architectures altogether, we worked this year on the following problem: given a network of concurrent processes (Kahn-style) where each process is in turn a data-flow process network (SDF-style), can we decide in an efficient fashion (not NP-hard) whether a given assignment of communications to bounded local memories is schedulable (in a way that two simultaneous communications cannot require more than the available memory). A technical report is in preparation.

7.10. Behavioral Equivalence of Open Systems

Participants: Eric Madelaine, Cristian Grigoriu, Zechen Hou.

We consider Open (concurrent) Systems where the environment is represented as a number of processes which behavior is unspecified. Defining their behavioral semantics and equivalences from a Model-Based Design perspective naturally implies model transformations. To be proven correct, they require equivalence of “Open” terms, in which some individual component models may be omitted. Such models take into account various kind of data parameters, including, but not limited to, time. The middle term goal is to build a formal framework, but also an effective tool set, for the compositional analysis of such programs. In collaboration with ENS Lyon and Inria Lille, we studied an application of this approach to the verification of BIP architectures; this work extends previous dedicated approaches for compositional verification of BIP systems to data-dependent synchronizations [22]. Following last year results we have devised dedicated algorithms for checking equivalence of such systems [27], [41], currently under implementation in collaboration with ECNU Shanghai.

In order to facilitate the usage of our tools, we have also defined a language for defining open systems in terms of parameterized networks of synchronized automata (pNets, [4]), and implemented this language as an Eclipse-based editor in the VerCors tool (see Software section), together with interfaces to the semantic construction and equivalence checking algorithms.

7.11. Calculi with Union and Intersection types

Participants: Luigi Liquori, Claude Stolze.

Union and intersection types are interesting to improve actual programming languages static disciplines with alternative form of polymorphism. Since type inference is undecidable, our research vein focus on finding suitable “type decorations” in term syntax permitting to make type checking decidable, *i.e.*$\lambda x.x : (\sigma \to \sigma) \cap (\tau \to \tau)$ becomes $\langle \lambda x : \sigma.x, \lambda x : \tau.x \rangle : (\sigma \to \sigma) \cap (\tau \to \tau)$ in a fully-typed syntax. Those type systems uses intensively a subtyping relation stating *e.g.* that $\sigma \cap \tau \leq \sigma$ or $\sigma \leq \sigma \cup \tau$. Deciding whether $\sigma \leq \tau$ can be extremely difficult in complexity (space and time): actually, there are few algorithms in the literature dealing with union and intersection types. Recently [45] we have proved and certified in Coq a subtype algorithm of a type theory with union and intersection types; we have also extracted a running functional code. Subtyping constraints could be easily interpreted as temporal constraints in a suitable temporal algebra, like those that could be specified in CCSL. Advances of typed-calculi featuring those type disciplines are presented in [42], [31] and [14].

7.12. Bull, an Interactive Type Checker with Union and Intersection Types

Participants: Luigi Liquori, Claude Stolze.

Starting from our theoretical researches on Intersection and Union Types and related Subtype Theories, we have designed and implemented a prototype of an Interactive Typechecker based on the 2018 work on the Δ-framework [43], on the 2017 work on decidable subtyping logic for Intersection and Union types [45], and on our recent advances on the Δ-calculus [42] and [14]. The prototype is called *Bull*; Bull has a command-line interface where the user can declare axioms, terms, and perform computations. These terms can be incomplete, therefore the type checking algorithm uses unification to try to construct the missing subterms. A Read-Eval-Print-Loop allows to define axioms and definitions, and performs some basic terminal-style features like error pretty-printing, subexpressions highlighting, and file loading. Moreover, it can typecheck a proof and normalize it. We use the syntax of *Pure Type Systems* of Berardi to improve the compactness and the modularity of the kernel. Abstract and concrete syntax are mostly aligned: the concrete syntax is similar to the concrete syntax of the ITP Coq. We have also designed and implemented a *higher-order unification algorithmà la* Huet for terms, while typechecking and partial type inference are done by our *bidirectional refinement algorithm*. The refinement can be split into two parts: the essence refinement and the typing refinement. The bidirectional refinement algorithm aims to have partial type inference, and to give as much information as possible to the unifier. For instance, if we want to find a $?y$ such that

$\vdash_\Sigma \langle \lambda x : \sigma.x, \lambda x : \tau.?y \rangle : (\sigma \to \sigma) \cap (\tau \to \tau)$, we can infer that $x : \tau \vdash ?y : \tau$ and that $\wr ?y \wr =_\beta x$. We are experimenting with classical examples in Bull, like the ones formalized by Pfenning with his Refinement Types in LF, and we are looking for examples taking into account preorders, constraints and operators (like *e.g.*$<, \leq, >, \geq, \cup, \cap$...) that could be interpreted as timed algebras expressions *à la* CCSL. This would be a little step toward the formal and certified definition of a simple timed type systems for the λ-calculus and a Timed Logical Framework.

The software can be actually retrieved on the GitHub repository Bull (registration to the BIL Inria data base is in progress).

7.13. Co-Modeling for Better Co-Simulations

Participants: Julien Deantoni, Giovanni Liboni.

A Collaborative simulation consists in coordinating the execution of heterogeneous models executed by different tools. In most of the approaches from the state of the art, the coordination is unaware of the behavioral semantics of the different models under execution; *i.e.*, each model and the tool to execute it is seen as a black box. We highlighted that it introduces performance and accuracy problems [44].

In order to improve the performance and correctness of co-simulations, we proposed a language to defined model behavioral interfaces, *i.e.*, to expose some information about the model behavioral semantics. We also proposed another language to make explicit the way to coordinate the different models by using dedicated connectors. The goal is to provide few information about the models to avoid intellectual property violations, but enough to allow an expert to make relevant choices concerning their coordination. The resulting models can then be exploited to generate a dedicated coordination, aware of the specificity of each model [29]. Future work mainly consists in experimenting a new co-simulation interface taking advantage of the model behavioral interface and proposed as a generalization of co-simulation interfaces from the state of the art.

This work is realized in the context of the GLOSE project (see Section 1) in collaboration with Safran and other Inria teams (namely HyCOMES and DiVerSE).

7.14. CCSL for Models Behavioral Composition

Participants: Julien Deantoni, Frédéric Mallet, Hui Zhao.

The growing use of models for separating concerns in complex systems has lead to a proliferation of model composition operators. These composition operators have traditionally been defined from scratch following various approaches differing in formality, level of detail, chosen paradigm, and styles. Due to the lack of proper foundations for defining model composition (concepts, abstractions, or frameworks), it is difficult to compare or reuse composition operators. In [17], we proposed research directions towards a unifying framework that reduces all structural composition operators to structural merging, and all composition operators acting on discrete behaviors to event scheduling. Our belief is that CCSL, embedding both synchronous and asynchronous relations, is a good candidate to specify the event scheduling corresponding to the coordination of the different behaviors. However, as already stated in previous sections, to achieve such a status, some extensions to CCSL must be proposed. One of them was the possibility to prioritize events in the presence of synchronous relations. This was formally defined in [26] and implemented in the TimeSquare tool.Other interesting extensions are under study in the context of heterogeneous models, see Section 7.13.

As part of Zhao Hui's PhD work, we have proposed a language to bring together subsets of existing predefined languages in a bid to combine their expressiveness. Rather than trying to build the ultimate unified language, sum of all languages, we would rather select meaningful features in existing languages and build a new language based on those features. As an example of application, we have shown how to combine the functional models of Capella with the security models of SysML-sec in an ad-hoc security-aware language for functional analysis [36].

7.15. Expressing IoT security constraints

Participants: Stéphanie Challita, Robert de Simone.

In the framework of Inria Project Lab SPAI, we are considering extensions of the logical time constraint style of CCSL, in order to encompass locality information as well as the duality between (dynamic) agents and (static) resources. Once an appropriate framework has been defined to express occupancy of resources by agents through (logical) time, notions of access rights, enclaves, privileges and priorities may be encoded straightforwardly, and rules governing their proper secure use can be expressed as properties. Results will be presented at the completion of Stephanie Challita postdoctoral period.

7.16. Real-Time Systems Compilation

Participants: Dumitru Potop Butucaru, Hugo Pompougnac, Jad Khatib.

This work took place in the framework of the PIA ES3CAP project (see section 9.2.5) and in close collaboration with Inria PARKAS, Airbus, Safran Aircraft Engines, Kalray, and the IRT Saint-Exupéry. It funded the last year of Keryan Didier PhD thesis (before the Paris Kairos subteam was created).

The key difficulty of real-time scheduling is that timing analysis and resource allocation depend on each other. An exhaustive search for the optimal solution not being possible for complexity reasons, heuristic approaches are used to break this dependency cycle. Two such approaches are typical in real-time systems design. The first one uses unsafe timing characterizations for the tasks (*e.g.* measurements) to build the system, and then checks the respect of real-time requirements through a global timing analysis. The second approach uses a formal model of the hardware platform enabling timing characterizations that are safe for all possible resource allocations (worst-case bounds). So far, the practicality of the second approach had never been established. Automated real-time parallelization flows still relied on simplified hypotheses ignoring much of the timing behavior of concurrent tasks, communication and synchronization code. And even with such unsafe hypotheses, few studies and tools considered the (harmonic) multi-periodic task graphs of real-world control applications, and the problem of statically managing all their computational, memory, synchronization and communication resources.

Our work has provided the first demonstration of the feasibility of the second approach, showing good practical results for classes of real-world applications and multiprocessor execution platforms whose timing predictability allows keeping pessimism under control. This requires something that is missing in previous work:the tight orchestration of all implementation phases: WCET analysis, resource allocation, generation of glue code ensuring the sequencing of tasks on cores and the synchronization and memory coherency between the cores, compilation and linking of the resulting C code. This orchestration is conducted on a very detailed timing model that considers both the tasks and the generated glue code, and which includes resource access interferences due to multi-core execution. Orchestration is not a mere combination of existing tools and algorithms. Enabling predictable execution and keeping pessimism under control requires the formal and algorithmic integration of all design phases, which in turn required the definition of an application normalization phase that facilitates timing analysis, of an original code generation algorithm designed to provide mapping-independent worst-case execution time bounds, and of new real-time scheduling algorithms capable of orchestrating memory allocation and scheduling.

Extensive results on the application of this method to real-file avionics case studies (>5000 unique nodes) mapped on the Kalray MPPA256 Bostan many-core have been presented in [15], [21] and in the PhD thesis of Keryan Didier, defended in September.

The Kalray MPPA platform provides excellent support for safety-critical real-time implementation, by allowing the computation of static WCET bounds. This is no longer true on more classical multi-cores such as those with ARM and POWER micro-architecture. We are currently aiming at extending our method to allow mapping on such multi-cores. Full schedulability guarantees cannot be provided on such platforms. Instead, our aim is to allow the synthesis of implementations that are functionally correct, efficient, and where impredictability is reduced to a minimum by eliminating controllable sources of timing variability. This line of work has been pursued in the context of the collaboration contracts with Airbus and IRT Saint-Exupéry. First results are promising.

Further extensions of our method are under way, most notably to cover timing predictable architectures different from the Kalray MPPA 256.

7.17. Formal Modeling of Concurrent Implementations

Participant: Dumitru Potop Butucaru.

Concurrent programming is notoriously difficult, especially in constrained embedded contexts. Threads, in particular, are wildly non-deterministic as a model of computation, and difficult to analyze in the general case. Fortunately, it is often the case that multi-threaded, semaphore-synchronized embedded software implements high-level functional specifications written in a deterministic data-flow language such as Scade or (safe subsets of) Simulink. We claim that in this case the implementation process should build not just the multi-threaded C code, but (first and foremost) a richer model exposing the data-flow organization of the computations performed by the implementation. From this model, the C code is extracted through selective pretty-printing, while knowledge of the data-flow organization facilitates analysis.

This year, we have proposes a language for describing such implementation models that expose the data-flow behavior hiding under the form of a multi-threaded program. The language allows the representation of efficient implementations featuring pipelined scheduling and optimized memory allocation and synchronization. We showed applicability on a large-scale industrial avionics case study and on a commercial many-core [24].

7.18. Scalability of Constraint Programming for Real-Time Scheduling

Participants: Dumitru Potop Butucaru, Robert de Simone.

Given two abstract modeling descriptions, one of a dataflow process network for the application, one of a block diagram structure for the computing platform and its interconnects, together with cost functions for the elementary computations and communications, one is bound to seek optimal mappings pairing the two. Amongst all the possible techniques, an obvious one consists in using general constraint solvers (real, integer, or boolean constraint programming, SMT solvers, CP solvers, etc.). Given the NP-hard nature of the problem, the issue here is to experimentally determine the empyrical complexity of various scheduling problems, and thus help in determining when solvers can be used for the resolution of scheduling problems.

In previous years we addressed this issue for ILP and SMT solvers. This year, we considered a Constraint Programming solver with dedicated support for modeling and solving real-time scheduling problems (IBM ILOG CPLEX CP Optimizer). The work was conducted in the framework of Bimael Iosif's student internship, and the writing of a paper is under way.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

Safran : Desir/Glose We participate to the bilateral collaborative program Desir, put up by Safran to work with selected academic partners. We share the Glose project started in this program with two other Inria teams : HyComes, and DiverSE. The aim of the project is to improve early stages of system engineering by allowing early execution and co-simulation of heterogeneous models. The technical content of our contributions is described in section 7.13. A CIFRE PhD is funded by Renault on related topics.

IRT Saint-Exupery ATIPPIC This cooperative project aims at building a computing digital electronic structure of micro-satellites on ordinary, "COTS" processors. The project was accepted for 30 months and will reach completion by the end of 2019. It funds two temporary research engineers working under our own supervision, while exchanging extensively with the rest of the ATIPPIC project, which is actually physically hosted by Inria. The technical content of our contributions is described in section 7.2.

Airbus In the continuation of the ITEA3 ASSUME project, Airbus has provided funding for the extension of the Real-Time Systems Compilation method to allow parallelization onto multi-cores with classical ARM or POWER architecture. The technical content of our contributions is described in section 7.16. The technical content of our contributions is described in section 7.2.

IRT Saint-Exupery The CAPHCA project of IRT Saint-Exupéry has provided funding for the extension of the Real-Time Systems compilation method to allow parallelization onto timing predictable multi-cores different from the Kalray MPPA 256. The targets of this work are Infineon TC27x and FlexPRET.

Renault Software Lab We have started, at the end of 2018, a collaboration with Renault Software Labs on the definition of rules for ensuring safe maneuvers in autonomous vehicles. The rules express conditions from the environments, safety rules to preserve the integrity of the vehicles, driving legislation rules, local rules from the authorities. The rules must be updated dynamically when the vehicle evolves and are used to monitor at run-time the behavior of the ADAS. While the ADAS contains several algorithms relying on machine learning, the monitoring system must be predictive and rules must guarantee formally that the system does not cause any accident. So it can be seen as a way to build trustworthy monitoring of learning algorithms. A CIFRE PhD is funded by Renault on this topic and has started in April 2019.

Accenture Labs We have continued discussions with Accenture Labs, started in 2018, on Smart Contract languages for permissioned blockchains. A CIFRE funding is under way.
In recent years, various platform developments focused on so-called *private* (or *permissioned*) blockchain(s) and digital ledgers. Almost all private blockchains present their own implementation of Smart Contract. Between public and private blockchains we are observing a wide variety of different languages with different capabilities and limitations. Inspired by our researches in object-oriented languages [40], we aim at designing a language which might extend an object instance upon receiving a message, an ability referred to by Cardelli as *self-inflicted* operation. Public and private blockchains would take advantage of this novel capability in building safe and flexible intelligent smart contracts.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. Université Côte d'Azur Academy 1 and EUR DS4H

In the context of the local UCA-Jedi IDEX program and its RISE Academy, we were afforded a three years funding, including a postdoctoral position, for the "Smart IoT for Mobility" project. This project, lead by the LEAT UMR and Kairos, aims at building a formal language for the design of smart contracts in the context of a mobility project, in collaboration with Renault Software Labs and Symag, a subsidiary of BNP Paribas. This agreement was operational in preparing the larger ANR project SIM, that was accepted this year, while an even larger European project is under proposal.

9.1.2. PSPC-Region project ADAVEC

This project was recently accepted, and not yet started in practice. It associates Renault Software Labs with UCA (represented by our team), together with Avisto Telecom and EPICnPOC companies. The focus is on requirements and specification for Automated Driving Assistance, and more specially the transitions that need to be properly handled when control needs to be held back to the human driver.

9.2. National Initiatives

9.2.1. ANR Project SIM

The ANR SIM (Smart IoT for Mobility) is a PRCE project co-funded by ANR (AAPG 2019) and DGA for 42 months. The national coordinator is the LEAT (UMR CNRS) and the other partners are Renault Software Labs and Symag. The goal is to provide a formal meta-language to describe smart contracts that can be used in the context of an autonomous vehicles to provide services to the users. The services are related to the combined use of multi-model transportation systems by having a single smart contracts that can enforce all the intermediate transactions with all the actors involved (car manufacturing, parking lease, highway toll companies, insurances, bike rental companies).

9.2.2. Competitivity Clusters

The Kairos team is involved in the actions of the cluster SCS (Systèmes Communicants Sécurisés) and Frédéric MALLET is elected in the steering committee of SCS. One of the more prominent action is to build, in partnership with University Aix-Marseille, a Digital Innovation Hub, to open the access (with actions of transfer and valorization) to Digital Innovations for companies that would benefit from it, like public institutions (hospitals, human resources, employment institutions) or private companies that could use IoT for agriculture, tourism, smart infrastructures (harbours, buildings, cities).

9.2.3. CNRS GDRs

We are registered members of three GDR funded by CNRS : **SoC**^{2}, on topics of Hardware-software codesign and Non-Functional Property modeling for co-simulation; **LTP**, on verification and language design for reactive CPS systems; **GPL**, on software engineering and Domain-Specific Languages.

9.2.4. Inria Project Lab SPAI

This collaborative action, targeting *Security by Program Analysis for the IoT (SPAI)*, is headed by the Indes Project, and associated the Antique, Privatics and Celtique EPIs. See 7.15 for our contribution.

9.2.5. PAI ES3CAP

ES3CAP (Embedded Smart Safe Secure Computing Autonomous Platform) is a PIA (Programme d'Investissements d'Avenir) project. Its budget is of 22.2MEuros, over 36 months. The national coordinator is Kalray, and other partners include Safran, Renault, and MBDA. The objectives of the project are to:

- Build a hardware and software industry-grade solution for the development of computation-intensive critical application. The solution should cover the needs of industrial end users, and target multi/many-core hardware platforms. The solution will come with 3 to 6 usage profiles specific to various industries (automotive, aerospace, defence)
- Improve the technology readiness level of the proposed development flow from TRL4-5 (technology development) to TRL6-7, thus approaching as much as possible commercialization.
- Build an alternate, perennial ecosystem for critical real-time OSs and development tools for computer vision, data fusion and neural networks. The tools and components must be available on a prototyping and demonstration platform that is safe and secure.
- Capitalize on the convergence between the automotive and aerospace markets on subjects such as security, safety, decision making, and big data.

Our technical contributions to this project are described in 7.16. This project partially finances Hugo Pompugnac's PhD and Jad Khatib's post-doc.

9.3. International Initiatives

9.3.1. Inria International Partners

9.3.1.1. IIP TuMuLT

Title: Trustworthy Modeling using Logical Time

International Partner (Institution - Laboratory - Researcher):

E.C.N.U. (Shanghai, China) - Departement of Software Engineering and Computer Science - Zhang Min

Duration: 2018 - 2022

See also: https://team.inria.fr/tumult/

- Modeling the Uncertain Environments of Cyber-Physical Systems: Logical Time is one of the main scientific foundation of the KAIROS Team. From the background in theory of concurrency, we are used to consider mainly discrete control systems that can guarantee a functional determinism independently of any implementation-specific timing variation. Addressing Cyber-Physical Systems and the Internet of Things means widening those assumptions to consider the external environment, typically involving uncertainty, as part of the design. This task explores the definition of sound extensions to logical time to capture both the physical continuous behavior and make an abstract characterization as a statistical approximation.
- SMT For Logical Time: While synchronous systems usually focus on finite state-based control systems, our abstraction of logical time relies on both Boolean algebra (for synchronous operations) and integer arithmetic (for synchronizing mechanisms), In that context, SMT is a promising solution to solve systems that combine several theories. We had first results on this aspect [SCP'17] but we still need to increase the subset of constraints that can be addressed efficiently as well as the performances of the solving tools.
- Spatio-Temporal Specification for Trustworthy Intelligent Transportation Systems: Focusing on Intelligent Transportation Systems as a subset of Cyber-Physical Systems, we encounter specific problems. This task would focus on extensions of our framework for a spatio-temporal logics based on logical time. This means a description of the location of infrastructures as well as the ability to build constraints that depend both on time (logic or physical) and locations (logical or physical).
- Symbolic approaches for models and analysis of Open systems: Methods for analyzing and guaranteeing the properties of critical and complex systems, including their data and time depend aspects, have strongly evolved with the emergence of efficient SAT and SMT engines. We are working on novel methods combining classical verification paradigms with SMT approaches to create symbolic and compositional verification methods and tool platforms [22], [27].

Collaboration will come in the form of scientific short or middle term visits, student exchanges (master and PhD), and organization of events (workshops and conferences).

9.3.1.2. Informal International Partners

- Luigi Liquori has a steady collaboration with researchers from University of Udine and Turin, Italy.
- We keep close informal relations with the Universities of Kiel and Bamberg Germany, in the context of the Synchronous Reactive academic community. We all attended the yearly Synchron seminar, held this year in Aussois (together with researchers from Verimag and the Parkas and Spades Inria teams).
- Frédéric Mallet has a collaboration with Peter Olvecsky from University of Oslo. He was funded in 2019 by a program of the French Embassy in Norway called Asgard.

9.3.2. Participation in Other International Programs

- PHC Cai Yuan Pei: The partnership is a joint funding from Campus France and Chinese Scholarship Council (CSC) to fund short exchanges of permanent staffs and long exchanges of PhD students. A 2-week visit was carried out by Frédéric Mallet in 2019, while Xiaohong Chen is visiting France during 3 months starting in mid-November. The program is funded for three years and a PhD student (Zhang Juan) will visit our team during 16 months in 2020.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

- Xiaohong Chen, Assistant Professor at East China Normal University (Shanghai), from Nov 2019 to Feb 2020.
- Grygoriy Zholtkevych, Professor at V.N. Karazin Kharkiv National University (Ukraine), from Oct 2019 until Nov 2019.
- Peter Olvescky, Professor at University of Oslo, from November 24th to November 29th, 2019.
- Matteo Sereno, Professor, University of Turin, Italy, in May 2019.
- Thomas Ehrhard, University of Paris, in September 2019.

9.4.2. Visits to International Teams

9.4.2.1. Research Stays Abroad

- E. Madelaine spent 4 weeks visiting the Software Engineering an Computer Science department at ECNU Shanghai (2 weeks in May, 2 weeks in September), founded by the foreign expert program of ECNU; and 1 week visiting the Institute of Software of the Chinese Academy of Science (ISCAS, Beijing), funded by ISCAS.
- Marie-Agnès Peraldi Frati spent 10 days at Danang University in May 2019 in the context of the joined UCA/UD international DNIIT laboratory for student supervision and scientific meetings. The visit was funded by Mobility Contract Erasmus Mundus.
- Frédéric Mallet stayed three weeks in Shanghai in August 2019. He stayed one week in Hangzhou in September as part of a Chinese competition for oversea professors. He also stayed two weeks in Shanghai in November 2019 through the PHC Cai Yuan Pei program.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events: Organisation

10.1.1.1. General Chair, Scientific Chair

- F. Mallet was Track Scientific Chair for DATE2019 organized in Firenze in March 2019.
- E. Madelaine is Chair of the Steering Committee of the Formal Aspects of Component Systems (FACS) conference.
- J.Deantoni was Chair of the first international workshops on “Multi-Paradigm Modeling for Cyber-Physical Systems” and “Modeling Language Engineering and Execution”.
- J.Deantoni was Chair of “Computational Science” track of the RIVF 2019 conference.

10.1.2. Scientific Events: Selection

10.1.2.1. Chair of Conference Program Committees

- F. Mallet was Program Co-Chair of the 10th Workshop on Formal Techniques for Safety Critical Systems (FTSCS), organized as a satellite event of ICFEM 2019, in Shenzhen, Chine, in November 2019.
- F. Mallet was Program Co-Chair of ICTERI 2019 organized in Kherson, Ukraine, in May 2019.

10.1.2.2. Member of the Conference Program Committees

- J.Deantoni was in the program committee of: CoSim-CPS'19 and DSD'19
- F. Mallet was in the program committees of SEFM'19, DATE'19, FDL'19, DSD'19, Modelsward'19.
- D. Potop-Butucaru was in the program committee of FDL'19 and ACSD'19

10.1.2.3. Reviewer

- E. Madelaine is reviewer for the Formal Aspects of Component Systems (FACS), and industrial Formal Methods (iFM) conferences.
- L. Liquori and Claude Stolze reviewed for the conference FOSSACS/ETAPS.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- F. Mallet is now in the editorial board of Springer journal Software-Intensive Cyber-Physical Systems (SICS) dedicated to all topics around software in embedded and cyber-physical systems.
- F. Mallet was guest editor for a special issue of Elsevier Science of Computer Programming dedicated to the Theoretical Aspects of Software Engineering.

10.1.3.2. Reviewer - Reviewing Activities

- E. Madelaine was reviewer for the Journal of Systems and Software (JSS), and for Science of Computer Programming (SCP).
- L. Liquori and Claude Stolze reviewed for Fundamenta Informaticae.
- F. Mallet was reviewer for IEEE Transactions on Software Engineering (TSE) and Elsevier Journal on Microprocessors and Microsystems (MICPRO).

10.1.4. Invited Talks

- J.Deantoni was invited for a talk in the Danang University during the RIVF conference.
- J.Deantoni was invited for a talk during the "Computer Automated Multi-Paradigm Modelling 2019" meeting in Bellairs.
- F. Mallet was invited as a keynote speaker to the 11th IEEE TASE 2019 organized in Guilin, Chine (July 2019).
- L. Liquori is invited for a talk at the Bamberg University, Jan 2020.

10.1.5. Scientific Expertise

- F. Mallet is an elected member of the Conseil National des Universités (CNU) for section 27.
- F. Mallet has made an expertise of projects for the Belgium Agency of Research (FNRS).

10.1.6. Research Administration

- F. Mallet is Deputy Director of UMR I3S Laboratory and as such, member of its "comité de direction" and "conseil de laboratoire", together with the steering committee of the graduate school (EUR) DS4H.
- Sid Touati is member of the direction committee of I3S laboratory.
- M.A Peraldi-Frati is member of the I3S Laboratory council. She has been recently appointed member of UCA Academic Council.
- Luigi Liquori is member of the IFIP working group WG1.6 on Rewriting.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence : Sid TOUATI, Fondement machine, 75 heures eq TD, L1 informatique, Université Côte d'Azur.

Licence : Sid TOUATI, Architecture machine, 45 heures eq TD, L3 informatique, Université Côte d'Azur.

Licence : Sid TOUATI, Compilation, 33 heures eq TD, L3 informatique, Université Côte d'Azur.

Master: Sid TOUATI, Architectures et logiciels hautes performances, 81 heures eq TD, Master 1 informatique, Université Côte d'Azur.

Master international: Sid TOUATI, Advanced operating systems, 30 heures eq TD, Master 1 informatique, Université Côte d'Azur.

International Master: Frédéric Mallet, Safety-Critical Systems, 32h.

Master: Frédéric Mallet, Software Engineering, 32h.

Master : Robert de Simone, Formal Methods for NoC-based design, 36 heures eq TD, M2 International Ubinet, Université Côte d'Azur.

License: Marie-Agnès Peraldi-Frati teaches Web security (20h eq TD), Security of connected objects (20h eq TD), IoT Infrastructure deployment (20 H) and Large scale plateform for IoT (20h eq TD) in a licence cursus dedicated to Internet of Objects, Infrastructure and Applications.

Master:Marie-Agnès Paraldi Frati, Web Security and IoT Platform, 20h eq TD, Master 2 SICOM, Univ Avignon.

Master : Luigi Liquori, Peer-to-peer systems, 32 eq TD, Université Côte d'Azur.

Master: Luigi Liquori, Rewriting Systems and Pattern Matching, 12 eq TD, Université de Lorraine.

Ph.D.: Winter School on Theoretical Foundations of Computer Science, 4-9 February 2019, Georgia. Luigi Liquori. Peer-to-peer and related systems, International Black Sea University and Shota Rustaveli National Science Foundation of Georgia.

Ph.D.: 12th International School on Rewriting (ISR) July 2020, Spain. Luigi Liquori. Pattern matching λ-calculi.

Master: Julien Deantoni, Finite State Machine, 54h eq TD, Polytech'Nice.

Master: Julien Deantoni, Multi Paradigm Programming in C++, 54h eq TD, Polytech'Nice.

Master: Julien Deantoni, Domain Specific Languages, 32h eq TD, Polytech'Nice.

Master: Julien Deantoni, Language Interpreter, 32h eq TD, Polytech'Nice.

Master: Julien Deantoni, Micro-controller programming, 8h eq TD, Polytech'Nice.

Master: Dumitru Potop-Butucaru, A synchronous approach to the design of embedded real-time systems, 30h, EPITA Engineering School, Paris.

Master: Dumitru Potop-Butucaru, Real-time embedded systems, 42h, EIDD (École d'Ingenieur Denis Diderot), Paris

10.2.2. Supervision

- HDR : Julien Deantoni, *Towards Formal System Modeling: Making Explicit and Formal the Concurrent and Timed Operational Semantics to Better Understand Heterogeneous Models*, Université Côte d'Azur, Juillet 2019 [13]
- PhD : Claude Stolze, Combining union, intersection and dependent types in an explicitly typed lambda-calculus, Université Côte d'Azur, Dec 16th 2019, Luigi Liquori. [14]
- PhD in progress : Carsten BRUNS, Performance analysis and optimisation of C++ applications, Université Côte d'Azur, 2021, Sid TOUATI.

- PhD in progress : Giovanni Liboni, Coordination of discrete (Cyber) Models, Université Cote d'Azur, end 2021, Frédéric Mallet, Julien DeAntoni.
- PhD in progress : Joelle Abou Faysal, A Formal Language for Ensuring Safety Scenarios in Autonomous Vehicules, Université Cote d'Azur, 2022, Frédéric Mallet.
- PhD: Keryan Didier, Contributions to the safe and efficient parallelisation of hard real-time systems. Sorbonne University, September 19, 2019, Dumitru Potop-Butucaru.
- PhD in progress : Hugo Pompougnac, Sorbonne University, 2022, Dumitru Potop-Butucaru.

10.2.3. Juries

- Frederic Mallet was president of the PhD Jury of Ines Array, Université Cote d'Azur, March 2019.
- Eric Madelaine was member of the PhD jury of Frédéric Lemoine (CNAM, Paris), July 2019.
- Frederic Mallet was reviewer for the PhD Jury of Frédéric Giroudot (ISAE, Toulouse), December 13th 2019.
- Frederic Mallet was reviewer for the PhD Jury of Ngo Minh Thang NGUYEN (Centrale Supélec/CEA), December 16th 2019.
- Dumitru Potop-Butucaru was a member of the PhD jury of Lina Marsso (Univ. Grenoble-Alpes, Inria, CNRS, GrenobleINP), December 10, 2019.
- Dumitru Potop-Butucaru was a member of the PhD jury of Pierre Donat-Bouilloud (Sorbonne University), December 6, 2019.
- Luigi Liquori was member of the PhD jury of Claude Stolze, Université Côte d'Azur, December 2019.

10.3. Popularization

10.3.1. Interventions

Luigi Liquori. Table ronde: "Journée Internationale du m-Tourisme 2019. Blockchain for Tourism", M-Tourism Day, Telecom Valley, Panel, Cannes, 2019.

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Major publications by the team in recent years

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Project-Team LEMON

Littoral Environment: M0dels and Numerics

IN PARTNERSHIP WITH:
CNRS

Université de Montpellier

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Earth, Environmental and Energy Sciences

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Creation of the Team: 2014 January 01, updated into Project-Team: 2019 January 01

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1. Team, Visitors, External Collaborators

Research Scientists

Antoine Rousseau [Team leader, Inria, Researcher, HDR]
Pascal Finaud Guyot [Univ de Montpellier, Researcher, from Oct 2019]
Gwladys Toulemonde [Univ de Montpellier, Researcher]

Faculty Members

Carole Delenne [Univ de Montpellier, Associate Professor, HDR]
Vincent Guinot [Univ de Montpellier, Professor, HDR]

PhD Students

Vita Ayoub [Univ de Montpellier, PhD Student, from Oct 2019]
Yassine Bel Ghaddar [Univ de Montpellier, PhD Student, from Oct 2019]
Joao Guilherme Caldas Steinstraesser [Inria, PhD Student]
Cecile Choley [Engees, PhD Student, from Nov 2019]
Joseph Luis Kahn Casapia [Univ de Montpellier, PhD Student]

Post-Doctoral Fellow

Fatima Palacios Rodriguez [Inria, Post-Doctoral Fellow, until Aug 2019]

Administrative Assistant

Annie Aliaga [Inria, Administrative Assistant]

2. Overall Objectives

2.1. Context

Coastal areas are increasingly threatened by global warming-induced sea level rise. At the same time, 60% of the world population lives in a 100 km wide coastal strip (80% within 30 km from the shore in French Brittany). This is why coastlines are concerned with many issues of various types: economical, ecological, social, political, etc. Coastal areas are natural interfaces between various media (*e.g.* wind/sea/sand/land). The physical processes acting on these media have very different time scales, hence the need to build complex systems coupling nonlinear partial differential equations and random processes to describe them. To address these crucial issues, **LEMON is an interdisciplinary team working on the design, analysis and application of deterministic and stochastic models for inland and marine littoral processes, with an emphasis on coupled and hybrid systems.**

The spot of Montpellier offers large opportunities:

- additionally to IMAG [0] and HSM [0], we collaborate with **several local academic research partners**. To mention but a few examples, we are in close contact in Montpellier with UMR MISTEA (pollution and remediation of water resources), UMR Geosciences (morphodynamics), UMR G-Eau (hydraulics and data assimilation), UMR MARBEC (lagoon environment), UMR LISAH (hydrology in agricultural areas).
- The LEMON members are **involved in projects** funded by the current NUMEV Labex and **actively participate in new initiatives** pertaining to *sea and coast* modelling, both through the recently awarded MUSE project in Montpellier and through external (national, European, international) calls.
- From the **transfer & innovation viewpoint**, the team members already interact with several local partners such as Cereg Ingénierie, Tour du Valat, Predict Services and Berger-Levrault.
- **Regional urban development and land use policies** are natural application fields for the developments undertaken in LEMON.

The general scope of the LEMON project-team is to develop mathematical and computational methods for the modelling of coastal processes. The mathematical tools used are deterministic (PDEs, ODEs) and/or probabilistic (extreme value theory). Applications range from regional oceanography to coastal management, including risk assessment for natural hazards on the coastline (submersion and urban floods, tsunamis, pollution).

[0] Institut Montpelliérain Alexander Grothendieck - UMR5149
[0] HydroSciences Montpellier - UMR 5569

LEMON is a common research team between IMAG, Inria and HSM, whose faculty members have never been associated to Inria groups in the past. All fellows share a strong background in mathematical modelling, together with a taste for applications to the littoral environment. As reflected in the expected contributions below, the research conducted by LEMON is interdisciplinary [0], thanks to the team members expertise (deterministic and stochastic modelling, computational and experimental aspects) and to regular collaborations with scientists from other domains. We believe this is both an originality and a strength of LEMON.

3. Research Program

3.1. Foreword

The team has three main scientific objectives. The first is to develop new models and advanced mathematical methods for inland flow processes. The second is to investigate the derivation and use of coupled models for marine and coastal processes (mainly hydrodynamics, but not only). The third is to develop theoretical methods to be used in the mathematical models serving the first two objectives. As mentioned above, the targeted applications cover PDE models and related extreme events using a hierarchy of models of increasing complexity. LEMON members also contribute to research projects that are not in the core of the team topics and that correspond to external collaborations: they are mentioned in the fourth section below.
In every section, people involved in the project are listed in alphabetical order, except for the first one (underlined) which corresponds to the leading scientist on the corresponding objective.

3.2. Inland flow processes

3.2.1. Shallow water models with porosity

3.2.1.1. State of the Art

Simulating urban floods and free surface flows in wetlands requires considerable computational power. Two-dimensional shallow water models are needed. Capturing the relevant hydraulic detail often requires computational cell sizes smaller than one meter. For instance, meshing a complete urban area with a sufficient accuracy would require 10^6 to 10^8 cells, and simulating one second often requires several CPU seconds. This makes the use of such model for crisis management impossible. Similar issues arise when modelling wetlands and coastal lagoons, where large areas are often connected by an overwhelming number of narrow channels, obstructed by vegetation and a strongly variable bathymetry. Describing such channels with the level of detail required in a 2D model is impracticable. A new generation of models overcoming this issue has emerged over the last 20 years: porosity-based shallow water models. They are obtained by averaging the two-dimensional shallow water equations over large areas containing both water and a solid phase [29]. The size of a computational cell can be increased by a factor 10 to 50 compared to a 2D shallow water model, with CPU times reduced by 2 to 3 orders of magnitude [48]. While the research on porosity-based shallow water models has accelerated over the past decade [43], [59], [62], [39], [38], [48], [73], [74], [68], [69], a number of research issues remain pending.

3.2.1.2. Four year research objectives

The research objectives are (i) to improve the upscaling of the flux and source term models to be embedded in porosity shallow water models, (ii) to validate these models against laboratory and in situ measurements. Improving the upscaled flux and source term models for urban applications requires that description of anisotropy in porosity models be improved to account for the preferential flows induced by building and street alignment. The description of the porosity embedded in the most widespread porosity approach, the so-called Integral Porosity model [59], [41], has been shown to provide an incomplete description of the connectivity properties of the urban medium. Firstly, the governing equations are strongly mesh-dependent because of

[0] HSM is a research unit (UMR) affiliated to the National Institute for Sciences of the Universe (INSU) of CNRS, while the IMAG UMR is affiliated to the National Institute for Mathematical Sciences and Interactions (INSMI).

consistency issues [41]. Secondly, the flux and source term models fail to reproduce the alignment with the main street axes in a number of situations [40]. Another path for improvement concerns the upscaling of obstacle-induced drag terms in the presence of complex geometries. Recent upscaling research results obtained by the LEMON team in collaboration with Tour du Valat suggest that the effects of microtopography on the flow cannot be upscaled using "classical" equation-of-state approaches, as done in most hydraulic models. A totally different approach must be proposed. The next four years will be devoted to the development and validation of improved flux and source term closures in the presence of strongly anisotropic urban geometries and in the presence of strongly variable topography. Validation will involve not only the comparison of porosity model outputs with refined flow simulation results, but also the validation against experimental data sets. No experimental data set allowing for a sound validation of flux closures in porosity models can be found in the literature. Laboratory experiments will be developed specifically in view of the validation of porosity models. Such experiments will be set up and carried out in collaboration with the Université Catholique de Louvain (UCL), that has an excellent track record in experimental hydraulics and the development of flow monitoring and data acquisition equipment. These activities will take place in the framework of the PoroCity Associate International Laboratory (see next paragraph).

3.2.1.3. People

Vincent Guinot, Carole Delenne, Pascal Finaud-Guyot, Antoine Rousseau.

3.2.1.4. External collaborations

- Tour du Valat (O. Boutron): the partnership with TdV focuses on the development and application of depth-dependent porosity models to the simulation of coastal lagoons, where the bathymetry and geometry is too complex to be represented using refined flow models.
- University of California Irvine (B. Sanders): the collaboration with UCI started in 2014 with research on the representation of urban anisotropic features in integral porosity models [48]. It has led to the development of the Dual Integral Porosity model [42]. Ongoing research focuses on improved representations of urban anisotropy in urban floods modelling.
- Université Catholique de Louvain - UCL (S. Soares-Frazão): UCL is one of the few places with experimental facilities allowing for the systematic, detailed validation of porosity models. The collaboration with UCL started in 2005 and will continue with the PoroCity Associate International Laboratory proposal. In this proposal, a four year research program is set up for the validation, development and parametrization of shallow water models with porosity.
- Luxembourg Institute of Technology (R. Hostache): the collaboration with LIST started in 2018 with the project CASCADE funded by the Fond National de la Recherche du Luxembourg, and the co-direction of Vita Ayoub. The depth-dependant porosity model is applied to simulate the flooding of the Severn river (UK).

3.2.2. Forcing

3.2.2.1. State of the Art

Reproducing optimally realistic spatio-temporal rainfall fields is of salient importance to the forcing of hydrodynamic models. This challenging task requires combining intense, usual and dry weather events. Far from being straightforward, this combination of extreme and non-extreme scenarii requires a realistic modelling of the transitions between normal and extreme periods. [52] have proposed in a univariate framework a statistical model that can serve as a generator and that takes into account low, moderate and intense precipitation. In the same vein, [70] developed a bivariate model. However, its extension to a spatial framework remains a challenge. Existing spatial precipitation stochastic generators are generally based on Gaussian spatial processes [15], [50], that are not adapted to generate extreme rainfall events. Recent advances in spatio-temporal extremes modelling based on generalized Pareto processes [32], [65] and semi-parametric simulation techniques [21] are very promising and could form the base for relevant developments in our framework.

3.2.2.2. Four year research objectives

The purpose is to develop stochastic methods for the simulation of realistic spatio-temporal processes integrating extreme events. Two steps are identified. The first one is about the simulation of extreme events and the second one concerns the combination of extreme and non extreme events in order to build complete, realistic precipitations time series. As far as the first step is concerned, a first task is to understand and to model the space-time structure of hydrological extremes such as those observed in the French Mediterranean basin, that is known for its intense rainfall events (Cevenol episodes), which have recently received increased attention. We will propose modelling approaches based on the exceedance, which allows the simulated fields to be interpreted as events. Parametric, semi-parametric and non-parametric approaches are currently under consideration. They would allow a number of scientific locks to be removed. Examples of such locks are e.g. accounting for the temporal dimension and for various dependence structures (asymptotic dependence or asymptotic independence possibly depending on the dimension and/or the distance considered). Methodological aspects are detailed in Section 3.4.1. The second step, which is not straightforward, consists in combining different spatio-temporal simulations in order to help to ultimately develop a stochastic precipitation generator capable of producing full precipitation fields, including dry and non-extreme wet periods.

3.2.2.3. People

Gwladys Toulemonde, Carole Delenne, Vincent Guinot.

3.2.2.4. External collaborations

The Cerise (2016-2018) and Fraise (2019-2021) projects (see 8.2), led by Gwladys Toulemonde, are funded by the action MANU (MAthematical and Numerical methods) of the CNRS LEFE program [0]. Among others, they aim to propose methods for simulating scenarii integrating spatio-temporal extremes fields with a possible asymptotic independence for impact studies in environmental sciences. Among the members of this project, Jean-Noel Bacro (IMAG, UM), Carlo Gaetan (DAIS, Italy) and Thomas Opitz (BioSP, MIA, INRA) are involved in the first step as identified in the research objectives of the present sub-section. Denis Allard (BioSP, MIA, INRA), Julie Carreau (IRD, HSM) and Philippe Naveau (CNRS, LSCE) will be involved in the second one.

3.2.3. Parametrization of shallow water models with porosity

3.2.3.1. State of the Art

Numerical modelling requires data acquisition, both for model validation and for parameter assessment. Model benchmarking against laboratory experiments is an essential step and is an integral part of the team's strategy. However, scale model experiments may have several drawbacks: (i) experiments are very expensive and extremely time-consuming, (ii) experiments cannot always be replicated, and measurement have precision and reliability limitations, (iii) dimensional similarity (in terms of geometry and flow characteristic variables such as Froude or Reynolds numbers) cannot always be preserved.

An ideal way to obtain data would be to carry out in situ measurements. But this would be too costly at the scale of studied systems, not to mention the fact that field may become impracticable during flood periods.

Geographical and remote sensing data are becoming widely available with high spatial and temporal resolutions. Several recent studies have shown that flood extends can be extracted from optical or radar images [35], for example: to characterize the flood dynamics of great rivers [53], to monitor temporary ponds [63], but also to calibrate hydrodynamics models and assess roughness parameters (e.g. [72].

Upscaled models developed in LEMON (see 3.2.1) embed new parameters that reflect the statistical properties of the medium geometry and the subgrid topography. New methods are thus to be developed to characterize such properties from remote sensing and geographical data.

3.2.3.2. Four year research objectives

This research line consists in deriving methods and algorithms for the determination of upscaled model parameters from geodata.

[0] Les Enveloppes Fluides et l'Environnement

For applications in urban areas, it is intended to extract information on the porosity parameters from National geographical survey databases largely available in developed countries. Such databases usually incorporate separate layers for roads, buildings, parking lots, yards, etc. Most of the information is stored in vector form, which can be expected to make the treatment of urban anisotropic properties easier than with a raster format. In developing countries, data is made increasingly available over the world thanks to crowdsourcing (e.g. OpenStreetMap) the required level of detail sometimes not available in vector format, especially in suburban areas, where lawns, parks and other vegetated areas, that may also contribute to flood propagation and storage, are not always mapped. In this context, the necessary information can be extracted from aerial and/or satellite images, that are widely available and the spatial resolution of which improves constantly, using supervised classification approaches.

For applications in great rivers the main objective is to develop an efficient framework for optimally integrating remote sensing derived flood information to compensate the lack of observation related to riverbed bathymetry and river discharge. The effective integration of such remote sensing-derived flood information into hydraulic models remains a critical issue. In partnership with R. Hostache (LIST), we will investigate new ways for making use of SEO data (i.e. flooded areas and water level estimates derived from SAR data collections) for retrieving uncertain model parameters and boundary conditions. The method will be developed and validated using synthetically generated data sets as well as real-event data retrieved from the European Space Agency's archives. Extensive testing will be carried out in a number of high magnitude events recorded over the Severn (United Kingdom) and Zambezi (Mozambique) floodplain areas.

In wetlands applications, connectivity between different ponds is highly dependent on the free surface elevation, thus conditioning the presence of a flow. Characterizing such connectivity requires that topographical variations be known with high accuracy. Despite the increased availability of direct topographic measurements from LiDARS on riverine systems, data collection remains costly when wide areas are involved. Data acquisition may also be difficult when poorly accessible areas are dealt with. If the amount of topographic points is limited, information on elevation contour lines can be easily extracted from the flood dynamics visible in simple SAR or optical images. A challenge is thus to use such data in order to estimate continuous topography on the floodplain combining topographic sampling points and located contour lines the levels of which are unknown or uncertain.

3.2.3.3. People

Carole Delenne, Vincent Guinot, Antoine Rousseau, Pascal Finaud-Guyot

3.2.3.4. External collaborations

- A first attempt for topography reconstruction in wetlands was done in collaboration with J.-S. Bailly (LISAH) in 2016 [30]. It is intended to reactivate this topic in the coming years.
- Porosity model calibration for application on great rivers will be done in the framework of CASCADE project in collaboration with R. Hostache (LIST).
- A collaboration started with the LISAH laboratory to investigate the feasibility of depth-dependent porosity laws reconstruction over cultivates areas. LISAH personel involved: D. Feurer, D. Raclot.

3.3. Marine and coastal systems

3.3.1. Multi-scale ocean modelling

The expertise of LEMON in this scientific domain is more in the introduction and analysis of new boundary conditions for ocean modelling systems, that can be tested on academical home-designed test cases. This is in the core of Antoine Rousseau's contributions over the past years. The real implementation, within operational ocean models, has to be done thanks to external collaborations which have already started with LEMON (see below).

3.3.1.1. State of the Art

In physical oceanography, all operational models - regardless of the scale they apply to - are derived from the complete equations of geophysical fluid dynamics. Depending on the considered process properties (nonlinearity, scale) and the available computational power, the original equations are adapted with some simplifying hypotheses. The reader can refer to [58], [51] for a hierarchical presentation of such models.
In the nearshore area, the hydrostatic approximation that is used is most large scales models (high sea) cannot be used without a massive loss of accuracy. In particular, shallow water models are inappropriate to describe the physical processes that occur in this zone (see Figure 1). This is why Boussinesq-type models are prefered: see [49]. They embed dispersive terms that allow for shoaling and other bathymetry effects. Since the pioneering works of Green and Naghdi (see [36]), numerous theoretical and numerical studies have been delivered by the "mathematical oceanography" community, more specifically in France (see the works of Lannes, Marche, Sainte-Marie, Bresch, etc.). The corresponding numerical models (BOSZ, WaveBox) must thus be integrated in any reasonable nearshore modelling platform.

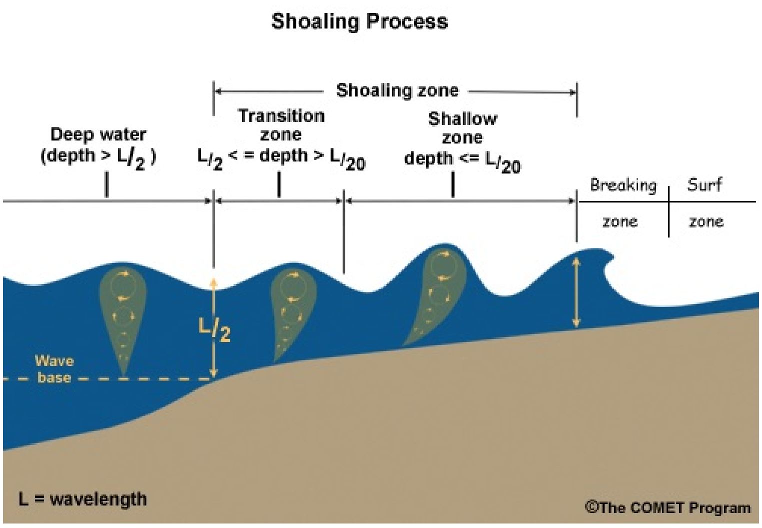

Figure 1. Deep sea, shoaling, and breaking zones.

However, these models cannot simply replace all previous models everywhere in the ocean: dispersive models are useless away from the shore and it is known that wave breaking cannot be simulated using Boussinesq-type equations. Hence the need to couple these models with others. Some work has been done in this direction with a multi-level nesting using software packages such as ROMS, but to the best of our knowledge, all the "boxes" rely on the same governing equations with different grid resolutions. A real coupling between different models is a more difficult task since different models may have different mathematical properties, as shown in the work by Eric Blayo and Antoine Rousseau on shallow water modelling (see [17]).

3.3.1.2. Four year research objectives

Starting from the knowledge acquired in the collaboration with Eric Blayo on model coupling using domain decomposition techniques, our ambition is to propose theoretical and numerical tools in order to incorporate nearshore ocean models into large complex systems including several space and time scales. Two complementary research directions are considered:

- **Dispersive *vs* non-dispersive shallow water models**. As depicted in Figure 1 above, Boussinesq-type models (embedding dispersive effects) should be used in the so-called shoaling zone. The coupling with classical deep-sea / shallow water models has to be done such that all the processes in Figure 1 are correctly modelled (by different equations), with a reduced numerical cost. As a first guess, we think that Schwarz-type methods (widely used by the DDM community) could be good candidates, in particular when the interface locations are well-known. Moving interfaces (depending on the flow, the bathymetry and naturally the wind and all external forcings) is a more challenging objective that will be tackled after the first step (known interface) is achieved.

- **spectral *vs* time-domain models**. In the context of mathematical modelling and numerical simulation for the marine energy, we want to build a coupled numerical model that would be able to simulate wave propagation in domains covering both off-shore regions, where spectral models are used, and nearshore regions, better described by nonlinear dispersive (Boussinesq-type) models.
  While spectral models work with a statistical and phase-averaged description of the waves, solving the evolution of its energy spectrum, Boussinesq-type models are phase-resolving and solves nonlinear dispersive shallow water equations for physical variables (surface elevation and velocity) in the time domain. Furthermore, the time and space scales are very different: they are much larger in the case of spectral models, which justifies their use for modelling off-shore propagation over large time frames. Moreover, important small scale phenomena in nearshore areas are better captured by Boussinesq models, in which the time step is limited by the CFL condition.
  From a mathematical and modelling point of view, this task mainly consists in working on the boundary conditions of each model, managing the simultaneous use of spectral and time series data, while studying transparent boundary conditions for the models and developing domain decomposition approaches to improve the exchange of information.

3.3.1.3. People

Antoine Rousseau, Joao Guilherme Caldas Steinstraesser

3.3.1.4. External collaborations

- **Eric Blayo** is the former scientific leader of team MOISE in Grenoble, where Antoine Rousseau was first recruited. Eric Blayo and Antoine Rousseau have co-advised 3 PhDs and continue to work together on coupling methods in hydrodynamics, especially in the framework of the COMODO ANR network.
- **Fabien Marche** (at IMAG, Montpellier, currently on leave in Bordeaux) is an expert in numerical modelling and analysis of Boussinesq-type models. He is the principal investigator of the WaveBox software project, to be embedded in the national scale Uhaina initiative.
- In the framework of its collaboration with **MERIC**, Antoine Rousseau and Joao Guilherme Caldas Steinstraesser collaborate with the consortium DiMe (ANR-FEM project), and more particularly with Jean-François Filipot ans Volker Roeber for the coupling of spectral and time-domain methods.

3.3.2. Data-model interactions

3.3.2.1. State of the Art

An alternative to direct observations is the chaining of numerical models, which for instance represent the physic from offshore to coastal areas. Typically, output data from atmospheric and ocean circulation models are used as forcings for a wave model, which in turn feeds a littoral model. In the case of extreme events, their numerical simulation from physical models is generally unreachable. This is due to a lack of knowledge on boundary conditions and on their physical reliability for such extreme quantities. Based on numerical simulated data, an alternative is to use statistical approaches. [21] proposed such an approach. They first produced and studied a 52-year hindcast using the WW3 wave model [19], [22], [20], [66]. Then stemming from parts of the original work of [18], [37], [32], [21] proposed a semi-parametric approach which aims to simulate extreme space-time waves processes to, in turn, force a littoral hazard model. Nevertheless their approach allows only a very small number of scenarii to be simulated.

3.3.2.2. Four year research objectives

A first objective is to establish the link between the simulation approach proposed by [21] and the Pareto Processes [32]. This will allow the work of [21] to be generalized, thus opening up the possibility of generating an infinity of extreme scenarii. While continuing to favor the semi- or non-parametric approaches made possible by the access to high spatial resolution calculations, we will try to capture the strength of potentially decreasing extremal dependence when moving towards higher values, which requires the development of models that allow for so-called asymptotic independence.

3.3.2.3. People

Gwladys Toulemonde, Fátima Palacios Rodríguez, Antoine Rousseau

3.3.2.4. External collaborations

- since late 2019, LEMON has started a collaboration with IRT Saint-Exupéry on the hybridization of models and large amounts of data for the modelling of urban floods
- The collaboration with Romain Chailan (IMAG, UM, CNRS) and Frédéric Bouchette (Geosciences, UM) started in 2012 during the PhD of Romain entitled Application of scientific computing and statistical analysis to address coastal hazards.
- During her post doctoral position, Fátima Palacios Rodríguez with her co-advisors will considered a generalization of the proposed simulation method by [21].

3.4. Methodological developments

In addition to the application-driven sections, the team also works on the following theoretical questions. They are clearly connected to the abovementioned scientific issues but do not correspond to a specific application or process.

3.4.1. Stochastic models for extreme events

3.4.1.1. State of the Art

Max-stable random fields [61], [60], [46], [26], [54] are the natural limit models for spatial maximum data and have spawned a very rich literature. An overview of typical approaches to modelling maxima is due to [28]. Physical interpretation of simulated data from such models can be discussed. An alternative to the max-stable framework are models for threshold exceedances. Processes called GPD processes, which appear as a generalization of the univariate formalism of the high thresholds exceeding a threshold based on the GPD, have been proposed [32], [65]. Strong advantages of these thresholding techniques are their capability to exploit more information from the data and explicitly model the original event data. However, the asymptotic dependence stability in these limiting processes for maximum and threshold exceedance tends to be overly restrictive when asymptotic dependence strength decreases at high levels and may ultimately vanish in the case of asymptotic independence. Such behaviours appear to be characteristic for many real-world data sets such as precipitation fields [27], [64]. This has motivated the development of more flexible dependence models such as max-mixtures of max-stable and asymptotically independent processes [71], [13] for maxima data, and Gaussian scale mixture processes [55], [45] for threshold exceedances. These models can accommodate asymptotic dependence, asymptotic independence and Gaussian dependence with a smooth transition. Extreme events also generally present a temporal dependence [67] . Developing flexible space-time models for extremes is crucial for characterizing the temporal persistence of extreme events spanning several time steps; such models are important for short-term prediction in applications such as the forecasting of wind power and for extreme event scenario generators providing inputs to impact models, for instance in hydrology and agriculture. Currently, only few models are available from the statistical literature (see for instance [24], [25], [44]) and remain difficult to interpret.

3.4.1.2. Four year research objectives

The objective is to extend state-of-the-art methodology with respect to three important aspects: 1) adapting well-studied spatial modelling techniques for extreme events based on asymptotically justified models for threshold exceedances to the space-time setup; 2) replacing restrictive parametric dependence modelling by semiparametric or nonparametric approaches; 3) proposing more flexible spatial models in terms of asymmetry or in terms of dependence. This means being able to capture the strength of potentially decreasing extremal dependence when moving towards higher values, which requires developing models that allow for so-called asymptotic independence.

3.4.1.3. People

Gwladys Toulemonde, Fátima Palacios Rodríguez

3.4.1.4. External collaborations

In a natural way, the Cerise and Fraise project members are the main collaborators for developing and studying new stochastic models for extremes.

- More specifically, research with Jean-Noel Bacro (IMAG, UM), Carlo Gaetan (DAIS, Italy) and Thomas Opitz (BioSP, MIA, INRA) focuses on relaxing dependence hypothesis.
- The asymmetry issue and generalization of some Copula-based models are studied with Julie Carreau (IRD, HydroSciences, UM).

3.4.2. Integrating heterogeneous data

3.4.2.1. State of the Art

Assuming that a given hydrodynamic models is deemed to perform satisfactorily, this is far from being sufficient for its practical application. Accurate information is required concerning the overall geometry of the area under study and model parametrization is a necessary step towards the operational use. When large areas are considered, data acquisition may turn out prohibitive in terms of cost and time, not to mention the fact that information is sometimes not accessible directly on the field. To give but one example, how can the roughness of an underground sewer pipe be measured? A strategy should be established to benefit from all the possible sources of information in order to gather data into a geographical database, along with confidence indexes.

The assumption is made that even hardly accessible information often exists. This stems from the increasing availability of remote-sensing data, to the crowd-sourcing of geographical databases, including the inexhaustible source of information provided by the Internet. However, information remains quite fragmented and stored in various formats: images, vector shapes, texts, etc.

This path of research begun with the Cart'Eaux project (2015-2018), that aims to produce regular and complete mapping of urban wastewater system. Contrary to drinkable water networks, the knowledge of sewer pipe location is not straightforward, even in developed countries. Over the past century, it was common practice for public service providers to install, operate and repair their networks separately [57]. Now local authorities are confronted with the task of combining data produced by different parts, having distinct formats, variable precision and granularity [23].

3.4.2.2. Four year research objectives

The overall objective of this research line is to develop methodologies to gather various types of data in the aim of producing an accurate mapping of the studied systems for hydrodynamics models.

Concerning wastewater networks, the methodology applied consists in inferring the shape of the network from a partial dataset of manhole covers that can be detected from aerial images [56]. Since manhole covers positions are expected to be known with low accuracy (positional uncertainty, detection errors), a stochastic algorithm is set up to provide a set of probable network geometries [4]. As more information is required for hydraulic modelling than the simple mapping of the network (slopes, diameters, materials, etc.), text mining techniques such as used in [47] are particularly interesting to extract characteristics from data posted on the Web or available through governmental or specific databases. Using an appropriate keyword list, thematic entities are identified and linked to the surrounding spatial and temporal entities in order to ease the burden of data collection. It is clear at this stage that obtaining numerical values on specific pipes will be challenging. Thus, when no information is found, decision rules will be used to assign acceptable numerical values to enable the final hydraulic modelling.

In any case, the confidence associated to each piece of data, be it directly measured or reached from a roundabout route, should be assessed and taken into account in the modelling process. This can be done by generating a set of probable inputs (geometry, boundary conditions, forcing, etc.) yielding simulation results along with the associated uncertainty.

Combining heterogeneous data for a better knowledge of studied systems raises the question of data fusion. What is the reality when contradictory information is collected from different sources? Dealing with spatial information, offset are quite frequent between different geographical data layers; pattern comparison approaches should be developed to judge whether two pieces of information represented by two elements close to each other are in reality identical, complementary, or contradictory.

3.4.2.3. People

Carole Delenne, Vincent Guinot, Antoine Rousseau, Gwladys Toulemonde

3.4.2.4. External collaborations

The Cart'Eaux project has been a lever to develop a collaboration with Berger-Levrault company and several multidisciplinary collaborations for image treatment (LIRMM), text analysis (LIRMM and TETIS) and network cartography (LISAH, IFSTTAR).

- The MeDo project lead by N. Chahinian (HSM) in collaboration with linguists of UMR Praxiling, uses data mining and text analysis approaches to retrieve information on wastewater networks from the Web. Carole Delenne has a slight implication in this project, as domain expert to guide the text annotations and for the uncertainties definition and representation in the mapping of the data collected.
- Concerning geographical data fusion for the wastewater network cartograhpy, the Phd thesis of Yassine Bel-Ghaddar has been funded by the French Association of Research and Technology (ANRT) in collaboration with Berger-Levrault company and in co-direction with A. Begdouri (LSIA Fès, Morocco).

3.4.3. Numerical methods for porosity models

3.4.3.1. State of the Art

Porosity-based shallow water models are governed by hyperbolic systems of conservation laws. The most widespread method used to solve such systems is the finite volume approach. The fluxes are computed by solving Riemann problems at the cell interfaces. This requires that the wave propagation properties stemming from the governing equations be known with sufficient accuracy. Most porosity models, however, are governed by non-standard hyperbolic systems.

Firstly, the most recently developed DIP models include a momentum source term involving the divergence of the momentum fluxes [42]. This source term is not active in all situations but takes effect only when positive waves are involved [39], [40]. The consequence is a discontinuous flux tensor and discontinuous wave propagation properties. The consequences of this on the existence and uniqueness of solutions to initial value problems (especially the Riemann problem) are not known, or are the consequences on the accuracy of the numerical methods used to solve this new type of equations.

Secondly, most applications of these models involve anisotropic porosity fields [48], [59]. Such anisotropy can be modelled using 2×2 porosity tensors, with principal directions that are not aligned with those of the Riemann problems in two dimensions of space. The solution of such Riemann problems has not been investigated yet. Moreover, the governing equations not being invariant by rotation, their solution on unstructured grids is not straightforward.

Thirdly, the Riemann-based, finite volume solution of the governing equations require that the Riemann problem be solved in the presence of a porosity discontinuity. While recent work [31] has addressed the issue for the single porosity equations, similar work remains to be done for integral- and multiple porosity-based models.

3.4.3.2. Four year research objectives

The four year research objectives are the following:

- investigate the properties of the analytical solutions of the Riemann problem for a continuous, anisotropic porosity field,
- extend the properties of such analytical solutions to discontinuous porosity fields,
- derive accurate and CPU-efficient approximate Riemann solvers for the solution of the conservation form of the porosity equations.

3.4.3.3. People

Vincent Guinot, Pascal Finaud-Guyot

3.4.3.4. External collaborations

Owing to the limited staff of the LEMON team, external collaborations will be sought with researchers in applied mathematics. Examples of researchers working in the field are

- Minh Le, Saint Venant laboratory, Chatou (France): numerical methods for shallow water flows, experience with the 2D, finite element/finte volume-based Telemac2D system.
- M.E. Vazquez-Cendon, Univ. Santiago da Compostela (Spain): finite volume methods for shallow water hydrodynamics and transport, developed Riemann solvers for the single porosity equations.
- A. Ferrari, R. Vacondio, S. Dazzi, P. Mignosa, Univ. Parma (Italy): applied mathematics, Riemann solvers for the single porosity equations.
- O. Delestre, Univ. Nice-Sophia Antipolis (France): development of numerical methods for shallow water flows (source term treatment, etc.)
- F. Benkhaldoun, Univ. Paris 13 (France): development of Riemann solvers for the porous shallow water equations.

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3.4.4. Inland hydrobiological systems

3.4.4.1. State of the Art

Water bodies such as lakes or coastal lagoons (possibly connected to the sea) located in high human activity areas are subject to various kinds of stress such as industrial pollution, high water demand or bacterial blooms caused by freshwater over-enrichment. For obvious environmental reasons, these water resources have to be protected, hence the need to better understand and possibly control such fragile ecosystems to eventually develop decision-making tools. From a modelling point of view, they share a common feature in that they all involve interacting biological and hydrological processes. According to [33], models may be classified into two main types: “minimal dynamic models” and “complex dynamic models”. These two model types do not have the same objectives. While the former are more heuristic and rather depict the likelihood of considered processes, the latter are usually derived from fundamental laws of biochemistry or fluid dynamics. Of course, the latter necessitate much more computational resources than the former. In addition, controlling such complex systems (usually governed by PDEs) is by far more difficult that controlling the simpler ODE-driven command systems.

LEMON has already contributed both to the reduction of PDE models for the simulation of water confinement in coastal lagoons [34], [16] and to the improvement of ODE models in order to account for space-heterogeneity of bioremediation processes in water resources [14].

3.4.4.2. Four year research objectives

In collaboration with colleagues from the ANR-ANSWER project and colleagues from INRA, our ambition is to improve existing models of lagoon/marine ecosystems by integrating both accurate and numerically affordable coupled hydrobiological systems. A major challenge is to find an optimal trade-off between the level of detail in the description of the ecosystem and the level of complexity in terms of number of parameters (in particular regarding the governing equations for inter-species reactions). The model(s) should be able to reproduce the inter-annual variability of the observed dynamics of the ecosystem in response to meteorological forcing. This will require the adaptation of hydrodynamics equations to such time scales (reduced/upscaled models such as porosity shallow water models (see Section 3.2.1) will have to be considered) together with the coupling with the ecological models. At short time scales (i.e. the weekly time scale), accurate (but possibly CPU-consuming) 3D hydrodynamic models processes (describing thermal stratification, mixing, current velocity, sediment resuspension, wind waves...) are needed. On the longer term, it is intended to develop reduced models accounting for spatial heterogeneity.

The team will focus on two main application projects in the coming years:

- the ANR ANSWER project (2017-2021, with INRA Montpellier and LEESU) focusing on the cyanobacteria dynamics in lagoons and lakes. A PhD student is co-advised by Antoine Rousseau in collaboration with Céline Casenave (INRA, Montpellier).
- the long term collaboration with Alain Rapaport (INRA Montpellier) will continue both on the bioremediation of water resources such as the Tunquen lagoon in Chile and with a new ongoing project on water reuse (converting wastewater into water that can be reused for other purposes such as irrigation of agricultural fields). Several projects are submitted to the ANR and local funding structures in Montpellier.

3.4.4.3. People

Céline Casenave (INRA Montpellier), Antoine Rousseau, Vincent Guinot, Joseph Luis Kahn Casapia.

3.4.4.4. External collaborations

- ANR ANSWER consortium: Céline Casenave (UMR MISTEA, INRA Montpellier), Brigitte Vinçon-Leite (UM LEESU, ENPC), Jean-François Humbert (UMR IEES, UPMC). ANSWER is a French-Chinese collaborative project that focuses on the modelling and simulation of eutrophic lake ecosystems to study the impact of anthropogenic environmental changes on the proliferation of cyanobacteria. Worldwide the current environmental situation is preoccupying: man-driven water needs increase, while the quality of the available resources is deteriorating due to pollution of various kinds and to hydric stress. In particular, the eutrophication of lentic ecosystems due to excessive inputs of nutrients (phosphorus and nitrogen) has become a major problem because it promotes cyanobacteria blooms, which disrupt the functioning and the uses of the ecosystems.
- A. Rousseau has a long lasting collaboration with Alain Rapaport (UMR MISTEA, INRA Montpellier) and Héctor Ramirez (CMM, Université du Chili).

4. Highlights of the Year

4.1. Highlights of the Year

- Antoine Rousseau and Cécile Choley have participated to the Climate Change Conference (COP25) in Madrid.
- Year 2019 has been a year with lots of changes for the team with 4 new members and 1 departure:
  - Since October 2019, Fátima Palacios Rodríguez is hired as associate professor at the *Departement Economía Financiera Actuarial y Estadística de Facultad de Ciencias Económicas y Empresariales de Universidad Complutense de Madrid*

– 4 new members joined the team in 2019: Pascal Finaud-Guyot (associate professor at the Montpellier University, Laboratory HydroSciences Montpellier) has a permanent member and Cécile Choley (PhD, funding: ANR Project DEUFI), Vita Ayoub (PhD, funding: Luxembourg National Research Fund) and Yassine Bel-Ghaddar (PhD, funding: Bourse CIFRE ANRT).

5. New Software and Platforms

5.1. SW2D

Shallow Water 2 Dimensions

KEYWORDS: Numerical simulations - Shallow water equations

FUNCTIONAL DESCRIPTION: Urban floods are usually simulated using two-dimensional shallow water models. A correct representation of the urban geometry and hydraulics would require that the average computational cell size be between 0.1 m and 1 m. The meshing and computation costs make the simulation of entire districts/conurbations impracticable in the current state of computer technology.

An alternative approach consists in upscaling the shallow water equations using averaging techniques. This leads to introducing storage and conveyance porosities, as well as additional source terms, in the mass and momentum balance equations. Various versions of porosity-based shallow water models have been proposed in the literature. The Shallow Water 2 Dimensions (SW2D) computational code embeds various finite volume discretizations of these models. Ituses fully unstructured meshes with arbitrary numbers of edges. The key features of the models and numerical techniques embedded in SW2D are :

- specific momentum/energy dissipation models that are active only under transient conditions. Such models, that are not present in classical shallow water models, stem from the upscaling of the shallow water equations and prove essential in modeling the features of fast urban flow transients accurately

- modified HLLC solvers for an improved discretization of the momentum source terms stemming from porosity gradients

- higher-order reconstruction techniques that allow for faster and more stable calculations in the presence of wetting/drying fronts.

RELEASE FUNCTIONAL DESCRIPTION: GUI, C++ translation

- Participant: Vincent Guinot
- Partner: Université de Montpellier
- Contact: Vincent Guinot

5.2. WindPoS-SDM-LAM

KEYWORDS: Numerical simulations - 3D - Fluid mechanics

FUNCTIONAL DESCRIPTION: Software platform for wind modeling.

- Authors: Antoine Rousseau, Cristian Paris Ibarra, Jacques Morice, Mireille Bossy and Sélim Kraria
- Contact: Mireille Bossy
- URL: https://windpos.inria.fr

5.3. SDM

Stochastic Downsaling Method

FUNCTIONAL DESCRIPTION: The computation of the wind at small scale and the estimation of its uncertainties is of particular importance for applications such as wind energy resource estimation. To this aim, starting in 2005, we have developed a new method based on the combination of an existing Numerical Weather Prediction model providing a coarse prediction, and a Lagrangian Stochastic Model for turbulent flows. This Stochastic Downscaling Method (SDM) requires a specific modeling of the turbulence closure, and involves various simulation techniques whose combination is totally original (such as Poisson solvers, optimal transportation mass algorithm, original Euler scheme for confined Langevin stochastic processes, and stochastic particle methods).

- Participants: Antoine Rousseau, Antoine Rousseau, Claire Chauvin, Frederic Bernardin and Mireille Bossy
- Contact: Mireille Bossy

5.4. OceaPoS-SDM

KEYWORDS: 3D - Turbulence - Oceanography - Numerical simulations - Stochastic models - Marine Energies

FUNCTIONAL DESCRIPTION: Simulation platform for ocean turbulence and interaction with hydroturbines

- Partner: MERIC
- Contact: Mireille Bossy

6. New Results

6.1. Inland flow processes

6.1.1. Shallow water models with porosity

We propose in [10] a discussion on the publication 'Dam break in rectangular channels with different upstream-downstream widths' (Valiani and Caleffi, 2019). The authors consider an augmented shallow water system for modelling the dam-break problem in a channel with discontinuous width and present its analytical solutions depending on the upstream-downstream water depth and channel's width ratios. In this discussion we contest the conservation of the hydraulic head through the width's discontinuity, which is stated by the authors, and we exemplify it by performing 2D Shallow water simulations reproducing some test cases presented in the paper.

6.1.2. Forcing

A book chapter entitled *Space-time simulations of extreme rainfall : why and how ?* involving among others two members of the team, Vincent Guinot and Gwladys Toulemonde has been written and accepted for publication [6]. The book whose title is *Mathematical Modeling of Random and Deterministic Phenomena* will be published by Wiley. This chapter aims to present practical interest of doing space-time simulations of extreme rainfall and to propose a state-of-art about that.

6.2. Marine and coastal systems

6.2.1. Numerical Modelling of Hydrokinetic Turbines

Recent studies have pointed out the potential of several coastal or river areas to provide significant energy resources in the near future. However, technological processes for extracting energy using Marine Current Energy Converters (MCEC) are not generically "field-ready" and still require significant research to be set up. The book chapter [8] comes within this framework: we develop the numerical model OceaPoS, useful to carry out a comprehensive description of turbulent flow patterns past MCEC and forward optimize the turbine arrays configurations and evaluate their environmental effects. The OceaPos model consists in describing the fluid as an ensemble of Lagrangian particles ruled by a Stochastic process. OceaPos follows the same methodology than SDM-WindPoS model for wind farm simulations and adapts the Lagrangian stochastic downscaling method (SDM) to the tidal and oceanic boundary layer. We also introduce a Lagrangian version of actuator discs to take account of one or several MCEC's devices and their effects on the flow dynamics. Several benchmarks are presented, and numerical predictions are compared to experimental results.

6.2.2. Multi-scale ocean modeling

In [3], we derive discrete transparent boundary conditions for a class of linearized Boussinesq equations. These conditions happen to be non-local in time and we test numerically their accuracy with a Crank-Nicolson time-discretization on a staggered grid. We use the derived transparent boundary conditions as interface conditions in a domain decomposition method, where they become local in time. We analyze numerically their efficiency thanks to comparisons made with other interface conditions.
In Cemracs 2019 in Marseille, Joao CALDAS was enrolled in the project "Model analysis for tsunami generation by landslides", with Louis EMERALD (PhD student, Université de Rennes), Emmanuel AUDUSSE (maître de conférences, Université Paris 13), Martin PARISOT (chargé de recherche, Inria Bordeaux, CARDAMOM team), Philippe HEINRICH (researcher, CEA) and Alexandre PARIS (PhD student, CEA). The project, funded by CEA, aims to study and compare different fluid mechanics models (Navier-Stokes, Boussinesq, Shallow Water equations) in the simulation of waves generated by landslides. The observed behaviour of the models is correlated to the amount of energy transferred from the sediments to the fluid, both in the wave generation zone (next to the landslide) and in the wave propagation zone (far away from it). An inverse problem is proposed for recovering the landslide from a given evolution of the free surface elevation. A publication will appear in the proceedings of CEMRACS 2019.

6.3. Stochastic models for extreme events

6.3.1. Hierarchical space-time modeling of exceedances

This novel approach is presented in this subsection but it is important to note that it also could has been presented in the subsection *Forcing* because the proposed method could be used as rainfall forcing and because it answers to some mentionned challenges.

The statistical modeling of space-time extremes in environmental applications is a valuable approach to understand complex dependencies in observed data and to generate realistic scenarios for impact models. Motivated by hourly rainfall data in Southern France presenting asymptotic independence, we propose in a joint work (J.N. Bacro, C. Gaetan, T. Opitz and G. Toulemonde) published in the Journal of the ASA [2] a novel hierarchical model for high threshold exceedances leading to asymptotic independence in space and time. Our approach is based on representing a generalized Pareto distribution as a Gamma mixture of an exponential distribution, enabling us to keep marginal distributions which are coherent with univariate extreme value theory. The key idea is to use a kernel convolution of a space-time Gamma random process based on influence zones defined as cylinders with an ellipsoidal basis to generate anisotropic spatio-temporal dependence in exceedances. Statistical inference is based on a composite likelihood for the observed censored excesses. The practical usefulness of our model is illustrated on the previously mentionned hourly precipitation data set from a region in Southern France. This work has also been presented by Gwladys Toulemonde in 2019 in two invited talks (EVA, Zagreb 2019; CMStatistics, ERCIM, London 2019), in one contributed international conference (ISI, Kuala Lumpur, 2019) and one seminar organized by the "Ecole Polytechnique" (Paris, 2019).

6.3.2. Extension of the XGumbel copula to the spatial framework

An extension of the XGumbel copula to the spatial framework has been developped. This work has been presented in the international conference Extreme Value Analysis (EVA 2019, Zagreb) and is currently under review [9]. The XGumbel copula combines two Gumbel copulas with weight parameters, termed extra-parameters, taking values in the unit hyper-cube. In a multisite study, the copula dimension being the number of sites, the XGumbel copula quickly becomes over-parametrized. In addition, interpolation to ungauged locations is not easily achieved. We propose a spatial model for maxima that combines a spatial regression for GEV marginals built with a vector generalized linear model and the spatialized XGumbel copula defined thanks to a spatial mapping for the extra-parameters. The mapping is designed shaped as a disk according to bivariate properties of the XGumbel copula. An Approximate Bayesian Computation (ABC) scheme that seeks to reproduce upper tail dependence coefficients for distance classes is used to infer the parameters. The extension of the XGumbel copula to the spatial framework has been used to study annual maxima of daily precipitation totals at 177 gauged stations over a 57 year period in the French Mediterranean.

7. Bilateral Contracts and Grants with Industry

7.1. IRT

In late 2019, we started a new collaboration with IRT Saint-Exupéry for the hybridization of numerical models and large amount of data for the modeling of urban floods.

7.2. Berger-Levrault

A research collaboration convention was signed with Berger-Levrault company (Montpellier) for three years, in the framework of Yassine Bel-Ghaddar thesis (CIFRE ANRT France/Maroc).

7.3. CEREG/GERIMU

The GERIMU project entered its second phase in 2019. The industrial version of the SW2D computational code was parallelized and tested by ASA Company (subcontractor). Integration of all software components into the final software product will take place during the first half of 2020.

8. Partnerships and Cooperations

8.1. Regional Initiatives

The MeDo project (lead by N. Chahinian) in which Carole Delenne participates is funded by Occitanie Region.

8.2. National Initiatives

Antoine Rousseau is member of the ANR project ANSWER (PI Céline Casenave), 2016-2020

Gwladys Toulemonde is head of a project (2019-2021) funded by INSU via the action MANU (MAthematical and NUmerical methods) of the LEFE program. This project, called Fraise, is focused on rainfall forcing by stochastic simulation for hydrological impact studies from dry periods to extreme events. The consortium involved in this project is larger than the Cerise one (14 researchers from 8 partners : AgroParisTech, CNRS, INRA, Inria, IRD, Université de Lyon 1, Université de Montpellier and the University of Venise in Italy).

Gwladys Toulemonde is member of the ANR project Gambas (PI Frédéric Mortier, Cirad), 2019-2023. The project GAMBAS focuses on joint species distribution models. These models can provide a better understanding and more accurate predictions of species distributions based on environmental variables while taking into account the effects of all other co-occurring species (e.g. competition).

Pascal Finaud-Guyot is member of the ANR project DEUFI (PI André Paquier, IRSTEA Lyon), 2019-2022

All the team is involved in the Inria ADT named SW2D-Lemon. This development project led to 2 coding sprints (of 2 weeks each) with the development team in Sophia. Thanks to this project, SW2D is now a C++ platform, with a dedicate GUI.

8.3. International Initiatives

Gwladys Toulemonde is member of the PHC Utique project (with Tunisia) AMANDE (PI Julie Carreau, IRD), 2019-2021. The project AMANDE focuses on stochastic and semi-parametric approaches combined to teledetection for the study of the water stress.

8.3.1. Inria International Labs

Inria Chile. Associate Team involved in the International Lab: NEMOLOCO

Title: NEw MOdeLing tOols for Coastal Oceanography

International Partner (Institution - Laboratory - Researcher): Pontificia Universidad Católica de Chile (Chile) - CIGIDEN - Rodrigo Cienfuegos

Start year: 2017

See also: https://team.inria.fr/lemon/en/

The NEMOLOCO project targets the improvement of models in the coastal zone. Expected contributions concern: 1) design and implementation of domain decomposition and coupling techniques for coastal modeling; 2) high resolution ocean simulation (including nesting) thanks to the software ROMS-CROCO, applied to biological tracers tracking.

8.3.2. Inria International Partners

8.3.2.1. Informal International Partners

A research collaboration agreement was signed with LSIA, Fès University, Morocco in the framework of Yassine Bel-Ghaddar PhD thesis.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

Carlo Gaetan from the University of Venise in Italy has been invited thanks to the Fraise project one week in april, 2019.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events: Selection

9.1.1.1. Member of the Conference Program Committees

Gwladys Toulemonde is member of the scientific committee of Spatial Statistics 2019 (Sitges, Spain)

9.1.2. Journal

9.1.2.1. Member of the Editorial Boards

Gwladys Toulemonde is guest editor of a special issue of the Journal Spatial Statistics entitled Space-time modeling of rare events and environmental risks. This special issue is related to the conference METMA 9 organized in 2018 in Montpellier by Gwladys Toulemonde and Liliane Bel.

Antoine Rousseau is associate editor of Discrete and Continuous Dynamical Systems series S DCDS-S.

9.1.2.2. Reviewer - Reviewing Activities

Carole Delenne is a reviewer for Journal of Hydraulic Research, Water, Computers Environment and Urban Systems (1 to 3 manuscripts/year)

Vincent Guinot is a reviewer for Journal of Hydrology, Advances in Water Resources, Mathematical Problems in Engineering (3 manuscripts/year)

Antoine Rousseau is a reviewer for Journal of Hydrology and Environmental Modeling & Assessment (3 manuscripts/year)

Pascal Finaud-Guyot is a reviewer for Journal of Hydroinformatics, Advances in Water Resources, Environmental Modelling and Software, Journal of Hydrology (2 manuscripts/year)

Gwladys Toulemonde is a reviewer for computational statistics and data analysis, Dependence modeling, Extremes, Journal of applied Statistics, Journal of Statistical Theory and Practice, Statistics and Computing, Water Ressources research (1 to 3 manuscripts/year)

9.1.3. Invited Talks

Gwladys Toulemonde was invited in a session of the Extreme Value Analysis (EVA) conference in July, 2019 (Zagreb, Croatia).

Gwladys Toulemonde was invited in a session of the ERCIM-CMStatistics conference in December, 2019 (London, UK).

Antoine Rousseau was invited at side event on AI and numerical modelling at COP25 (Madrid, Spain) in December 2019.

9.1.4. Leadership within the Scientific Community

Antoine Rousseau is the scientific coordinator of the the research line *advanced modeling for marine energy* at MERIC (Santiago, Chile).

9.1.5. Scientific Expertise

Gwladys Toulemonde is appointed by the Occitanie region to the scientific board in charge of innovation projects in the field of intelligent systems and digital data chain

Antoine Rousseau is member of the international scientific board of the Climat-AmSud program

9.1.6. Research Administration

Vincent Guinot is head of the ETH team at HSM (10 staff members),

Vincent Guinot is a member of the HSM steering board,

Carole Delenne is elected member of the HSM board (UMR 5569),

Antoine Rousseau is head of the LEMON team at Inria CRI-SAM (5 staff members),

Antoine Rousseau is a member of the Inria CRI-SAM steering board (*Comité des Projets*)

Antoine Rousseau is a member of the Inria CRI-SAM scientific board (*Bureau du Comité des Projets*)

Gwladys Toulemonde is elected member of the IMAG board (UMR 5149)

Gwladys Toulemonde is elected member of the MIPS Scientific Department (Mathematics, Computer Science, Physics and Systems), a component of the University of Montpellier

Gwladys Toulemonde is elected member of the French Statistical Society board (*Société Française de Statistique, SFdS*) and vice-president since july 2019

Gwladys Toulemonde is elected member of Environment group of the French Statistical Society board (*Société Française de Statistique, SFdS*)

Gwladys Toulemonde is elected member of the liaison commitee of the MAS Group (*Modélisation Aléatoire et Statistique*), SMAI (*Société de Mathématiques Appliquées et Industrielles*)

Gwladys Toulemonde was appointed in 2019 external member of a MCF recruitment at the university of Compiègne (MCF 4121, section CNU 26).

Gwladys Toulemonde was appointed in 2019 external member of a MCF recruitment at the university of Nice (MCF 4576, section CNU 26).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Four LEMON permanent members (out of five) are university staff and have teaching duties. Most of their lectures are given at master level at Polytech Montpellier in the departments Informatics and Management (IG), Water Sciences and Technologies (STE) and Water and Civil Engineering (EGC) as well in other courses of University of Montpellier. The teaching load is summarized in Table 1.

Table 1. Teaching

Antoine Rousseau	Teaching M1 level: 0 to 30 hrs/year Student supervision: 50 hrs/year
Carole Delenne	Teaching L1-M2 level: 200-250 hrs/year hydraulics, applied mathematics, informatics Student tutorship and supervision: 50-100 hrs/year
Gwladys Toulemonde	50% CNRS delegation in 2019 Teaching L3/M1/M2 level: 128 hrs in 2019 mathematics, probability, statistics, data mining
Pascal Finaud-Guyot	Teaching L3/M1/M2 level: 200-250 hrs/year hydraulics, applied mathematics, informatics Student tutorship and supervision: 50-100 hrs/year
Vincent Guinot	Teaching L3/M1/M2 level: 290 hrs/year Student tutorship and supervision: 50-100 hrs/year

Gwladys Toulemonde is responsible for student recruitment at the IG department (Polytech Montpellier).

9.2.2. Supervision

PostDoc: Gwladys Toulemonde advises a post-doctoral fellow (F. Palacios-Rodriguez) from october 2017 to september 2019 on spatio-temporal extreme processes to assess flood hazards [11], [12] (NUMEV funding until Oct 2018)

PhD : Gwladys Toulemonde has co-supervised a PhD thesis defended in september 2019 in an established collaboration with Sanofi and is also involved in two other industrial collaborations (BALEA, Twin Solutions)

PhD in progress :

- Vita Ayoub, "Assimilation of satellite derived flood information for better parameterizing and controlling large scale hydraulic models over data scarse areas", november 2018, Carole Delenneand R. Hostache (LIST, Luxembourg).
- Yassine Bel-Ghaddar, "Data fusion for urban network mapping. Application to sanitation networks", may 2019, Carole Delenneand A. Begdouri (LSIA, Fès, Morocco).
- Joseph Luis Kahn Casapia, "Coupling hydro-ecological reduced models for the simulation of fresh water ecosystems", September 2018, Antoine Rousseau and C. Casenave (INRA, Montpellier).
- Joao Guilherme Caldas Steinstraesser, "Coupling large and small scale shallow water models with porosity in the presence of anisotropy", October 2019, Antoine Rousseau and Vincent Guinot.
- Cécile Choley, "Experimental an numerical study of the street-building exchange during urban floods", November 2019, Pascal Finaud-Guyot.

9.2.3. Juries

Gwladys Toulemonde has participated to the PhD thesis jury of Abdul-Fattah Abu-Awwad defended in June 2019 at the University of Lyon.

Carole Delenne was invited member of the PhD thesis jury of Gabrielle Rudi Chovelon, defended in May 2019 at SupAgro Montpellier.

9.3. Popularization

9.3.1. Internal or external Inria responsibilities

Gwladys Toulemonde is involved in the board of the CFEM (commission française pour l'enseignement des mathématiques) since october, 2019, representing the SFdS.

Gwladys Toulemonde is involved in the board of Animath since october, 2019, representing the SFdS.

Gwladys Toulemonde is a member of the organizing committee of the Forum Emploi Math (FEM 2019, Paris).

Antoine Rousseau is member of the scientific board of Fondation Blaise Pascal

Antoine Rousseau is member of the *MakeSEnS* group at Inria, instructed by Inria's management to make proposals for the institute to tackle current environmental issues: see [7]

Antoine Rousseau is co-editor of the national blog binaire, published by Le Monde

9.3.2. Articles and contents

- *Pour une écologie numérique* (in french), blog post on binaire, Antoine Rousseau, 2019.
- *Ces océans qu'on modélise* (in french), blog post on binaire, Antoine Rousseau and coauthors, 2019.

9.3.3. Education

In 2019, Antoine Rousseau gave public lectures in the junior school of Aubais, France (30 kids, 10 years old): 2.5 days of introduction to coding.

9.3.4. Interventions

Antoine Rousseau gave a 2h lecture in Lycée Joffre (high school), Montpellier, France (60 students, 18-20 years old). The conference was linked to the 2019-2020 topic for the french engineering schools competition (TIPE): mathematical modelling for oceans. Antoine Rousseau also dedicated one full day to help young students to design their TIPE project.

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Major publications by the team in recent years

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Articles in International Peer-Reviewed Journal

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Scientific Books (or Scientific Book chapters)

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Research Reports

[7] F. BERTHOUD, P. GUITTON, L. LEFÈVRE, S. QUINTON, A. ROUSSEAU, J. SAINTE-MARIE, C. SERRANO, J.-B. STEFANI, P. STURM, E. A. TANNIER.*Sciences, Environnements et Sociétés : Rapport long du groupe de travail MakeSEnS d'Inria*, Inria, October 2019, https://hal.inria.fr/hal-02340948

Scientific Popularization

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Other Publications

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Project-Team MATHNEURO

Mathematics for Neuroscience

IN COLLABORATION WITH: Laboratoire Jean-Alexandre Dieudonné (JAD)

IN PARTNERSHIP WITH:
CNRS

Université Nice - Sophia Antipolis

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Computational Neuroscience and Medicine

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Project-Team MATHNEURO

Creation of the Team: 2016 January 01, updated into Project-Team: 2019 January 01

Keywords:

Computer Science and Digital Science:

A6. - Modeling, simulation and control
A6.1. - Methods in mathematical modeling
A6.1.1. - Continuous Modeling (PDE, ODE)
A6.1.2. - Stochastic Modeling
A6.1.4. - Multiscale modeling
A6.2. - Scientific computing, Numerical Analysis & Optimization
A6.2.1. - Numerical analysis of PDE and ODE
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A6.2.3. - Probabilistic methods
A6.3. - Computation-data interaction
A6.3.4. - Model reduction

Other Research Topics and Application Domains:

B1. - Life sciences
B1.2. - Neuroscience and cognitive science
B1.2.1. - Understanding and simulation of the brain and the nervous system
B1.2.2. - Cognitive science

1. Team, Visitors, External Collaborators

Research Scientists

Mathieu Desroches [Team leader, Inria, Researcher, HDR]
Fabien Campillo [Inria, Senior Researcher, HDR]
Pascal Chossat [CNRS, Emeritus, HDR]
Olivier Faugeras [Inria, Emeritus, HDR]
Maciej Krupa [Univ Côte d'Azur, LJAD, Senior Researcher]
Simona Olmi [Inria, Starting Research Position]
Romain Veltz [Inria, Researcher]

External Collaborators

Daniele Avitabile [VU Amsterdam, Netherlands]
Benjamin Aymard [Thales, from Mar 2019]
Elif Köksal Ersöz [Univ de Rennes I]

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Yuri Rodrigues [Univ Côte d'Azur, PhD Student]
Halgurd Taher [Inria, PhD Student]

Post-Doctoral Fellows

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Émilie Soret [Inria, Post-Doctoral Fellow, until Aug 2019]

Administrative Assistant

Marie-Cecile Lafont [Inria, Administrative Assistant]

2. Overall Objectives

2.1. Overall Objectives

MATHNEURO focuses on the applications of multi-scale dynamics to neuroscience. This involves the modelling and analysis of systems with multiple time scales and space scales, as well as stochastic effects. We look both at single-cell models, microcircuits and large networks. In terms of neuroscience, we are mainly interested in questions related to synaptic plasticity and neuronal excitability, in particular in the context of pathological states such as epileptic seizures and neurodegenerative diseases such as Alzheimer.

Our work is quite mathematical but we make heavy use of computers for numerical experiments and simulations. We have close ties with several top groups in biological neuroscience. We are pursuing the idea that the "unreasonable effectiveness of mathematics" can be brought, as it has been in physics, to bear on neuroscience.

Modeling such assemblies of neurons and simulating their behavior involves putting together a mixture of the most recent results in neurophysiology with such advanced mathematical methods as dynamical systems theory, bifurcation theory, probability theory, stochastic calculus, theoretical physics and statistics, as well as the use of simulation tools.

We conduct research in the following main areas:

1. Neural networks dynamics
2. Mean-field and stochastic approaches
3. Neural fields
4. Slow-fast dynamics in neuronal models
5. Modeling neuronal excitability
6. Synaptic plasticity
7. Visual neuroscience

3. Research Program

3.1. Neural networks dynamics

The study of neural networks is certainly motivated by the long term goal to understand how brain is working. But, beyond the comprehension of brain or even of simpler neural systems in less evolved animals, there is also the desire to exhibit general mechanisms or principles at work in the nervous system. One possible strategy is to propose mathematical models of neural activity, at different space and time scales, depending on the type of phenomena under consideration. However, beyond the mere proposal of new models, which can rapidly result in a plethora, there is also a need to understand some fundamental keys ruling the behaviour of neural networks, and, from this, to extract new ideas that can be tested in real experiments. Therefore, there is a need to make a thorough analysis of these models. An efficient approach, developed in our team, consists of analysing neural networks as dynamical systems. This allows to address several issues. A first, natural issue is to ask about the (generic) dynamics exhibited by the system when control parameters vary. This naturally leads to analyse the bifurcations [70] [71] occurring in the network and which phenomenological parameters control these bifurcations. Another issue concerns the interplay between the neuron dynamics and the synaptic network structure.

3.2. Mean-field and stochastic approaches

Modeling neural activity at scales integrating the effect of thousands of neurons is of central importance for several reasons. First, most imaging techniques are not able to measure individual neuron activity (microscopic scale), but are instead measuring mesoscopic effects resulting from the activity of several hundreds to several hundreds of thousands of neurons. Second, anatomical data recorded in the cortex reveal the existence of structures, such as the cortical columns, with a diameter of about $50\mu m$ to $1mm$, containing of the order of one hundred to one hundred thousand neurons belonging to a few different species. The description of this collective dynamics requires models which are different from individual neurons models. In particular, when the number of neurons is large enough averaging effects appear, and the collective dynamics is well described by an effective mean-field, summarizing the effect of the interactions of a neuron with the other neurons, and depending on a few effective control parameters. This vision, inherited from statistical physics requires that the space scale be large enough to include a large number of microscopic components (here neurons) and small enough so that the region considered is homogeneous.

Our group is developing mathematical and numerical methods allowing on one hand to produce dynamic mean-field equations from the physiological characteristics of neural structure (neurons type, synapse type and anatomical connectivity between neurons populations), and on the other so simulate these equations; see Figure 1. These methods use tools from advanced probability theory such as the theory of Large Deviations [59] and the study of interacting diffusions [3].

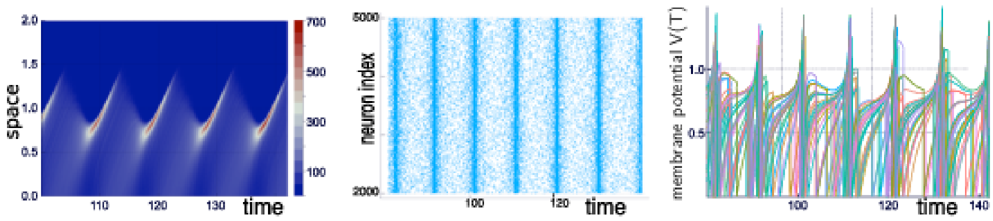

Figure 1. Simulations of the quasi-synchronous state of a stochastic neural network with $N = 5000$ neurons. Left: empirical distribution of membrane potential as a function (t, v). Middle: (raster plot) spiking times as a function of neuron index and time. Right: several membrane potentials $v_i(t)$ as a function of time for $i \in [1, 100]$. Simulated with the Julia Package PDMP.jl from [17]. This figure has been slightly modified from [11].

3.3. Neural fields

Neural fields are a phenomenological way of describing the activity of population of neurons by delayed integro-differential equations. This continuous approximation turns out to be very useful to model large brain areas such as those involved in visual perception. The mathematical properties of these equations and their solutions are still imperfectly known, in particular in the presence of delays, different time scales and noise.

Our group is developing mathematical and numerical methods for analysing these equations. These methods are based upon techniques from mathematical functional analysis, bifurcation theory [14], [72], equivariant bifurcation analysis, delay equations, and stochastic partial differential equations. We have been able to characterize the solutions of these neural fields equations and their bifurcations, apply and expand the theory to account for such perceptual phenomena as edge, texture [50], and motion perception. We have also developed a theory of the delayed neural fields equations, in particular in the case of constant delays and propagation delays that must be taken into account when attempting to model large size cortical areas [16], [73]. This theory is based on center manifold and normal forms ideas [15].

3.4. Slow-fast dynamics in neuronal models

Neuronal rhythms typically display many different timescales, therefore it is important to incorporate this slow-fast aspect in models. We are interested in this modeling paradigm where slow-fast point models, using Ordinary Differential Equations (ODEs), are investigated in terms of their bifurcation structure and the patterns of oscillatory solutions that they can produce. To insight into the dynamics of such systems, we use a mix of theoretical techniques — such as geometric desingularisation and centre manifold reduction [63] — and numerical methods such as pseudo-arclength continuation [54]. We are interested in families of complex oscillations generated by both mathematical and biophysical models of neurons. In particular, so-called *mixed-mode oscillations (MMOs)* [9], [52], [62], which represent an alternation between subthreshold and spiking behaviour, and *bursting oscillations* [53], [60], also corresponding to experimentally observed behaviour [51]; see Figure 2. We are working on extending these results to spatio-temporal neural models [2].

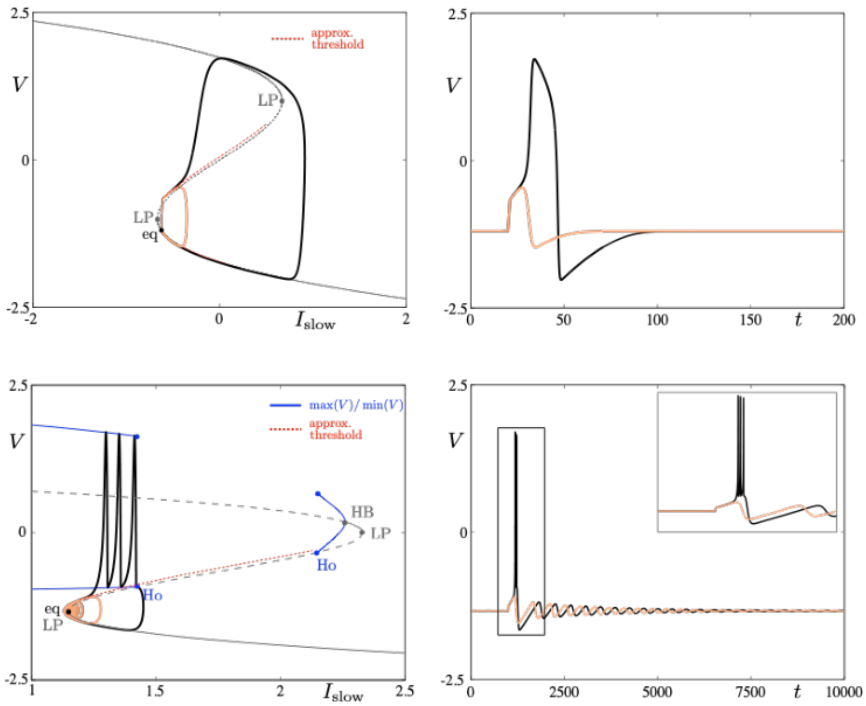

Figure 2. Excitability threshold as slow manifolds in a simple spiking model, namely the FitzHugh-Nagumo model, (top panels) and in a simple bursting model, namely the Hindmarsh-Rose model (bottom panels). This figure is unpublished.

3.5. Modeling neuronal excitability

Excitability refers to the all-or-none property of neurons [58], [61]. That is, the ability to respond nonlinearly to an input with a dramatic change of response from "none" — no response except a small perturbation that returns to equilibrium — to "all" — large response with the generation of an action potential or spike before the neuron returns to equilibrium. The return to equilibrium may also be an oscillatory motion of small amplitude; in this case, one speaks of resonator neurons as opposed to integrator neurons. The combination of a spike followed by subthreshold oscillations is then often referred to as mixed-mode oscillations (MMOs) [52]. Slow-fast ODE models of dimension at least three are well capable of reproducing such complex neural oscillations.

Part of our research expertise is to analyse the possible transitions between different complex oscillatory patterns of this sort upon input change and, in mathematical terms, this corresponds to understanding the bifurcation structure of the model. Furthermore, the shape of time series of this sort with a given oscillatory pattern can be analysed within the mathematical framework of dynamic bifurcations; see the section on slow-fast dynamics in Neuronal Models. The main example of abnormal neuronal excitability is hyperexcitability and it is important to understand the biological factors which lead to such excess of excitability and to identify (both in detailed biophysical models and reduced phenomenological ones) the mathematical structures leading to these anomalies. Hyperexcitability is one important trigger for pathological brain states related to various diseases such as chronic migraine [65], epilepsy [75] or even Alzheimer's Disease [64]. A central central axis of research within our group is to revisit models of such pathological scenarios, in relation with a combination of advanced mathematical tools and in partnership with biological labs.

3.6. Synaptic Plasticity

Neural networks show amazing abilities to evolve and adapt, and to store and process information. These capabilities are mainly conditioned by plasticity mechanisms, and especially synaptic plasticity, inducing a mutual coupling between network structure and neuron dynamics. Synaptic plasticity occurs at many levels of organization and time scales in the nervous system [49]. It is of course involved in memory and learning mechanisms, but it also alters excitability of brain areas and regulates behavioral states (e.g., transition between sleep and wakeful activity). Therefore, understanding the effects of synaptic plasticity on neurons dynamics is a crucial challenge.

Our group is developing mathematical and numerical methods to analyse this mutual interaction. On the one hand, we have shown that plasticity mechanisms [8], [13], Hebbian-like or STDP, have strong effects on neuron dynamics complexity, such as synaptic and propagation delays [16], dynamics complexity reduction, and spike statistics.

4. Highlights of the Year

4.1. Highlights of the Year

4.1.1. Awards

Ariane Delrocq received on 29th November 2019, a price from Ecole Polytechnique Paris for her research internship co-supervised by E. Deval and R. Veltz.

5. New Results

5.1. Neural Networks as dynamical systems

5.1.1. Metastable Resting State Brain Dynamics

Participants: Peter Beim Graben [Brandenburg University of Technology Cottbus, Germany], Antonio Jimenez-Marin [Computational Neuroimaging Lab, BioCruces-Bizkaia Health Research Institute, Spain], Ibai Diez [Harvard Medical School, Massachusetts General Hospital, Boston, MA, USA], Jesus M Cortes [Computational Neuroimaging Lab, BioCruces-Bizkaia Health Research Institute, Spain], Mathieu Desroches, Serafim Rodrigues [Ikerbasque & MCEN team, Basque Center for Applied Mathematics, Spain].

Metastability refers to the fact that the state of a dynamical system spends a large amount of time in a restricted region of its available phase space before a transition takes place, bringing the system into another state from where it might recur into the previous one. Beim Graben and Hutt (2013) [74] suggested to use the recurrence plot (RP) technique introduced by Eckmann et al. (1987) [57] for the segmentation of system's trajectories into metastable states using recurrence grammars. Here, we apply this recurrence structure analysis (RSA) for the first time to resting-state brain dynamics obtained from functional magnetic resonance imaging (fMRI). Brain regions are defined according to the brain hierarchical atlas (BHA) developed by Diez et al. (2015) [56], and as a consequence, regions present high-connectivity in both structure (obtained from diffusion tensor imaging) and function (from the blood-level dependent-oxygenation–BOLD–signal). Remarkably, regions observed by Diez et al. were completely time-invariant. Here, in order to compare this static picture with the metastable systems dynamics obtained from the RSA segmentation, we determine the number of metastable states as a measure of complexity for all subjects and for region numbers varying from 3 to 100. We find RSA convergence toward an optimal segmentation of 40 metastable states for normalized BOLD signals, averaged over BHA modules. Next, we build a bistable dynamics at population level by pooling 30 subjects after Hausdorff clustering. In link with this finding, we reflect on the different modeling frameworks that can allow for such scenarios: heteroclinic dynamics, dynamics with riddled basins of attraction, multiple timescale dynamics. Finally, we characterize the metastable states both functionally and structurally, using templates for resting state networks (RSNs) and the automated anatomical labeling (AAL) atlas, respectively.

This work has been published in Frontiers in Computational Neuroscience and is available as [20].

5.1.2. Controlling seizure propagation in large-scale brain networks

Participants: Simona Olmi, Spase Petkoski [Institut de Neurosciences des Systèmes, Marseille], Maxime Guye [CEMEREM, Hôpital de la Timone, Marseille], Fabrice Bartolomei [Hôpital de la Timone, Marseille], Viktor Jirsa [Institut de Neurosciences des Systèmes, Marseille].

Information transmission in the human brain is a fundamentally dynamic network process. In partial epilepsy, this process is perturbed and highly synchronous seizures originate in a local network, the so-called epileptogenic zone (EZ), before recruiting other close or distant brain regions. We studied patient-specific brain network models of 15 drug-resistant epilepsy patients with implanted stereotactic electroencephalography (SEEG) electrodes. Each personalized brain model was derived from structural data of magnetic resonance imaging (MRI) and diffusion tensor weighted imaging (DTI), comprising 88 nodes equipped with region specific neural mass models capable of demonstrating a range of epileptiform discharges. Each patients virtual brain was further personalized through the integration of the clinically hypothesized EZ. Subsequent simulations and connectivity modulations were performed and uncovered a finite repertoire of seizure propagation patterns. Across patients, we found that (i) patient-specific network connectivity is predictive for the subsequent seizure propagation pattern; (ii) seizure propagation is characterized by a systematic sequence of brain states; (iii) propagation can be controlled by an optimal intervention on the connectivity matrix; (iv) the degree of invasiveness can be significantly reduced via the here proposed seizure control as compared to traditional resective surgery. To stop seizures, neurosurgeons typically resect the EZ completely. We showed that stability analysis of the network dynamics using graph theoretical metrics estimates reliably the spatiotemporal properties of seizure propagation. This suggests novel less invasive paradigms of surgical interventions to treat and manage partial epilepsy.

This work has been published in PLoS Computational Biology and is available as [29].

5.1.3. Chimera states in pulse coupled neural networks: the influence of dilution and noise

Participants: Simona Olmi, Alessandro Torcini [Institute of Complex Systems, Florence, Italy].

We analyse the possible dynamical states emerging for two symmetrically pulse coupled populations of leaky integrate-and-fire neurons. In particular, we observe broken symmetry states in this set-up: namely, breathing chimeras, where one population is fully synchronized and the other is in a state of partial synchronization (PS) as well as generalized chimera states, where both populations are in PS, but with different levels of synchronization. Symmetric macroscopic states are also present, ranging from quasi-periodic motions, to collective chaos, from splay states to population anti-phase partial synchronization. We then investigate the influence disorder, random link removal or noise, on the dynamics of collective solutions in this model. As a result, we observe that broken symmetry chimera-like states, with both populations partially synchronized, persist up to 80 % of broken links and up to noise amplitudes 8 % of threshold-reset distance. Furthermore, the introduction of disorder on symmetric chaotic state has a constructive effect, namely to induce the emergence of chimera-like states at intermediate dilution or noise level.

This work has been published as a chapter in the book Nonlinear Dynamics in Computational Neuroscience (Springer, 2019) and is available as [35].

5.1.4. Enhancing power grid synchronization and stability through time delayed feedback control

Participants: Halgurd Taher, Simona Olmi, Eckehard Schöll [Technical University Berlin, Germany].

We study the synchronization and stability of power grids within the Kuramoto phase oscillator model with inertia with a bimodal frequency distribution representing the generators and the loads. We identify critical nodes through solitary frequency deviations and Lyapunov vectors corresponding to unstable Lyapunov exponents. To cure dangerous deviations from synchronization we propose time-delayed feedback control, which is an efficient control concept in nonlinear dynamic systems. Different control strategies are tested and compared with respect to the minimum number of controlled nodes required to achieve synchronization and Lyapunov stability. As a proof of principle, this fast-acting control method is demonstrated using a model of the German power transmission grid.

This work has been published in Physical Review E and is available as [32].

5.1.5. Stability and control of power grids with diluted network topology

Participants: Liudmila Tumash [gipsa-lab, CNRS, Grenoble], Simona Olmi, Eckehard Schöll [Technical University Berlin, Germany].

In the present study we consider a random network of Kuramoto oscillators with inertia in order to mimic and investigate the dynamics emerging in high-voltage power grids. The corresponding natural frequencies are assumed to be bimodally Gaussian distributed, thus modeling the distribution of both power generators and consumers: for the stable operation of power systems these two quantities must be in balance. Since synchronization has to be ensured for a perfectly working power grid, we investigate the stability of the desired synchronized state. We solve this problem numerically for a population of N rotators regardless of the level of quenched disorder present in the topology. We obtain stable and unstable solutions for different initial phase conditions, and we propose how to control unstable solutions, for sufficiently large coupling strength, such that they are stabilized for any initial phase. Finally, we examine a random Erdös-Renyi network under the impact of white Gaussian noise, which is an essential ingredient for power grids in view of increasing renewable energy sources.

This work has been published in Chaos: An Interdisciplinary Journal of Nonlinear Science and is available as [33].

5.1.6. Modeling dopaminergic modulation of clustered gamma rhythms

Participants: Denis Zakharov [Center for Cognition and Decision Making, HSE, Moscow, Russia], Martin Krupa [UCA, LJAD, Inria MathNeuro], Boris Gutkin [Laboratoire de Neurosciences Cognitives, ENS, Paris].

Gamma rhythm (20-100Hz) plays a key role in numerous cognitive tasks: working memory, sensory processing and in routing of information across neural circuits. In comparison with lower frequency oscillations in the brain, gamma-rhythm associated firing of the individual neurons is sparse and the activity is locally distributed in the cortex. Such "weak" gamma rhythm results from synchronous firing of pyramidal neurons in an interplay with the local inhibitory interneurons in a "pyramidal-interneuron gamma" or PING. Experimental evidence shows that individual pyramidal neurons during such oscillations tend to fire at rates below gamma, with the population showing clear gamma oscillations and synchrony. One possible way to describe such features is that this gamma oscillation is generated within local synchronous neuronal clusters. The number of such synchronous clusters defines the overall coherence of the rhythm and its spatial structure. The number of clusters in turn depends on the properties of the synaptic coupling and the intrinsic properties of the constituent neurons. We previously showed that a slow spike frequency adaptation current in the pyramidal neurons can effectively control cluster numbers. These slow adaptation currents are modulated by endogenous brain neuromodulators such as dopamine, whose level is in turn related to cognitive task requirements. Hence we postulate that dopaminergic modulation can effectively control the clustering of weak gamma and its coherence. In this paper we study how dopaminergic modulation of the network and cell properties impacts the cluster formation process in a PING network model.

This work has been accepted for publication in Communications in Nonlinear Science and Numerical Simulation and is available as [34].

5.2. Mean field theory and stochastic processes

5.2.1. Mean-field limit of interacting 2D nonlinear stochastic spiking neurons

Participants: Benjamin Aymard, Fabien Campillo, Romain Veltz.

In this work, we propose a nonlinear stochastic model of a network of stochastic spiking neurons. We heuristically derive the mean-field limit of this system. We then design a Monte Carlo method for the simulation of the microscopic system, and a finite volume method (based on an upwind implicit scheme) for the mean-field model. The finite volume method respects numerical versions of the two main properties of the mean-field model, conservation and positivity, leading to existence and uniqueness of a numerical solution. As the size of the network tends to infinity, we numerically observe propagation of chaos and convergence from an individual description to a mean-field description. Numerical evidences for the existence of a Hopf bifurcation (synonym of synchronised activity) for a sufficiently high value of connectivity, are provided.

This work has been submitted for publication and is available as [38].

5.2.2. Stochastic modeling for biotechnologies Anaerobic model AM2b

Participants: Fabien Campillo, Mohsen Chebbi [ENIT, University of Tunis, Tunisia], Salwa Toumi [INSAT, University of Carthage, Tunisia].

The model AM2b is conventionally represented by a system of differential equations. However, this model is valid only in a large population context and our objective is to establish several stochastic models at different scales. At a microscopic scale, we propose a pure jump stochastic model that can be simulated exactly. But in most situations this exact simulation is not feasible, and we propose approximate simulation methods of Poisson type and of diffusive type. The diffusive type simulation method can be seen as a discretization of a stochastic differential equation. Finally, we formally present a result of law of large numbers and of functional central limit theorem which demonstrates the convergence of these stochastic models towards the initial deterministic models.

This work has been published in ARIMA and is available as [22].

5.2.3. Cross frequency coupling in next generation inhibitory neural mass models

Participants: Andrea Ceni [University of Exeter, UK], Simona Olmi, Alessandro Torcini [Institute of Complex Systems, Florence, Italy], David Angulo-Garcia [Polytechnic University of Cartagena, Colombia].

Coupling among neural rhythms is one of the most important mechanisms at the basis of cognitive processes in the brain. In this study we consider a neural mass model, rigorously obtained from the microscopic dynamics of an inhibitory spiking network with exponential synapses, able to autonomously generate collective oscillations (COs). These oscillations emerge via a super-critical Hopf bifurcation, and their frequencies are controlled by the synaptic time scale, the synaptic coupling and the excitability of the neural population. Furthermore, we show that two inhibitory populations in a master-slave configuration with different synaptic time scales can display various collective dynamical regimes: namely, damped oscillations towards a stable focus, periodic and quasi-periodic oscillations, and chaos. Finally, when bidirectionally coupled the two inhibitory populations can exhibit different types of theta-gamma cross-frequency couplings (CFCs): namely, phase-phase and phase-amplitude CFC. The coupling between theta and gamma COs is enhanced in presence of a external theta forcing, reminiscent of the type of modulation induced in Hippocampal and Cortex circuits via optogenetic drive.

This work has been submitted for publication and is available as [40].

5.2.4. Conductance-Based Refractory Density Approach for a Population of Bursting Neurons

Participants: Anton Chizhov [IOFFE Institute, St Petersburg, Russia], Fabien Campillo, Mathieu Desroches, Antoni Guillamon [Polytechnic University of Catalonia, Barcelona, Spain], Serafim Rodrigues [Ikerbasque & MCEN team, Basque Center for Applied Mathematics, Spain].

The conductance-based refractory density (CBRD) approach is a parsimonious mathematical-computational framework for modelling interacting populations of regular spiking neurons, which, however, has not been yet extended for a population of bursting neurons. The canonical CBRD method allows to describe the firing activity of a statistical ensemble of uncoupled Hodgkin-Huxley-like neurons (differentiated by noise) and has demonstrated its validity against experimental data. The present manuscript generalises the CBRD for a population of bursting neurons; however, in this pilot computational study, we consider the simplest setting in which each individual neuron is governed by a piecewise linear bursting dynamics. The resulting population model makes use of slow-fast analysis, which leads to a novel methodology that combines CBRD with the theory of multiple timescale dynamics. The main prospect is that it opens novel avenues for mathematical explorations, as well as, the derivation of more sophisticated population activity from Hodgkin-Huxley-like bursting neurons, which will allow to capture the activity of synchronised bursting activity in hyper-excitable brain states (e.g. onset of epilepsy).

This work has been published in Bulletin of Mathematical Biology and is available as [23].

5.2.5. Long time behavior of a mean-field model of interacting neurons

Participants: Quentin Cormier [Inria Tosca], Étienne Tanré [Inria Tosca], Romain Veltz.

We study the long time behavior of the solution to some McKean-Vlasov stochastic differential equation (SDE) driven by a Poisson process. In neuroscience, this SDE models the asymptotic dynamics of the membrane potential of a spiking neuron in a large network. We prove that for a small enough interaction parameter, any solution converges to the unique (in this case) invariant measure. To this aim, we first obtain global bounds on the jump rate and derive a Volterra type integral equation satisfied by this rate. We then replace temporary the interaction part of the equation by a deterministic external quantity (we call it the external current). For constant current, we obtain the convergence to the invariant measure. Using a perturbation method, we extend this result to more general external currents. Finally, we prove the result for the non-linear McKean-Vlasov equation.

This work has been published in Stochastic Processes and their Applications and is available as [24].

5.2.6. Effective low-dimensional dynamics of a mean-field coupled network of slow-fast spiking lasers

Participants: Axel Dolcemascolo [INPHYNI, Nice], Alexandre Miazek [INPHYNI, Nice], Romain Veltz, Francesco Marino [National Institute of Optics, Italy], Stéphane Barland [INPHYNI, Nice].

Low dimensional dynamics of large networks is the focus of many theoretical works, but controlled laboratory experiments are comparatively very few. Here, we discuss experimental observations on a mean-field coupled network of hundreds of semiconductor lasers, which collectively display effectively low-dimensional mixed mode oscillations and chaotic spiking typical of slow-fast systems. We demonstrate that such a reduced dimensionality originates from the slow-fast nature of the system and of the existence of a critical manifold of the network where most of the dynamics takes place. Experimental measurement of the bifurcation parameter for different network sizes corroborate the theory.

This work has been submitted for publication and is available as [42].

5.2.7. The mean-field limit of a network of Hopfield neurons with correlated synaptic weights

Participants: Olivier Faugeras, James Maclaurin [NJIT, USA], Étienne Tanré [Inria Tosca].

We study the asymptotic behaviour for asymmetric neuronal dynamics in a network of Hopfield neurons. The randomness in the network is modelled by random couplings which are centered Gaussian correlated random variables. We prove that the annealed law of the empirical measure satisfies a large deviation principle without any condition on time. We prove that the good rate function of this large deviation principle achieves its minimum value at a unique Gaussian measure which is not Markovian. This implies almost sure convergence of the empirical measure under the quenched law. We prove that the limit equations are expressed as an infinite countable set of linear non Markovian SDEs.

This work has been submitted for publication and is available as [43].

5.2.8. Asymptotic behaviour of a network of neurons with random linear interactions

Participants: Olivier Faugeras, Émilie Soret, Étienne Tanré [Inria Tosca].

We study the asymptotic behaviour for asymmetric neuronal dynamics in a network of linear Hopfield neurons. The randomness in the network is modelled by random couplings which are centered i.i.d. random variables with finite moments of all orders. We prove that if the initial condition of the network is a set of i.i.d random variables with finite moments of all orders and independent of the synaptic weights, each component of the limit system is described as the sum of the corresponding coordinate of the initial condition with a centered Gaussian process whose covariance function can be described in terms of a modified Bessel function. This process is not Markovian. The convergence is in law almost surely w.r.t. the random weights. Our method is essentially based on the CLT and the method of moments.

This work has been submitted for publication and is available as [44].

5.2.9. On a toy network of neurons interacting through their dendrites

Participants: Nicolas Fournier [LPSM, Sorbonne Université], Étienne Tanré [Inria Tosca], Romain Veltz.

Consider a large number n of neurons, each being connected to approximately N other ones, chosen at random. When a neuron spikes, which occurs randomly at some rate depending on its electric potential, its potential is set to a minimum value vmin, and this initiates, after a small delay, two fronts on the (linear) dendrites of all the neurons to which it is connected. Fronts move at constant speed. When two fronts (on the dendrite of the same neuron) collide, they annihilate. When a front hits the soma of a neuron, its potential is increased by a small value w_n. Between jumps, the potentials of the neurons are assumed to drift in $[v_{min}, \infty)$, according to some well-posed ODE. We prove the existence and uniqueness of a heuristically derived mean-field limit of the system when $n, N \to \infty$ with $w_n \simeq N^{-1/2}$. We make use of some recent versions of the results of Deuschel and Zeitouni [55] concerning the size of the longest increasing subsequence of an i.i.d. collection of points in the plan. We also study, in a very particular case, a slightly different model where the neurons spike when their potential reach some maximum value v_{max}, and find an explicit formula for the (heuristic) mean-field limit.

This work has been accepted for publication in Annales de l'Institut Henri Poincaré (B) Probabilités et Statistiques and is available as [27].

5.2.10. Bumps and oscillons in networks of spiking neurons

Participants: Helmut Schmidt [Max Planck Institute for Human Cognitive and Brain Science, Germany], Daniele Avitabile [VU Amsterdam, Inria MathNeuro].

We study localized patterns in an exact mean-field description of a spatially-extended network of quadratic integrate-and-fire (QIF) neurons. We investigate conditions for the existence and stability of localized solutions, so-called bumps, and give an analytic estimate for the parameter range where these solutions exist in parameter space, when one or more microscopic network parameters are varied. We develop Galerkin methods for the model equations, which enable numerical bifurcation analysis of stationary and time-periodic spatially-extended solutions. We study the emergence of patterns composed of multiple bumps, which are arranged in a snake-and-ladder bifurcation structure if a homogeneous or heterogeneous synaptic kernel is suitably chosen. Furthermore, we examine time-periodic, spatially-localized solutions (oscillons) in the presence of external forcing, and in autonomous, recurrently coupled excitatory and inhibitory networks. In both cases we observe period doubling cascades leading to chaotic oscillations.

This work has been submitted for publication and is available as [46].

5.2.11. Slow-fast dynamics in the mean-field limit of neural networks

Participants: Daniele Avitabile [VU Amsterdam, Inria MathNeuro], Emre Baspinar, Mathieu Desroches, Olivier Faugeras.

In the context of the Human Brain Project (HBP, see section 5.1.1.1. below), we have recruited Emre Baspinar in December 2018 for a two-year postdoc. Within MathNeuro, Emre is working on analysing slow-fast dynamical behaviours in the mean-field limit of neural networks.
In a first project, he has been analysing the slow-fast structure in the mean-field limit of a network of FitzHugh-Nagumo neuron models; the mean-field was previously established in [3] but its slow-fast aspect had not been analysed. In particular, he has proved a persistence result of Fenichel type for slow manifolds in this mean-field limit, thus extending previous work by Berglund *et al.* [47], [48]. A manuscript is in preparation.
In a second project, he has been looking at a network of Wilson-Cowan systems whose mean-field limit is an ODE, and he has studied elliptic bursting dynamics in both the network and the limit: its slow-fast dissection, its singular limits and the role of canards. In passing, he has obtained a new characterisation of ellipting bursting via the construction of periodic limit sets using both the slow and the fast singular limits and unravelled a new singular-limit scenario giving rise to elliptic bursting via a new type of torus canard orbits. A manuscript is in preparation.

5.3. Neural fields theory

5.3.1. Next-generation neural field model: The evolution of synchrony within patterns and waves

Participants: Áine Byrne [Center for Neural Science, New York University, USA], Daniele Avitabile [VU Amsterdam, Inria MathNeuro], Stephen Coombes [University of Nottingham, UK].

Neural field models are commonly used to describe wave propagation and bump attractors at a tissue level in the brain. Although motivated by biology, these models are phenomenological in nature. They are built on the assumption that the neural tissue operates in a near synchronous regime, and hence, cannot account for changes in the underlying synchrony of patterns. It is customary to use spiking neural network models when examining within population synchronization. Unfortunately, these high-dimensional models are notoriously hard to obtain insight from. In this paper, we consider a network of θ-neurons, which has recently been shown to admit an exact mean-field description in the absence of a spatial component. We show that the inclusion of space and a realistic synapse model leads to a reduced model that has many of the features of a standard neural field model coupled to a further dynamical equation that describes the evolution of network synchrony. Both Turing instability analysis and numerical continuation software are used to explore the existence and stability of spatiotemporal patterns in the system. In particular, we show that this new model can support states above and beyond those seen in a standard neural field model. These states are typified by structures within bumps and waves showing the dynamic evolution of population synchrony.

This work has been published in Physical Review E and is available as [21].

5.3.2. The hyperbolic model for edge and texture detection in the primary visual cortex

Participant: Pascal Chossat [CNRS, Inria MathNeuro].

The modelling of neural fields in the visual cortex involves geometrical structures which describe in mathematical formalism the functional architecture of this cortical area. The case of contour detection and orientation tuning has been extensively studied and has become a paradigm for the mathematical analysis of image processing by the brain. Ten years ago an attempt was made to extend these models by replacing orientation (an angle) with a second-order tensor built from the gradient of the image intensity and named the structure tensor. This assumption does not follow from biological observations (experimental evidence is still lacking) but from the idea that the effectiveness of texture processing with the stucture tensor in computer vision may well be exploited by the brain itself. The drawback is that in this case the geometry is not Euclidean but hyperbolic instead, which complicates substantially the analysis. The purpose of this review is to present the methodology that was developed in a series of papers to investigate this quite unusual problem, specifically from the point of view of tuning and pattern formation. These methods, which rely on bifurcation theory with symmetry in the hyperbolic context, might be of interest for the modelling of other features such as color vision, or other brain functions.

This work has been accepted for publication in Journal of Mathematical Neuroscience and is available as [41].

5.3.3. A neural field model for color perception unifying assimilation and contrast

Participants: Anna Song [ENS Paris, France], Olivier Faugeras, Romain Veltz.

We address the question of color-space interactions in the brain, by proposing a neural field model of color perception with spatial context for the visual area V1 of the cortex. Our framework reconciles two opposing perceptual phenomena, known as simultaneous contrast and chromatic assimilation. They have been previously shown to act synergistically, so that at some point in an image, the color seems perceptually more similar to that of adjacent neighbors, while being more dissimilar from that of remote ones. Thus, their combined effects are enhanced in the presence of a spatial pattern, and can be measured as larger shifts in color matching experiments. Our model supposes a hypercolumnar structure coding for colors in V1, and relies on the notion of color opponency introduced by Hering. The connectivity kernel of the neural field exploits the balance between attraction and repulsion in color and physical spaces, so as to reproduce the sign reversal in the influence of neighboring points. The color sensation at a point, defined from a steady state of the neural activities, is then extracted as a nonlinear percept conveyed by an assembly of neurons. It connects the cortical and perceptual levels, because we describe the search for a color match in asymmetric matching experiments as a mathematical projection on color sensations. We validate our color neural field alongside this color matching framework, by performing a multi-parameter regression to data produced by psychophysicists and ourselves. All the results show that we are able to explain the nonlinear behavior of shifts observed along one or two dimensions in color space, which cannot be done using a simple linear model.

This work has been published in PLoS Computational Biology and is available as [31].

5.4. Slow-fast dynamics in Neuroscience

5.4.1. Local theory for spatio-temporal canards and delayed bifurcations

Participants: Daniele Avitabile [VU Amsterdam, Inria MathNeuro], Mathieu Desroches, Romain Veltz, Martin Wechselberger [University of Sydney, Australia].

We present a rigorous framework for the local analysis of canards and slow passages through bifurcations in a wide class of infinite-dimensional dynamical systems with time-scale separation. The framework is applicable to models where an infinite-dimensional dynamical system for the fast variables is coupled to a finite-dimensional dynamical system for slow variables. We prove the existence of centre-manifolds for generic models of this type, and study the reduced, finite-dimensional dynamics near bifurcations of (possibly) patterned steady states in the layer problem. Theoretical results are complemented with detailed examples and numerical simulations covering systems of local- and nonlocal-reaction diffusion equations, neural field models, and delay-differential equations. We provide analytical foundations for numerical observations recently reported in literature, such as spatio-temporal canards and slow-passages through Hopf bifurcations in spatially-extended systems subject to slow parameter variations. We also provide a theoretical analysis of slow passage through a Turing bifurcation in local and nonlocal models.

This work has been submitted for publication and is available as [37].

5.4.2. Pseudo-plateau bursting and mixed-mode oscillations in a model of developing inner hair cells

Participants: Harun Baldemir, Daniele Avitabile [VU Amsterdam, Inria MathNeuro], Krasimira Tsaneva-Atanasova [University of Exeter, UK].

Inner hair cells (IHCs) are excitable sensory cells in the inner ear that encode acoustic information. Before the onset of hearing IHCs fire calcium-based action potentials that trigger transmitter release onto developing spiral ganglion neurones. There is accumulating experimental evidence that these spontaneous firing patterns are associated with maturation of the IHC synapses and hence involved in the development of hearing. The dynamics organising the IHCs' electrical activity are therefore of interest.
Building on our previous modelling work we propose a three-dimensional, reduced IHC model and carry out non-dimensionalisation. We show that there is a significant range of parameter values for which the dynamics of the reduced (three-dimensional) model map well onto the dynamics observed in the original biophysical (four-dimensional) IHC model. By estimating the typical time scales of the variables in the reduced IHC model we demonstrate that this model could be characterised by two fast and one slow or one fast and two slow variables depending on biophysically relevant parameters that control the dynamics. Specifically, we investigate how changes in the conductance of the voltage-gated calcium channels as well as the parameter corresponding to the fraction of free cytosolic calcium concentration in the model affect the oscillatory model bahaviour leading to transition from pseudo-plateau bursting to mixed-mode oscillations. Hence, using fast-slow analysis we are able to further our understanding of this model and reveal a path in the parameter space connecting pseudo-plateau bursting and mixed-mode oscillations by varying a single parameter in the model.

This work has been accepted for publication in Communications in Nonlinear Science and Numerical Simulation and is available as [18].

5.4.3. *Parabolic bursting, spike-adding, dips and slices in a minimal model*

Participants: Mathieu Desroches, Jean-Pierre Françoise [LJLL, Sorbonne Université, Paris], Martin Krupa [LJAD, UCA, Inria MathNeuro].

A minimal system for parabolic bursting, whose associated slow flow is integrable, is presented and studied both from the viewpoint of bifurcation theory of slow-fast systems, of the qualitative analysis of its phase portrait and of numerical simulations. We focus the analysis on the spike-adding phenomenon. After a reduction to a periodically forced one-dimensional system, we uncover the link with the dips and slices first discussed by J.E. Littlewood in his famous articles on the periodically forced van der Pol system.

This work has been published in Mathematical Modelling of Natural Phenomena and is available as [26].

5.4.4. *Anticipation via canards in excitable systems*

Participants: Elif Köksal Ersöz [INSERM, Rennes, Inria MathNeuro], Mathieu Desroches, Claudio Mirasso [University of the Balearic Islands, Spain], Serafim Rodrigues [Ikerbasque & Basque Center for Applied Mathematics, Spain].

Neurons can anticipate incoming signals by exploiting a physiological mechanism that is not well understood. This article offers a novel explanation on how a receiver neuron can predict the sender's dynamics in a unidirectionally-coupled configuration, in which both sender and receiver follow the evolution of a multi-scale excitable system. We present a novel theoretical viewpoint based on a mathematical object, called *canard*, to explain anticipation in excitable systems. We provide a numerical approach, which allows to determine the transient effects of canards. To demonstrate the general validity of canard-mediated anticipation in the context of excitable systems, we illustrate our framework in two examples, a multi-scale radio-wave circuit (the van der Pol model) that inspired a caricature neuronal model (the FitzHugh-Nagumo model) and a biophysical neuronal model (a 2-dimensional reduction of the Hodgkin-Huxley model), where canards act as messengers to the senders' prediction. We also propose an experimental paradigm that would enable experimental neuroscientists to validate our predictions. We conclude with an outlook to possible fascinating research avenues to further unfold the mechanisms underpinning anticipation. We envisage that our approach can be employed by a wider class of excitable systems with appropriate theoretical extensions.

This work has been published in Chaos: An Interdisciplinary Journal of Nonlinear Science and is available as [28].

5.4.5. Canard-induced complex oscillations in an excitatory network

Participants: Elif Köksal Ersöz, Mathieu Desroches, Antoni Guillamon [Polytechnic University of Catalunya, Spain], John Rinzel [Center for Neural Science and Courant Institute of Mathematical Sciences, New York University, USA], Joel Tabak [University of Exeter, UK].

In this work we have revisited a rate model that accounts for the spontaneous activity in the developing spinal cord of the chicken embryo [69]. The dynamics is that of a classical square-wave burster, with alternation of silent and active phases. Tabak et al. [69] have proposed two different three-dimensional (3D) models with variables representing average population activity, fast activity-dependent synaptic depression and slow activity-dependent depression of two forms. In [66], [67], [68] various 3D combinations of these four variables have been studied further to reproduce rough experimental observations of spontaneous rhythmic activity. In this work, we have first shown the spike-adding mechanism via canards in one of these 3D models from [69] where the fourth variable was treated as a control parameter. Then we discussed how a canard-mediated slow passage in the 4D model explains the sub-threshold oscillatory behavior which cannot be reproduced by any of the 3D models, giving rise to mixed-mode bursting oscillations (MMBOs); see [10]. Finally, we related the canard-mediated slow passage to the intervals of burst and silent phase which have been linked to the blockade of glutamatergic or GABAergic/glycinergic synapses over a wide range of developmental stages [68].

This work has been submitted for publication and is available as [12].

5.5. Mathematical modeling of neuronal excitability

5.5.1. Modeling cortical spreading depression induced by the hyperactivity of interneurons

Participants: Mathieu Desroches, Olivier Faugeras, Martin Krupa [LJAD, UCA, Inria MathNeuro], Massimo Mantegazza [Institut de Pharmacologie Moléculaire et Cellulaire (IPMC), Sophia Antipolis].

Cortical spreading depression (CSD) is a wave of transient intense neuronal firing leading to a long lasting depolarizing block of neuronal activity. It is a proposed pathological mechanism of migraine with aura. Some forms of migraine are associated with a genetic mutation of the $Na_{v1.1}$ channel, resulting in its gain of function and implying hyperexcitability of interneurons. This leads to the counterintuitive hypothesis that intense firing of interneurons can cause CSD ignition. To test this hypothesis in silico, we developed a computational model of an E-I pair (a pyramidal cell and an interneuron), in which the coupling between the cells in not just synaptic, but takes into account also the effects of the accumulation of extracellular potassium caused by the activity of the neurons and of the synapses. In the context of this model, we show that the intense firing of the interneuron can lead to CSD. We have investigated the effect of various biophysical parameters on the transition to CSD, including the levels of glutamate or GABA, frequency of the interneuron firing and the efficacy of the KCC_2 co-transporter. The key element for CSD ignition in our model was the frequency of interneuron firing and the related accumulation of extracellular potassium, which induced a depolarizing block of the pyramidal cell. This constitutes a new mechanism of CSD ignition.

This work has been published in Journal of Computational Neuroscience and is available as [25].

The extension of this work is the topic of the PhD of Louisiane Lemaire, who started in October 2018. A first part of Louisiane's PhD has been to improve and extend the model published in [25] in a number of ways: replace the GABAergic neuron model used in [25], namely the Wang-Buszáki model, by a more recent fast-spiking cortical interneuron model due to Golomb and collaborators; implement the effect of the HM1a toxin used by M. Mantegazza to mimic the genetic mutation of sodium channels responsible for the hyperactivity of the GABAergic neurons; take into account ionic concentration dynamics (relaxing the hypothesis of constant reversal potentials) for the GABAergic as well whereas in [25] this was done only for the Pyramidal neuron. This required a great deal of modelling and calibration and the simulation results are closer to the actual experiments by Mantegazza than in our previous study. A manuscript is in preparation.

5.6. Modelling the visual system

5.6.1. Uniqueness of viscosity mean curvature flow solution in two sub-Riemannian structures

Participants: Emre Baspinar, Giovanna Citti [University of Bologna, Italy].

We provide a uniqueness result for a class of viscosity solutions to sub-Riemannian mean curvature flows. In a sub-Riemannian setting, uniqueness cannot be deduced by the comparison principle, which is known only for graphs and for radially symmetry surfaces. Here we use a definition of continuous viscosity solutions of sub-Riemannian mean curvature flows motivated from a regularized Riemannian approximation of the flow. With this definition, we prove that any continuous viscosity solution of the equation is a limit of a sequence of solutions of Riemannian flow and obtain as a consequence uniqueness and the comparison principle. The results are provided in the settings of both 3-dimensional rototranslation group $SE(2)$ and Carnot groups of step 2, which are particularly important due to their relation to the surface completion problem of a model of the visual cortex.

This work has been published in SIAM Journal on Mathematical Analysis and is available as [19].

5.6.2. A sub-Riemannian model of the visual cortex with frequency and phase

Participants: Emre Baspinar, Alessandro Sarti [CAMS, EHESS, Paris, France], Giovanna Citti [University of Bologna, Italy].

In this paper we present a novel model of the primary visual cortex (V1) based on orientation, frequency and phase selective behavior of the V1 simple cells. We start from the first level mechanisms of visual perception: receptive profiles. The model interprets V1 as a fiber bundle over the 2-dimensional retinal plane by introducing orientation, frequency and phase as intrinsic variables. Each receptive profile on the fiber is mathematically interpreted as a rotated, frequency modulated and phase shifted Gabor function. We start from the Gabor function and show that it induces in a natural way the model geometry and the associated horizontal connectivity modeling the neural connectivity patterns in V1. We provide an image enhancement algorithm employing the model framework. The algorithm is capable of exploiting not only orientation but also frequency and phase information existing intrinsically in a 2-dimensional input image. We provide the experimental results corresponding to the enhancement algorithm.

This work has been submitted for publication and is available as [39].

6. Partnerships and Cooperations

6.1. European Initiatives

6.1.1. FP7 & H2020 Projects

6.1.1.1. HBP

Title: The Human Brain Project

Program: FP7

Duration: October 2013 - March 2016 (first part), then : April 2016 - March 2018 (second part) and then : April 2018 - March 2020 (third part)

Coordinator: EPFL

Partners:
see the webpage of the project.

Olivier Faugeras is leading the task T4.1.3 entitled “Meanfield and population models” of the Worpackage W4.1 “Bridging Scales”.

Inria contact: Olivier Faugeras (first part) and then : Romain Veltz (second and third part)

Understanding the human brain is one of the greatest challenges facing 21st century science. If we can rise to the challenge, we can gain profound insights into what makes us human, develop new treatments for brain diseases and build revolutionary new computing technologies. Today, for the first time, modern ICT has brought these goals within sight. The goal of the Human Brain Project, part of the FET Flagship Programme, is to translate this vision into reality, using ICT as a catalyst for a global collaborative effort to understand the human brain and its diseases and ultimately to emulate its computational capabilities. The Human Brain Project will last ten years and will consist of a ramp-up phase (from month 1 to month 36) and subsequent operational phases.
This Grant Agreement covers the ramp-up phase. During this phase the strategic goals of the project will be to design, develop and deploy the first versions of six ICT platforms dedicated to Neuroinformatics, Brain Simulation, High Performance Computing, Medical Informatics, Neuromorphic Computing and Neurorobotics, and create a user community of research groups from within and outside the HBP, set up a European Institute for Theoretical Neuroscience, complete a set of pilot projects providing a first demonstration of the scientific value of the platforms and the Institute, develop the scientific and technological capabilities required by future versions of the platforms, implement a policy of Responsible Innovation, and a programme of transdisciplinary education, and develop a framework for collaboration that links the partners under strong scientific leadership and professional project management, providing a coherent European approach and ensuring effective alignment of regional, national and European research and programmes. The project work plan is organized in the form of thirteen subprojects, each dedicated to a specific area of activity.
A significant part of the budget will be used for competitive calls to complement the collective skills of the Consortium with additional expertise.

6.2. International Initiatives

6.2.1. Inria Associate Teams Not Involved in an Inria International Labs

6.2.1.1. NeuroTransSF

Title: NeuroTransmitter cycle: A Slow-Fast modeling approach

PI for Inria MathNeuro: Mathieu Desroches

International Partner (Institution - Laboratory - Researcher):

Basque Center for Applied Mathematics (BCAM) (Spain) - Mathematical, Computational and Experimental Neuroscience (MCEN) Team - Serafim Rodrigues

Start year: 2019

See also: https://team.inria.fr/neurotranssf/

This associated team project proposes to deepen the links between two young research groups, on strong Neuroscience thematics. This project aims to start from a joint work in which we could successfully model synaptic transmission delays for both excitatory and inhibitory synapses, matching experimental data, and to supplant it in two distinct directions. On the one hand, by modeling the endocytosis so as to obtain a complete mathematical formulation of the presynaptic neurotransmitter cycle, which will then be integrated within diverse neuron models (in particular interneurons) hence allowing a refined analysis of their excitability and short-term plasticity properties. On the other hand, by modeling the postsynaptic neurotransmitter cycle in link with long-term plasticity and memory. We will incorporate these new models of synapse in different types of neuronal networks and we will then study their excitability, plasticity and synchronisation properties in comparison with classical models. This project will benefit from strong experimental collaborations (UCL, Alicante) and it is coupled to the study of brain pathologies linked with synaptic dysfunctions, in particular certain early signs of Alzheimer's Disease. Our initiative also contains a training aspect with two PhD student involved as well as a series of mini-courses which we will propose to the partner institute on this research topic; we will also organise a "wrap-up" workshop in Sophia at the end of it. Finally, the project is embedded within a strategic tightening of our links with Spain with the objective of pushing towards the creation of a Southern-Europe network for Mathematical, Computational and Experimental Neuroscience, which will serve as a stepping stone in order to extend our influence beyond Europe.

6.2.2. Inria International Partners

6.2.2.1. Informal International Partners

VU Amsterdam (Netherlands), Faculty of Science, Mathematics: Daniele Avitabile

ENS Paris, Laboratoire de Neurosciences Cognitives: Boris Gutkin

University of the Balearic Islands (Spain), Dept of Applied Mathematics: Antonio Teruel

Polytechnic University of Catalunya (Spain), Dept of Applied Mathematics: Antoni Guillamon

6.3. International Research Visitors

6.3.1. Visits of International Scientists

Invitation of Nikola Popovic, University of Edinburgh (UK), April 2019

Invitation of Tomás Lázaro, Polytechnic University of Catalunya (Spain), May 2019

6.3.1.1. Internships

Ariane Delrocq (étudiante Ecole Polytechnique, Paris): April - July 2019

6.3.2. Visits to International Teams

Visit of Yuri Rodrigues and Romain Veltz to Cian O'Donnell (University of Bristol, UK) in December 2019

6.3.2.1. Research Stays Abroad

One-month research stay of Mathieu Desroches at BCAM (Bilbao, Spain) on an invited professor scholarship to work with Serafim Rodrigues, June-July 2019

7. Dissemination

7.1. Promoting Scientific Activities

7.1.1. Scientific Events: Organisation

7.1.1.1. General Chair, Scientific Chair

Mathieu Desroches was one of the Program Chairs of the Waves Côte d'Azur conference, held in Nice, 4-7 June, 2019.

7.1.1.2. Member of the Organizing Committees

Mathieu Desroches was on the Scientific Committee of the Waves Côte d'Azur conference, held in Nice, 4-7 June, 2019.

Olivier Faugeras and Romain Veltz were on the Advisory Board of the 5th International Conference on Mathematical Neuroscience, held in Copenhagen (Denmark), June 24 - 26, 2019.

7.1.2. Journal

7.1.2.1. Member of the Editorial Boards

Olivier Faugeras is the co-editor in chief of the open access Journal of Mathematical Neuroscience. This journal has a 2-year Impact Factor of 2.091.

Mathieu Desroches was Guest Editor of a Special Issue on "Excitable Dynamics in Neural and Cardiac Systems" of the journal Communications in Nonlinear Science and Numerical Simulation. This journal has 5-year Impact Factor of 3.637.

7.1.2.2. Reviewer - Reviewing Activities

Fabien Campillo acts as a reviewer for Journal of Mathematical Biology.

Mathieu Desroches acts as a reviewer for Physica D, SIAM Journal on Applied Dynamical Systems (SIADS), PLoS Computational Biology, Chaos: An International Journal of Nonlinear Science, Journal of Mathematical Biology, Journal of Neurophysiology, Journal of Mathematical Neuroscience, Nonlinear Dynamics.

Olivier Faugeras acts as a reviewer for the Journal of Mathematical Neuroscience, the Journal of Computational Neuroscience, the SIAM Journal on Applied Dynamical Systems (SIADS).

Martin Krupa acts as a reviewer for Nonlinearity, Proceedings of the National Academy of Sciences of the USA (PNAS), the SIAM Journal of Applied Dynamical Systems (SIADS).

Romain Veltz acts as a reviewer for Neural Computation, eLIFE, SIADS, PNAS, Journal of the Royal Society Interface, Plos Computational Biology and Acta Applicandae Mathematicae.

7.1.3. Invited Talks

Emre Baspinar, “A geometric model with frequency-phase and its application to image enhancemen”, conference “Shape Analysis in Biology”, Sorbonne Université, Paris, November 2019

Emre Baspinar, “A sub-Riemannian cortical model with frequency-phase and its application to orientation map construction.”, 1st meeting of the NeuroMod Institute, Fréjus (France), July 2019.

Emre Baspinar, “A sub-Riemannian model of the visual cortex based on frequency-phase and its applications” [poster], 5th International Conference on Mathematical Neuroscience, Copenhagen (Denmark), June 2019.

Emre Baspinar, “A sub-Riemannian cortical model with frequency-phase and its application to orientation map construction.”, Waves Côte d’Azur Conference, Nice (France), June 2019.

Mathieu Desroches, “Canards in excitatory networks”, XXXIXth Dynamics Days Europe Conference, Rostock (Germany), September 2019.

Mathieu Desroches, “Canards and spike-adding in neural bursters”, International Congress on Industrial and Applied Mathematics (ICIAM), Valencia (Spain), July 2019.

Mathieu Desroches, “Canards in excitatory networks”, SIAM Conference on Application of Dynamical Systems, Snowbird (USA), May 2019.

Mathieu Desroches, “Slow-fast analysis of bursting oscillations: old and new”, Bilateral International Meeting UK-France, Royal Society, Chicheley Hall, Milton Keynes (UK), February 2019.

Olivier Faugeras, “The meanfield limit of a network of Hopfield neurons with correlated synaptic weights”, Bilateral International Meeting UK-France, Royal Society, Chicheley Hall, Milton Keynes (UK), February 2019.

Louisiane Lemaire, “Modeling the initiation of cortical spreading depression triggered by the hyperactivity of GABAergic neurons” [poster], 1st meeting of the NeuroMod Institute, Fréjus (France), July 2019.

Louisiane Lemaire, “Modeling the initiation of cortical spreading depression triggered by the hyperactivity of GABAergic neurons” [poster], 5th International Conference on Mathematical Neuroscience, Copenhagen (Denmark), June 2019.

Martin Krupa, “Neuronal mechanisms for sequential activation of memory items”, International Congress on Industrial and Applied Mathematics (ICIAM), Valencia (Spain), July 2019.

Martin Krupa, “Modeling cortical spreading depression induced by the hyperactivity of interneurons”, Waves Côte d’Azur Conference, Nice (France), June 2019.

Simona Olmi, “Cross frequency coupling in next generation inhibitory neural mass models", Eugene Wigner Colloquium (Physics Colloquium), TU Berlin, Berlin (Germany), December 2019.

Simona Olmi, “Cross frequency coupling in next generation inhibitory neural mass models, XXXIXth Dynamics Days Europe Conference, Rostock (Germany), September 2019.

Simona Olmi, “Influence of network topology on spreading of epileptic seizure”, Waves Côte d’Azur Conference, Nice (France), June 2019.

Simona Olmi, “Influence of network topology on spreading of epileptic seizure", XXIV Convegno Nazionale di Fisica Statistica e dei Sistemi Complessi, Parma (Italy), June 2019.

Simona Olmi, “Enhancing power grid synchronization and stability through time delayed feedback control”, EPS conference “Statistical Physics of Complex Systems”, Stockholm (Sweden), May 2019.

Simona Olmi, “The Kuramoto model with inertia: from fireflies to power grids”, School and Workshop on Patterns of Synchrony: Chimera States and Beyond, Trieste (Italy), May 2019.

Yuri Rodrigues, “: A stochastic model of postsynaptic plasticity based on dendritic spine Ca^2+ downstream proteins”, PhD Seminar, Inria Sophia Antipolis, December 2019.

Yuri Rodrigues, “Towards a stochastic model of excitatory synapse”, 1st meeting of the NeuroMod Institute, Fréjus (France), July 2019.

Yuri Rodrigues, “A stochastic model of postsynaptic plasticity based on dendritic spine Ca^2+ downstream proteins” [poster], 5th International Conference on Mathematical Neuroscience, Copenhagen (Denmark), June 2019.

Halgurd Taher, “Heuristic mean-field model for short term synaptic plasticity” [poster], XXXIXth Dynamics Days Europe Conference, Rostock (Germany), September 2019.

Halgurd Taher, “Enhancing power grid synchronization and stability through time delayed feedback control”, XXXIXth Dynamics Days Europe Conference, Rostock (Germany), September 2019.

Halgurd Taher, “Mean-field model for short-term synaptic plasticity” [poster], 1st meeting of the NeuroMod Institute, Fréjus (France), July 2019.

Romain Veltz, “Dynamics of a mean field limit of interacting 2D nonlinear stochastic spiking neurons”, 5th International Conference on Mathematical Neuroscience, Copenhagen (Denmark), June 2019.

Romain Veltz, “Analysis of a mean field of 2d spiking neurons, theory and numerics”, Bilateral International Meeting UK-France, Royal Society, Chicheley Hall, Milton Keynes (UK), February 2019.

7.1.4. Scientific Expertise

Fabien Campillo was member of the local committee in charge of the scientific selection of visiting scientists (Comité NICE)

Mathieu Desroches was on the Advisory Board of the Complex Systems Academy of the UCA^{JEDI} Idex.

Olivier Faugeras was the President of the study group “Intelligence artificielle” of the *Académie des Sciences de Paris*. As such, he led the audition of experts of this research field, namely for 2019, Jean Ponce, Stéphane Mallat and Francis Bach. This study group has also produced a report for the 2019 G7 meeting.

7.2. Teaching - Supervision - Juries

7.2.1. Teaching

Master / Doctorat: Fabien Campillo, Introduction to Piecewise Deterministic Markov Processes and applications to Neuroscience, 10 hours, Basque Center for Applied Mathematics (BCAM), Bilbao, Spain.

Master : Mathieu Desroches, Modèles Mathématiques et Computationnels en Neuroscience (Lectures, example classes and computer labs), 30 hours, M1 (BIM), Sorbonne Université, Paris, France.

Master / Doctorat: Mathieu Desroches, Slow-fast dynamics in bursting neurons, Tutorial of 3 hours, ICMNS Conference, June 2019.

Master: Romain Veltz, Mathematical Methods for Neurosciences, 20 hours, M2 (MVA), Sorbonne Université, Paris, France.

7.2.2. Supervision

PhD in progress : Louisiane Lemaire, "Multi-scale mathematical modeling of cortical spreading depression", started in October 2018, co-supervised by Mathieu Desroches and Martin Krupa.

PhD in progress: Yuri Rodrigues, "Towards a model of post synaptic excitatory synapse", started in March 2018, co-supervised by Romain Veltz and Hélène Marie (IPMC, Sophia Antipolis).

PhD in progress: Halgurd Taher, "Next generation neural-mass models", started in November 2018, co-supervised by Simona Olmi and Mathieu Desroches.

PhD in progress: Quentin Cormier, "Biological spiking neural networks", started in September 2017, co-supervised by Romain Veltz and Etienne Tanré (Inria TOSCA).

PhD in progress: Pascal Helson, "Study of plasticity laws with stochastic processes", started in September 2016, co-supervised by Romain Veltz and Etienne Tanré (Inria TOSCA).

PhD in progress: Samuel Nyobe, "Inférence dans les modèles de Markov cachés : Application en foresterie", started in October 2017, co-supervised by Fabien Campillo, Serge Moto (University of Yaoundé, Camerun) and Vivien Rossi (CIRAD).

7.2.3. Juries

Fabien Campillo was reviewer and member of the jury of the PhD of Nicolas Thomas (École doctorale des sciences mathématiques de Paris centre (ED 386)), thesis of Sorbonne Université entitled "Stochastic numerical methods for Piecewise Deterministic Markov Processes. Applications in Neuroscience", 20 June 2019.

Mathieu Desroches was examiner and member of the Jury of the HDR of Arnaud Tonnelier (Inria Tripop, Grenoble) entitled "Piecewise linear dynamical systems and excitability", Inria Rhône Alpes, 20 June 2019.

Mathieu Desroches was reviewer and member of the Jury of the PhD of Marina Esteban (University of Seville, Spain) entitled "Dynamics and Bifurcations of Nonlinear Systems with Hysteresis", University of Seville (Spain), 4 March 2019.

Mathieu Desroches was member of the Jury of the PhD of Gabriela Capo Rangel (Basque Center for Applied Mathematics, Bilbao) entitled "Computational predictive modeling of integrated cerebral metabolism, electrophysiology and hemodynamics", University of the Basque Country (Leioa, Spain), 12 February 2019.

8. Bibliography

Major publications by the team in recent years

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Project-Team MCTAO

Mathematics for Control, Transport and Applications

IN COLLABORATION WITH: Institut Mathématique de Bourgogne, Laboratoire Jean-Alexandre Dieudonné (JAD)

IN PARTNERSHIP WITH:
CNRS

Université Nice - Sophia Antipolis

Université de Bourgogne

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Optimization and control of dynamic systems

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1. Team, Visitors, External Collaborators

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Sofya Maslovskaya [Inria, until Mars 2019]

Administrative Assistant
Claire Senica [Inria]

2. Overall Objectives

2.1. Control, Transport and Dynamics

Our goal is to develop methods in geometric control theory for finite-dimensional nonlinear systems, as well as in optimal transport, and to transfer our expertise through real applications of these techniques.

Our primary domain of industrial applications in the past years is space engineering, namely designing trajectories in space mechanics using optimal control and stabilization techniques: transfer of a satellite between two Keplerian orbits, rendez-vous problem, transfer of a satellite from the Earth to the Moon or more complicated space missions. A second field of applications is quantum control with applications to Nuclear Magnetic Resonance and medical image processing. A third and more recent one is the control of micro-swimmers, i.e. swimming robots where the fluid-structure coupling has a very low Reynolds number.

There is also a form of transfer to other mathematical fields: some problems in dynamical systems are being solved thanks to control theory techniques.

3. Research Program

3.1. Control Problems

McTAO's major field of expertise is control theory in the large sense. Let us give an overview of this field.

Modelling. Our effort is directed toward efficient methods for the control of real (physical) *systems*, based on a *model* of the system to be controlled. Choosing accurate models yet simple enough to allow control design is in itself a key issue. The typical continuous-time model is of the form $\mathrm{d}x/\mathrm{d}t = f(x, u)$ where x is the *state*, ideally finite dimensional, and u the *control*; the control is left free to be a function of time, or a function of the state, or obtained as the solution of another dynamical system that takes x as an input. Modelling amounts to deciding the nature and dimension of x, as well as the dynamics (roughly speaking the function f). Connected to modeling is identification of parameters when a finite number of parameters are left free in "f".

Controllability, path planning. Controllability is a property of a control system (in fact of a model) that two states in the state space can be connected by a trajectory generated by some control, here taken as an explicit function of time. Deciding on local or global controllability is still a difficult open question in general. In most cases, controllability can be decided by linear approximation, or non-controllability by "physical" first integrals that the control does not affect. For some critically actuated systems, it is still difficult to decide local or global controllability, and the general problem is anyway still open. Path planning is the problem of constructing the control that actually steers one state to another.

Optimal control. In optimal control, one wants to find, among the controls that satisfy some contraints at initial and final time (for instance given initial and final state as in path planning), the ones that minimize some criterion. This is important in many control engineering problems, because minimizing a cost is often very relevant. Mathematically speaking, optimal control is the modern branch of the calculus of variations, rather well established and mature [71], [47], [34], but with a lot of hard open questions. In the end, in order to actually compute these controls, ad-hoc numerical schemes have to be derived for effective computations of the optimal solutions. See more about our research program in optimal control in section 3.2.

Feedback control. In the above two paragraphs, the control is an explicit function of time. To address in particular the stability issues (sensitivity to errors in the model or the initial conditions for example), the control has to be taken as a function of the (measured) state, or part of it. This is known as closed-loop control; it must be combined with optimal control in many real problems. On the problem of stabilization, there is longstanding research record from members of the team, in particular on the construction of "Control Lyapunov Functions", see [62], [73].

Classification of control systems One may perform various classes of transformations acting on systems, or rather on models... The simpler ones come from point-to-point transformations (changes of variables) on the state and control, and more intricate ones consist in embedding an extraneous dynamical system into the model, these are dynamic feedback transformations, they change the dimension of the state. In most problems, choosing the proper coordinates, or the right quantities that describe a phenomenon, sheds light on a path to the solution; these proper choices may sometimes be found from an understanding of the modelled phenomenons, or it can come from the study of the geometry of the equations and the transformation acting on them. This justifies the investigations of these transformations on models for themselves. These topics are central in control theory; they are present in the team, see for instance the classification aspect in [52] or —although this research has not been active very recently— the study [70] of dynamic feedback and the so-called "flatness" property [65].

3.2. Optimal Control and its Geometry

Let us detail our research program concerning optimal control. Relying on Hamiltonian dynamics is now prevalent, instead of the Lagrangian formalism in classical calculus of variations. The two points of view run parallel when computing geodesics and shortest path in Riemannian Geometry for instance, in that there is a clear one-to-one correspondance between the solutions of the geodesic equation in the tangent bundle and the solution of the Pontryagin Maximum Principle in the cotangent bundle. In most optimal control problems, on the contrary, due to the differential constraints (velocities of feasible trajectories do not cover all directions in the state space), the Lagrangian formalism becomes more involved, while the Pontryagin Maximum Principle keeps the same form, its solutions still live in the cotangent bundle, their projections are the extremals, and a minimizing curve must be the projection of such a solution.

Cut and conjugate loci. The cut locus —made of the points where the extremals lose optimality— is obviously crucial in optimal control, but usually out of reach (even in low dimensions), and anyway does not have an analytic characterization because it is a non-local object. Fortunately, conjugate points —where the extremals lose *local* optimality— can be effectively computed with high accuracy for many control systems. Elaborating on the seminal work of the Russian and French schools (see [76], [35], [36] and [53] among others), efficient algorithms were designed to treat the smooth case. This was the starting point of a series of papers of members of the team culminating in the outcome of the *cotcot* software [46], followed by the *Hampath* [55] code. Over the years, these codes have allowed for the computation of conjugate loci in a wealth of situations including applications to space mechanics, quantum control, and more recently swimming at low Reynolds number. With in mind the two-dimensional analytic Riemannian framework, a heuristic approach to the global issue of determining cut points is to search for singularities of the conjugate loci; this line is however very delicate to follow on problems stemming from applications in three or more dimensions (see *e.g.* [56] and [43]). In all these situations, the fundamental object underlying the analysis is the curvature tensor. In Hamiltonian terms, one considers the dynamics of subspaces (spanned by Jacobi fields) in the Lagrangian Grassmannian [33]. This point of view withstands generalizations far beyond the smooth case: In L^1-minimization, for instance, discontinuous curves in the Grassmannian have to be considered (instantaneous rotations of Lagrangian subspaces still obeying symplectic rules [60]). The cut locus is a central object in Riemannian geometry, control and optimal transport. This is the motivation for a series of conferences on "The cut locus: A bridge over differential geometry, optimal control, and transport", co-organized by team members and Japanese colleagues, the next one should take place in Nice in 2020.

Riemann and Finsler geometry. Studying the distance and minimising geodesics in Riemannian Geometry or Finsler Geometry is a particular case of optimal control, simpler because there are no differential constraints; it is studied in the team for the following two reasons. On the one hand, after some tranformations, like averaging (see section 3.2) or reduction, some more difficult optimal control problems lead to a Riemann or Finsler geometry problem. On the other hand, optimal control, mostly the Hamiltonian setting, brings a fresh viewpoint on problems in Riemann and Finsler geometry. On Riemannian ellipsoids of revolution, the optimal control approach allowed to decide on the convexity of the injectivity domain, which, associated with non-negativity of the Ma-Trudinger-Wang curvature tensor, ensures continuity of the optimal transport on the ambient Riemannian manifold [64], [63]. The analysis in the oblate geometry [44] was completed in [59] in the prolate one, including a preliminary analysis of non-focal domains associated with conjugate loci. Averaging in systems coming from space mechanics control (see sections 3.2 and 4.1) with L^2-minimization yields a Riemannian metric, thoroughly computed in [42] together with its geodesic flow; in reduced dimension, its conjugate and cut loci were computed in [45] with Japanese Riemannian geometers. Averaging the same systems for minimum time yields a Finsler Metric, as noted in [41]. In [51], the geodesic convexity properties of these two types of metrics were compared. When perturbations (other than the control) are considered, they introduce a "drift", *i.e.* the Finsler metric is no longer symmetric.

Sub-Riemannian Geometry. Optimal control problems that pertain to sub-Riemannian Geometry bear all the difficulties of optimal control, like the role of singular/abnormal trajectories, while having some useful structure. They lead to many open problems, like smoothness of minimisers, see the recent monograph [69] for an introduction. Let us detail one open question related to these singular trajectories: the Sard conjecture in sub-Riemannian geometry. Given a totally non-holonomic distribution on a smooth manifold, the Sard Conjecture is concerned with the size of the set of points that can be reached by singular horizontal paths starting from a given point. In the setting of rank-two distributions in dimension three, the Sard conjecture is that this set should be a subset of the so-called Martinet surface, indeed small both in measure and in dimension. In [39], it has been proved that the conjecture holds in the case where the Martinet surface is smooth. Moreover, the case of singular real-analytic Martinet surfaces was also addressed. In this case, it was shown that the Sard Conjecture holds true under an assumption of non-transversality of the distribution on the singular set of the Martinet surface. It is, of course, very intersting to get rid of the remaining technical assumption, or to go to higher dimension. Note that any Sard-type result has strong consequences on the regularity of sub-Riemannian distance functions and in turn on optimal transport problems in the sub-Riemannian setting.

Small controls and conservative systems, averaging. Using averaging techniques to study small perturbations of integrable Hamiltonian systems is as old an idea as celestial mechanics. It is very subtle in the case of multiple periods but more elementary in the single period case, here it boils down to taking the average of the perturbation along each periodic orbit [37], [75]. This line of research stemmed out of applications to space engineering (see section 4.1): the control of the super-integrable Keplerian motion of a spacecraft orbiting around the Earth is an example of a slow-fast controlled system. Since weak propulsion is used, the control itself acts as a perturbation, among other perturbations of similar magnitudes: higher order terms of the Earth potential (including J_2 effect, first), potential of more distant celestial bodies (such as the Sun and the Moon), atmospheric drag, or even radiation pressure. Properly qualifying the convergence properties (when the small parameter goes to zero) is important and is made difficult by the presence of control. In [41], convergence is seen as convergence to a differential inclusion; this applies to minimum time; a contribution of this work is to put forward the metric character of the averaged system by yielding a Finsler metric (see section 3.2). Proving convergence of the extremals (solutions of the Pontryagin Maximum Principle) is more intricate. In [58], standard averaging ([37], [75]) is performed on the minimum time extremal flow after carefully identifying slow variables of the system thanks to a symplectic reduction. This alternative approach allows to retrieve the previous metric approximation, and to partly address the question of convergence. Under suitable assumptions on a given geodesic of the averaged system (disconjugacy conditions, namely), one proves existence of a family of quasi-extremals for the original system that converge towards the geodesic when the small perturbation parameter goes to zero. This needs to be improved, but convergence of all extremals to extremals of an "averaged Pontryagin Maximum Principle" certainly fails. In particular, one cannot hope for C^1-regularity on the value function when the small parameter goes to zero as swallowtail-like singularities due to the structure of local minima in the problem are expected. (A preliminary analysis has been made in [57].)

Optimality of periodic solutions/periodic controls. When seeking to minimize a cost with the constraint that the controls and/or part of the states are periodic (and with other initial and final conditions), the notion of conjugate points is more difficult than with straightforward fixed initial point. In [48], for the problem of optimizing the efficiency of the displacement of some micro-swimmers (see section 4.3) with periodic deformations, we used the sufficient optimality conditions established by R. Vinter's group [80], [66] for systems with non unique minimizers due to the existence of a group of symmetry (always present with a periodic minimizer-candidate control). This takes place in a long term collaboration with P. Bettiol (Univ. Bretagne Ouest) on second order sufficient optimality conditions for periodic solutions, or in the presence of higher dimensional symmetry groups, following [80], [66]. Another question relevant to locomotion is the following. Observing animals (or humans), or numerically solving the optimal control problem associated with driftless micro-swimmers for various initial and final conditions, we remark that the optimal strategies of deformation seem to be periodic, at least asymptotically for large distances. This observation is the starting point for characterizing dynamics for which some optimal solutions are periodic, and asymptotically attract other solutions as the final time grows large; this is reminiscent of the "turnpike theorem" (classical, recently applied to nonlinear situations in [79]).

Software. These applications (but also the development of theory where numerical experiments can be very enlightening) require many algorithmic and numerical developments that are an important side of the team activity. The software *Hampath* (see section 6.1) is maintained by former members of the team in close collaboration with McTAO. We also use direct discretization approaches (such as the Bocop solver developed by COMMANDS) in parallel. Apart from this, we develop on-demand algorithms and pieces of software, for instance we have to interact with a production software developed by Thales Alenia Space. A strong asset of the team is the interplay of its expertise in geometric control theory with applications and algorithms (see sections 4.1 to 4.3) on one hand, and with optimal transport, and more recently Hamiltonian dynamics, on the other. In 2019, the ADT `ct` (Control Toolbox) has started with a first sprint in "AMDT mode" with Sophia SED during spring 2019. In addition to McTAO, researchers from the CAGE team (Inria Paris) and the APO team (CNRS Toulouse) are involved. The idea is to put together the efforts on BOCOP and HamPath to go towards a reference toolbox in optimal control. After the first sprint cycle (24 months being planned on the whole action), some starting points have been addressed including: continuous integration for BOCOP and HamPath, refresh on collaborative development tools, first steps of software refactoring, first test of a high-end interface (throught scripting, notebooks, or an *ad hoc* GUI). The next sprint is planned during spring 2020.

3.3. Optimal Transport

Given two measures, and calling transport maps the maps that transport the first measure into the second one, the Monge-Kantorovich problem of Optimal Transport is the search of the minimum of some cost on the set of transport maps. The cost of a map usually comes from some point to point cost and the transport measure. This topic attracted renewed attention in the last decade, and has ongoing applications of many types. Matching optimal transport with geometric control theory is one originality of our team. Let us sketch an important class of open problems. In collaboration with R. McCann [68], we worked towards identifying the costs that admit unique optimizers in the Monge-Kantorovich problem of optimal transport between arbitrary probability densities. For smooth costs and densities on compact manifolds, the only known examples for which the optimal solution is always unique require at least one of the two underlying spaces to be homeomorphic to a sphere. We have introduced a multivalued dynamics induced by the transportation cost between the target and source space, for which the presence or absence of a sufficiently large set of periodic trajectories plays a role in determining whether or not optimal transport is necessarily unique. This insight allows us to construct smooth costs on a pair of compact manifolds with arbitrary topology, so that the optimal transport between any pair of probability densities is unique. We investigated further this problem of uniquely minimizing costs and obtained in collaboration with Abbas Moameni [10] a result of density of uniquely minimizing costs in the C^0-topology. The results in higher topology should be the subject of some further research.

4. Application Domains

4.1. Aerospace Engineering

Participants: Bernard Bonnard, Jean-Baptiste Caillau, Thierry d'Argent, Lamberto Dell'Elce, Jean-Baptiste Pomet, Jérémy Rouot.

Space engineering is very demanding in terms of safe and high-performance control laws. It is therefore prone to fruitful industrial collaborations. McTAO now has an established expertise in space and celestial mechanics. Our collaborations with industry are mostly on orbit transfer problems with low-thrust propulsion. It can be orbit transfer to put a commercial satellite on station, in which case the dynamics are a Newtonian force field plus perturbations and the small control. There is also, currently, a renewed interest in low-thrust missions such as Lisa Pathfinder (ESA mission towards a Lagrange point of the Sun-Earth system) or BepiColombo (joint ESA-JAXA mission towards Mercury). Such missions look more like a controlled multibody system. In all cases the problem involves long orbit transfers, typically with many revolutions around the primary celestial body. When minimizing time, averaging techniques provide a good approximation. Another important criterion in practice is fuel consumption minimization (crucial because only a finite amount of fuel is onboard a satellite for all its "life"), which amounts to L^1-minimization. Both topics are studied by the team. We have a steady relationships with CNES and Thales Alenia Space (Cannes), that have financed or co-financed 3 PhDs and 2 post-docs in the Sophia location of the team in the decade and are a source of inspiration even at the methodological level. Team members also have close connections with Airbus-Safran (Les Mureaux) on launchers. Some of the authoritative papers in the field were written by team members, with an emphasis on the geometric analysis and on algorithms (coupling of shooting and continuation methods). There are also connections with peers more on the applied side, like D. Scheeres (Colorado Center for Astrodynamics Research at Boulder), the group of F. Bernelli (Politecnico Milano), and colleagues from U. Barcelona (A. Farrès, A. Jorba).

4.2. Magnetic resonance imaging (MRI)

Participants: Bernard Bonnard, Alice Nolot [Professeur Classes Préparatoires Troyes], Jérémy Rouot, Joseph Gergaud, Olivier Cots [ENSEEIHT, Toulouse], Stephen Glaser [TU München, Germany], Dominique Sugny [Univ. de Bourgogne].

The starting point of our interest in optimal control for quantum systems was a collaboration with physicist from ICB, University of Burgundy (Dominique Sugny), motivated by an ANR project where we worked on the control of molecular orientation in a dissipative environment using a laser field, and developed optimal control tools, combined with numerical simulations, to analyze the problem for Qubits. This was related to quantum computing rather than MRI. Using this expertise and under the impulse of Prof. S. Glaser and his group (Chemistry, TU München), we investigated Nuclear Magnetic resonance (NMR) for medical imaging (MRI), where the model is the Bloch equation describing the evolution of the Magnetization vector controlled by a magnetic field, but in fine is a specific Qubit model without decoherence. We worked on, and brought strong contributions to, the contrast problem: typically, given two chemical substances that have an importance in medicine, like oxygenated and de-oxygenated blood, find the (time-dependent) magnetic field that will produce the highest difference in brightness between these two species on the image resulting from Nuclear Magnetic Resonance. This has immediate and important industrial applications in medical imaging. Our contacts are with the above mentioned physics academic labs, who are themselves in contact with major companies. The team has produced and is producing important work on this problem. One may find a good overview in [50], a reference book has been published on the topic [54], a very complete numerical study comparing different optimization techniques was performed in [49]. We conduct this project in parallel with S. Glaser team, which validated experimentally the pertinence of the methods, the main achievement being the in vivo experiments realized at the Creatis team of Insa Lyon showing the interest to use optimal control methods implemented in modern softwares in MRI in order to produce a better image in a shorter time. A goal is to arrive to a cartography of the optimal contrast with respect to the relaxation parameters using LMI techniques and numerical simulations with the Hamapth and Bocop code; note that the theoretical study is connected to the problem of understanding the behavior of the extremal solutions of a controlled pair of Bloch equations, and this is an ambitious task. Also, one of the difficulties to go from the obtained results, checkable on experiments, to practical control laws for production is to deal with magnetic field space inhomogeneities.

4.3. Swimming at low-Reynolds number

Participants: Bernard Bonnard, Yacine El Alaoui-Faris, Laetitia Giraldi, Clément Moreau, Alice Nolot, Jean-Baptiste Pomet, Jérémy Rouot.

Following the historical reference for low Reynolds number locomotion [72], the study of the swimming strategies of micro-organisms is attracting increasing attention in the recent literature. This is both because of the intrinsic biological interest, and for the possible implications these studies may have on the design of bio-inspired artificial replicas reproducing the functionalities of biological systems. In the case of micro-swimmers, the surrounding fluid is dominated by the viscosity effects of the water and becomes reversible. In this regime, it turns out that the infinite dimensional dynamics of the fluid do not have to be retained as state variables, so that the dynamics of a micro-swimmer can be expressed by ordinary differential equations if its shape has a finite number of degrees of freedom. Assuming this finite dimension, and if the control is the rate of deformation, one obtains a control system that is linear (affine without drift) with respect to the controls, *i.e.* the optimal control problem with a quadratic cost defines a sub-Riemannian structure (see section 3.2). This is the case where the shape is “fully actuated”, *i.e.* if all the variables describing the shape are angles, there is an actuator on each of these angles. For artificial micro-swimmers, this is usually unrealistic, hence (artificial) magneto-elastic micro-swimmers, that are magnetized in order to be deformed by an external magnetic field. In this case, the control functions are the external magnetic field. In both cases, questions are controllability (straightforward in the fully actuated case), optimal control, possibly path planning. We collaborate with teams that have physical experiments for both.

- In collaboration with D. Takagi and M. Chyba (Univ of Hawaii), this approach is currently at the experimental level for copepod-like swimmer at the university of Hawaii: on the one hand, this zooplankton and its locomotion can be observed, and a robot micro swimmer mimicking a copepod has been constructed, but in fact large enough for direct actuation to be possible, and the low Reynolds number is achieved by using a more viscous fluid. This gives possibilities, through an inverse optimization problem, to determine what cost can be optimised by these crustaceans, see [40], [78], and to validate models on the robot.
- For magneto-elastic micro-robots, Y. El-Alaoui’s PhD is co-advised with Stéphane Régnier from the robotics lab ISIR, Univ. Paris 6. Magneto-elastic micro-robots and their magnetic actuation are actually built at ISIR and the aim of the collaboration is to validate models and improve the existing control laws both in performance and in energy; of course, the micro scale does make things difficult.

The questions about optimality of periodic controls raised in section 3.2 are related to these applications for periodic deformations, or strokes, playan important role in locomotion.

4.4. Stability of high frequency amplifiers

Participants: Sébastien Fueyo, Gilles Lebeau, Jean-Baptiste Pomet, Laurent Baratchart [FACTAS project-team].

Nonlinear hyper-frequency amplifiers are ubiquitous in cell phone relays and many other devices. They must be as compact as possible, yielding a more complicated design. Computer Assisted Design tools are extensively used; for a given amplifier design, they provide frequency responses but fail to provide information of the stability of the response for each frequency. This stability is crucial for an unstable response will not be observed in practice; the actual device should not be built before stability is asserted. Predicting stability/instability from "simulations" in the Computer Assisted Design tool is of utmost importance (simulation between quotation marks because these simulations are in fact computations in the frequency domain). Potential transfer is important.

Some techniques do exist, see [77], based on creating some virtual perturbations and treating them as the input of a (linearized) control system to be "simulated" using the same tools. In an ongoing collaboration between McTAO and the project-team FACTAS, we work on the mathematical ground of these methods and in particular of the relation between stability and the property of the identified time-varying infinite dimensional systems. See recent developments in Section 7.14.

4.5. Optimal control of microbial cells

Participants: Jean-Baptiste Caillau, Walid Djema [BIOCORE project-team], Laetitia Giraldi, Jean-Luc Gouzé [BIOCORE project-team], Sofya Maslovskaya, Jean-Baptiste Pomet, Agustín Yabo.

The growth of microorganisms is fundamentally an optimization problem which consists in dynamically allocating resources to cellular functions so as to maximize growth rate or another fitness criterion. Simple ordinary differential equation models, called self-replicators, have been used to formulate this problem in the framework of optimal and feedback control theory, allowing observations in microbial physiology to be explained. The resulting control problems are very challenging due to the nonlinearity of the models, parameter uncertainty, the coexistence of different time-scales, a dynamically changing environment, and various other physical and chemical constraints. In the framework of the ANR Maximic (PI Hidde de Jong, Inria Grenoble Rhône-Alpes) we aim at developing novel theoretical approaches for addressing these challenges in order to (i) study natural resource allocation strategies in microorganisms and (ii) propose new synthetic control strategies for biotechnological applications. In order to address (i), we develop extended self-replicator models accounting for the cost of regulation and energy metabolism in bacterial cells. We study these models by a combination of analytical and numerical approaches to derive optimal control solutions and a control synthesis, dealing with the bang-bang-singular structure of the solutions. Moreover, we define quasi-optimal feedback control strategies inspired by known regulatory mechanisms in the cell. To test whether bacteria follow the predicted optimal strategies, we quantify dynamic resource allocation in the bacterium Escherichia coli by monitoring, by means of time-lapse fluorescent microscopy, the expression of selected genes in single cells growing in a microfluidics device. In order to address (ii), we build self-replicator models that include a pathway for the production of a metabolite of interest. We also add a mechanism to turn off microbial growth by means of an external input signal, at the profit of the production of the metabolite. We formulate the maximization of the amount of metabolite produced as an optimal control problem, and derive optimal solutions and a control synthesis, as well as quasi-optimal feedback strategies satisfying chemical and physical design constraints. The proposed synthetic control strategies are being tested experimentally by growing E. coli strains capable of producing glycerol from glucose in a mini-bioreactor system. We aim at quantifying the amount of glucose consumed and glycerol produced, in the case of a predefined input signal (open-loop control) and the adaptive regulation of the input signal based on on-line measurements of the growth rate and the expression of fluorescent reporters of selected genes (closed-loop control). Currently, one PhD (A. Yabo) and one postdoc (S. Maslovskaya) are involved in these tasks and jointly supervised by colleagues from McTAO and Biocore teams at Sophia. Preliminary results concern the definition on extended (higher dimensional) models for the bacteria dynamics, check of second order optimality conditions on the resulting optimal control problem, and study of the turnpike phenomenon for these optimization problems.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

Laetita Giraldi has been awarded the price "My Innovation is" by SATT Sud & Corse for her research project on the control of swimming microbots.

6. New Software and Platforms

6.1. Hampath

KEYWORDS: Optimal control - Second order conditions - Differential homotopy - Ordinary differential equations

FUNCTIONAL DESCRIPTION: Hampath is a software developped to solve optimal control problems by a combination of Hamiltonian et path following methods. Hampath includes shooting and computation of conjugate points. It is an evolution of the software cotcot (apo.enseeiht.fr/cotcot). It has a Fortran kernel, uses Tapenade (www-sop.inria.fr/tropics/tapenade.html) for automatic differentiation and has a Matlab interface.

- Participants: Jean-Baptiste Caillau, Joseph Gergaud and Olivier Cots
- Contact: Jean-Baptiste Caillau
- URL: http://www.hampath.org

7. New Results

7.1. Analysis of singularities in minimum time control problems

Participants: Jean-Baptiste Caillau, Jacques Féjoz [Université Paris-Dauphine & Observatoire de Paris], Michaël Orieux [SISSA], Robert Roussarie [Université de Bourgogne-Franche Comté].

An important class of problems is affine control problems with control on the disk (or the Euclidean ball, in higher dimensions). Such problems show up for instance in space mechanics and have been quite extensively studied from the mathematical (geometric) and numerical point of view. Still, even for the simplest cost, namely time minimization, the analysis of singularities occuring was more or less open. Building on previous results of the team and on recent studies of Agrachev and his collaborators, we give a detailed account of the behaviour of minimum time extremals crossing the so-called singular locus (typically a switching surface). The result is twofold. First, we show that there the set of initial conditions of the Hamiltonian flow can be stratified, and that the flow is smooth on each stratum, one of them being the codimension stratum leading to the singular locus. This generalizes in higher codimension the known case of switching conditions of codimension one encountered, for instance, in L^1-minimization (consumption minimization, in aerospace applications). We give a clear geometric interpretation of this first result in terms of normally hyperbolic invariant manifold. Secondly, we provide a model for the singularity on the flow when strata are crossed, proving that it is of logarithmic type. This paves the way for *ad hoc* numerical methods to treat this kind of extremal flow. The crucial tool for the analysis is a combination of blow-up and normal form techniques for dynamical systems.

7.2. The Sard Conjecture in sub-Riemannian Geometry

Participants: Ludovic Rifford, André Belotto Da Silva [Univ. Aix-Marseille], Adam Parusinski [Univ. Côte d'Azur].

In a work in progress, we address the Sard conjecture for sub-Riemannian structures on analytic manifolds and related problems. We present a description of singular horizontal curves of a totally nonholonomic analytic distribution in term of the projections of the orbits of some integrable and isotropic subanalytic distribution in the cotangent bundle. In the generic smooth case, we obtain a extension of an important result by Chitour, Jean and Trélat by showing that singular curves are the projection of a Hamiltonian singular vector field. As a by-product of our first result, we obtain a proof of the so-called minimal rank Sard conjecture in some analytic cases. It establishes that from a given point the set of points accessible through singular horizontal curves of minimal rank, which corresponds to the rank of the distribution, has Lebesgue measure zero under additional technical assumptions.

7.3. Local controllability of magnetic micro-swimmers and more general classes of control systems

Participants: Laetitia Giraldi, Pierre Lissy [Univ. Paris Dauphine], Clément Moreau, Jean-Baptiste Pomet.

As a part of Clément Moreau's PhD, we gave fine results on local controlability of magnetized micro swimmers actuated by an external magnetic field. We had shown that the "two-link" magnetic swimmer had some local controllability around its straight configuration but that it was not Small Time Locally Controllable" (STLC) in the classical sense that asks that poin ts close to the initial condition can be reached using "small" controls.

We derived in [30] some necessary conditions for STLC of affine control systems with two scalar controls, around an equlibrium where not only the drift vector field vanishes but one of the two control vector fields vanishes too; we state various necessary conditions (involving the value at the equilibrium of some iterated Lie brackets of the system vector fields), where the "smallness" of the controls is intended in the L^∞ (classical) or $W^{1,\infty}$ (less classical, used in recent work by K. Beauchard and F. Marbach).

We also arrived to local controllability results in higher dimension than the "two-link" micro-robots, see [9]. This relies on the following remark: classical STLC does not hold, but STLC is concerned with small controls, hence with variations around the zero control... but, due to one of the control fields vanishing, the system also rests at the equilibrium for (infinitely many) nozero constant values of the control. It is proved that there is one nonzero value of the control such that STLC holds when considered *around this constant control* and not around the zero control. In other terms, classical STLC holds after a constant feedback transformation.

7.4. Time-optimal deorbiting maneuvers of solar sails

Participants: Jean-Baptiste Caillau, Lamberto Dell'Elce, Jean-Baptiste Pomet.

Increasing interest in optimal low-thrust orbital transfers was triggered in the last decade by technological progress in electric propulsion and by the ambition of efficiently leveraging on orbital perturbations to enhance the maneuverability of small satellites. This work was aimed at investigating time optimal propellantless deorbiting maneuvers in low-Earth orbit using solar sails. The solution of this problem was achieved by doubly averaging the optimal control Hamiltonian with respect to both satellite and Sun longitudes. Initial conditions for the osculating trajectory were inferred via a near-identity transformation that approximates the quasi-periodic oscillations of both state and adjoint variables [61]. The outcomes of the study were presented at the 4th KePASSA meeting in Logrono [18].

7.5. Long-term evolution of quasi-satellite orbits

Participants: Lamberto Dell'Elce, Nicola Baresi [Univ. of Surrey, UK], Josué Cardoso Dos Santos [Sao Paulo State Univ., Brazil], Yasuhiro Kawakatsu [JAXA, Japan].

The Martian Moons eXploration mission is currently under development at the Japan space agency (JAXA) and will be the first spacecraft mission to retrieve pristine samples from the surface of Phobos. In preparation for the sampling operations, MMX will collect observations of Phobos from stable retrograde relative trajectories, which are referred to as quasi-satellite orbits (QSOs). This study, started in 2018 in collaboration with JAXA, investigates the navigability of mid- and high-altitude QSOs in terms of relative orbit element. Our developments are based on the Yamanaka-Ankersen solution of the Tschauner-Hempel equations and capture the effects of the secondary's gravity and orbital eccentricity on the shape and orientation of near-equatorial retrograde relative orbits. The analytic solution that we obtained by averaging the equations of motion with respect to the longitude of the satellite is suitable to gain insight into the long-term evolution of QSOs. These results were recently published in [38].

7.6. Non-singular analytical solution of perturbed satellite motion using Milankovitch elements

Participants: Lamberto Dell'Elce, Pini Gurfil [Technion, Israel], Gianpaolo Izzo [Technion, Israel], Aaron J. Rosengren [Univ. of Arizona, US].

In the brief span of time after the launch of Sputnik, a whole succession of analyses was devoted to the problem poised by the drag-free motion of an artificial satellite about an oblate planet, employing almost every known perturbation method. Although in a sense, the problem is a classic one that also occurred among the natural satellites, it was necessary in the applications of artificial satellite motion to obtain a more general, detailed, and accurate solution. In this study, we developed a new formulation of the mean-to-osculating conversion for first-order oblateness perturbations based on the Milankovitch elements [74] that corrects the critical-inclination deficiency. We use the direct method of Kozai [67], and present an explicit analytical short-period correction in vector form that is valid for all orbits with nonzero angular momentum. Preliminary results were presented at the International Symposium of Space Flight Mechanics (ISSFM) [19].

7.7. Sub-Riemannian Geometry and Micro-Swimmers and Extensions to Control in Hydrodynamics

Participants: Bernard Bonnard, Piernicola Bettiol [Univ. Bretagne Ouest], Alice Nolot [Univ. de Bourgogne Franche Conté], Jérémy Rouot.

We pursue our study concerning the 1-copepod swimmer using techniques from SR-geometry and numerical simulations, see [40] for previously obtained results. Following Takagi model, a 2d-swimmer is currently analyzed whose aim is to perform a 2d-motion where the copepod swimmer can change its orientation. Preliminary study concerning this problem was analysed during the internship of A. Lenc in relation with the motion planning of a car. Under the impulse of O. Cots and B. Wembe an extension of the project is the developments of the geometric optimal control techniques in hydrodynamics. In particular we studied a Zermelo navigation problem in a current with a vortex [25] (submitted to ESAIM-COCV). An interesting and new phenomenon detected in optimal control is the existence for the geodesic flow of a Reeb foliation.

7.8. Swimming at low Reynolds number an optimal control problem

Participants: François Alouges [École Polytechnique], Luca Berti, Antonio Desimone [SISSA Trieste], Yacine El Alaoui-Faris, Laetitia Giraldi, Yizhar Or [Technion, Israel], Christophe Prud'Homme [Univ. de Strasbourg], Jean-Baptiste Pomet, Stéphane Régnier [Sorbonne Université], Oren Wiezel [Technion, Israel].

This part is devoted to study the displacement of micro-swimmers. We attack this problem using numerical tools and optimal control theory. Micro-scale swimmers move in the realm of negligible inertia, dominated by viscous drag forces, the fluid is governed by the Stokes equation. We study two types of models. First, deriving from the PDE system, in [5] we use Feel++, a finite elements library in order to simulate the motion of a one-hinged swimmer, which obeys to the scallop theorem. Then, we adress the flagellar microswimmers. In [31] we formulate the leading order dynamics of a $2D$ slender multi-link microswimmer assuming small-amplitude undulations about its straight configuration. The energy optimal stroke to achieve a given prescribed displacement in a given time period is obtained as the largest eigenvalue solution of a constrained optimal control problem. We prove that the optimal stroke is an ellipse lying within a two-dimensional plane in the $(N-1)$ dimensional space of shape variables, where N can be arbitrarily large. If the number of shape variables is small, we can consider the same problem when the prescribed displacement in one time period is large, and not attainable with small variations of the joint angles. The fully non-linear optimal control problem is solved numerically for the cases $N=3$ and $N=5$ showing that, as the prescribed displacement becomes small, the optimal solutions obtained using the small-amplitude assumption are recovered. We also show that, when the prescribed displacements become large, the picture is different. Finally, in [28] we present an automated procedure for the design of optimal actuation for flagellar magnetic microswimmers based on numerical optimization. Using this method, a new magnetic actuation method is provided which allows these devices to swim significantly faster compared to the usual sinusoidal actuation. This leads to a novel swimming strategy which shows that a faster propulsion is obtained when the swimmer is allowed to go out-of-plane. This approach is experimentally validated on a scaled-up flexible swimmer.

7.9. Periodic body deformations are optimal for locomotion

Participants: Laetitia Giraldi, Frédéric Jean.

A periodic cycle of body's deformation is a common strategy for locomotion (see for instance birds, fishes, humans). The aim of this work (see [29]) is to establish that the auto-propulsion of deformable object is optimally achieved using periodic strategies of body's deformations. This property is proved for a simple model using optimal control theory framework.

7.10. Optimal Control of Chemical Networks by Temperature Control

Participants: Bernard Bonnard, Jérémy Rouot.

The objective of the project is to develop previous results obtained at the end of the 90's by B. Bonnard and his collaborators to control the production of batch reactors by temperature control in relation with the Shell Company. These results were derived to analyze the simple (but relevant for applications) irreversible reaction scheme $\mathrm{A} \rightarrow \mathrm{B} \rightarrow \mathrm{C}$. More complicated weakly reversible scheme like the McKeithan network are currently under investigation taking into account the bridge phenomenon detected in [7], where complicated optimal policies with two singular arcs can occur. Preliminary results are presented in [3] where also the geometric techniques are described. See also the article in the 58th IEEE-CDC Nice conference [11].

7.11. Muscular Isometric Force Contraction by Electric Stimulation

Participants: Bernard Bonnard, Jérémy Rouot, Toufik Bakir [Univ. de Bourgogne Franche Conté].

This project started two years ago under the impulse of T. Bakir (ImVia-UBFC) who defended his HDR on the subject (November, 2018). The problem is the one of optimizing the train pulses of the FES signal to produce the muscular contraction. It is based on the Hill model refined by Ding et al to take into account the variations of the fatigue variable. Preliminary closed loop results were obtained using an MPC-method where the state variable is estimated with an non linear observer [2]. The problem can be stated in the optimal sampled-control data framework; with the collaboration of L. Bourdin (Maths Dept Limoges), Pontryagin-type necessary conditions were derived and partially numerically implemented [1]. The project is supported by a PEPS 1 AMIES and a PGMO Project. A CIFRE Thesis is planned to start in January, 2020 (Phd Student: Quentin Arnaud) in the Company SEGULA, supervised by T. Bakir and co-Supervised by B. Bonnard. See section 8.1.

7.12. Selection of microalgae

Participants: Walid Djema, Laetitia Giraldi, Olivier Bernard [BIOCORE project-team].

We investigate a minimal-time control problem in a chemostat continuous photo-bioreactor model that describes the dynamics of two distinct microalgae populations. Our objective is to optimize the time of separation between two species of microalgae by controlling the dilution rate. We focus on Droop's model. Using Pontryagin's principle, we develop a dilution-based control strategy that steers the model trajectories to a suitable target in minimal time. Our study reveals that the optimal solution has a turpike property [14] [27]. A numerical optimal-synthesis, based on direct optimal control tools, is performed in [15] and it shows that the optimal solution is of type bang-singular.

7.13. Extensions of the Zermelo-Markov-Dubins problem in optimal control

Participants: Ahmed Dieng, Jean-Baptiste Caillau, Jean-Baptiste Pomet, Sofya Maslovskaya.

Motivated by a collaboration with CGG in 2018, we continued investigating minimum time problems for simplified kinematic models of a marine vessel towing some equipments, with various curvature constraints. These are extensions (by adding the towed equipment) of the so-called Zermelo-Markov-Dubins problem. In [12], we describe the problem with the simplest possible model of the trailer, and show that the Hamiltonian system resulting from Pontryagin Principle for minimum time is integrable in that case, both for the "regular" flow and for the flow giving singular extremals; without giving an explicit analytic soltuon, this drastically simplifies the computation of optimal solutions; a description of the marine application solution is also given.

Ahmed Dieng's internship was the opportunity to test more complex models numerically and to have a qualitative approach of the results from [12].

Note that the collaboration with CGG (we had a short bilateral contract with this company in 2018) did not continue mainly because they stopped this activity and more generally marine acquisition. This recent press release details the transactions.

7.14. Stability of nonlinear high frequency amplifiers and stability of linear time-varying time-delay systems

Participants: Laurent Baratchart [FACTAS project-team], Sébastien Fueyo, Jean-Baptiste Pomet, Gilles Lebeau.

These amplifiers contain on the one hand nonlinear active components and on the other hand lines, that induce some sort of delays and make the system infinite-dimensional: they are, for each choice of a periodic input, a nonlinear infinite dimensional dynamical system. The Computer Aided Design tools mentioned in Section 4.4 provide a periodic solution under this periodic forcing and may also give the frequency response of the linearized system along this trajectory with some artificial "small" excitation. The goal is to deduce stability from these data.

It is an opportunity to build theoretical basis and justification to a stability analysis through harmonic identification; the latter is one of the specialties of FACTAS, we collaborate on the infinite-dimensional non-linear stability analysis for periodic solutions and how it works with the results of harmonic identification. This is the topic of Sébastien Fueyo's PhD.

On academic examples of simple circuits, we have given full justification (with some possible obstructions) to the prediction of stability through transfer function identification. The theoretical interest is that the spectrum of the operator that gives stability is not as elementary as predicted in the literature, but stability can be predicted nonetheless. Publication in progress on this point, a preliminary version was presented in [17].

It was also the oppoprtunity to re-visit stibility of time-delay time-varying linear system. A new sufficient condition can be found in [22], and a more general result is the purpose of a publication to come. These result are important to the domain of linear time-delay systems because the time-varying case has sedom been touched.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Grants with Industry

- A grant “PEPS AMIES”, title: “Conception d’un électrostimulateur intelligent”, was obtained, co-financed by AMIES and SEGULA.

  PI: Bernard Bonnard.

  Start: December 2018. Duration: 2 years.
- A grant CIFRE co-financed by and SEGULA, title: “Réalisation d’un prototype d’électrostimulateur intelligent”, was obtained.

  PI: Bernard Bonnard and T. Bakir (IMvia).

  Start: January 2020. Duration: 3 years.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

Sub-Riemannian Geometry and Interactions (SRGI). Started 2015 (decision ANR-15-CE40-0018), duration: 4 years. L. Rifford is a member.

Intéractions Systèmes Dynamiques Équations d’Évolution et Contrôle (ISDEEC). Started 2016 (decision ANR-16-CE40-0013), duration: 4 years. L. Rifford is a member.

Maximic: optimal control of microbial cells by natural and synthetic strategies. Started 2017, duration: 4 years. J.-B. Caillau, L. Giraldi, J.-B. Pomet are members.

9.1.2. Others

Défi InfIniti CNRS project, Control and Optimality of Magnetic Microrobots, (PI L. Giraldi). Started 2017, duration: 2 years. This project involves colleagues from Paris Sorbonne Université S. Régnier and from University of Strasbourg C. Prud’Homme’s.

PGMO grant (2017-2019) on “Algebro-geometric techniques with applications to global optimal control for Magnetic Resonance Imaging (MRI)”. B. Bonnard, A. Nolot and J. Rouot participate in this project, the PI is O. Cots, from ENSEIHHT, Toulouse.

PGMO grant (2019-2021) on "Sampled-Data Control Systems and Applications" (PI B. Bonnard).

The McTAO team participates in the GdR MOA, a CNRS network on Mathematics of Optimization and Applications.

J.-B. Caillau is associate researcher of the CNRS team Parallel Algorithms & Optimization at ENSEEIHT, Univ. Toulouse.

9.2. International Research Visitors

9.2.1. Visits of International Scientists

Prof. Sorin Sabau (Tokai University) visited Inria during two weeks in May 2019. He gave a talk on "The calculus of variations on Finsler manifolds".

9.2.1.1. Research Stays Abroad

- Bernard Bonnard visited the University of Hawaii at Manoa, Mars 2019 (1 month, host: M. Chyba).

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events: Organisation

10.1.1.1. General Chair, Scientific Chair

- J.-B. Caillau has been chair (with Didier Auroux, Castor team) of the 19th French-German-Swiss conference, held in Nice from September 17 to 19, 2019. The conference gathered around 150 researchers in optimization. More information on fgs-2019.sciencesconf.org
- L. Giraldi together with M. Chaves (Biocore) organized an invited session at the Conf. Decision and Control (Nice, France).

10.1.1.2. Member of the Organizing Committees

J.-B. Caillau has been member of the organizing committee of PGMO days held in Paris Saclay from December 3 to 4, 2019.

10.1.2. Journal

10.1.2.1. Reviewer - Reviewing Activities

The team members are regular reviewers for the leading journal in control (SIAM J. Control, ESAIM COCV...) and, more generally, for journals of pure and applied mathematics.

10.1.3. Invited Talks

- L. Rifford gave a plenary talk at the *2nd International Conference of Mathematics in Erbil* (Iraq), .
- L. Rifford was a keynote speaker at the *1st International MIPAnet Conference on Science and Mathematics* (Parapat, Indonesia), .
- L. Rifford gave a talk during the workshop *Real and Complex Singularities in Cargèse* at the IESC (Cargèse, France). .
- B. Bonnard gave the seminar *"Techniques Géométriques pour le Contrôle Optimal des Réacteurs Chimiques"* at the Department of Mathemathics of the Université de Genève, October 2019.
- L. Dell'Elce was a keynote speaker at the *4th International Workshop on Key topics in orbit Propagation Applied to Space Situational Awareness* (Logrono, Spain), .
- L. Dell'Elce gave the seminar *"Multi-Phase Averaging of Time-Optimal Low-Thrust Transfers"* at the Surrey Space Center in the Universitéy of Surrey, Octobre 19.
- J.-B. Caillau gave an invited talk at the *Learning week* if Air France, in Sophia Antipolis, December 2019.

10.1.4. Scientific Expertise

L. Giraldi is reviewer for DFG the Deutsche Forschungsgemeinschaft (German Research Foundation).

10.1.5. Research Administration

J.-B. Caillau is

- member of the Scientific Council of CNRS GdR Calcul Scientifique
- member of the Scientific Council of Programme Gaspard Monge pour l'Optimisation (PGMO)
- member of the Scientific Council of Institut de Mécanique Céleste et de Calcul des Ephémérides (Observatoire de Paris)
- member of the Scientific Council of 3IA

Jean-Baptiste Pomet is

- a member of the steering committee of the Center for Planetary Origin (C4PO),
- a member of the scientific council of Académie 2 “Complex system”, both for Université Côte d'Azur (UCA),
- an elected member of Commission d'Évaluation (Inria permanent evaluation committee).

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master in Astrophysics Université Côte Azur (MAUCA): Lamberto Dell'Elce, Build a Nanosatellite (Attitude Determination and Control System), 6 hours TH, niveau M1, Université Côte Azur, France.

Engineering school: J.-B. Caillau has a full teaching duty of Professor at L3, M1 and M2 level of the Applied Math. department of Polytech Nice Sophia. (He is the head of the department since September 2018.)

Licence : L. Giraldi, Colles de mathématiques, 90h (2h en MPSI et 2h en MP par semaine), MPSI-MP, Lycée internationale de Valbonne, France.

Master : L. Giraldi, Natation à bas nombre de Reynolds, 6h, Master 2 Recherche, Université de Srasbourg, France.

10.2.2. Supervision

PhD in progress : Sébastien Fueyo, “Testing stability of nonlinear amplifier by frequency-domain methods”, started October, 2016, co-supervised by J.-B. Pomet and L. Baratchart (FACTAS team).

PhD in progress : Yacine El alaoui-faris, “modeling magnetico-elastic micro-robot from theory to experiment”, started October, 2017, co-supervised by L. Giraldi, J.-B. Pomet and Stephane Régnier (Univ. Paris Sorbonne).

PhD in progress : Clément Moreau, “Contrôlabilité de systèmes en dimension finie ou infinie issus du vivant”, started September, 2017, co-supervised by L. Giraldi, Pierre Lissy and J.-B. Pomet.

PhD in progress : Agustín Yabo, “Optimal control of microbial cells”, started October, 2018, co-supervised by J.-L. Gouzé (Biocore team) and J.-B. Caillau.

10.2.3. Juries

L. Giraldi is member of the jury of agrégation de mathématiques.

L. Giraldi was examiner of the PhD Thesis of Fatima Tani (supervised by A. Rapaport).

J.-B. Pomet sat in the jury for Armand Koenig's PhD (Université côte d'Azur).

J.-B. Caillau sat in the PhD jury of Isabelle Santos (Toulouse), HDR jury of Max Cerf (Paris). He is member of the jury of agrégation de mathématiques.

10.3. Popularization

10.3.1. Internal or external Inria responsibilities

J.-B. Caillau belongs to the MASTIC initiative at Inria Sophia.

10.3.2. Interventions

Lamberto Dell'Elce is involved in the PoBot challenge promoted by MEDITES. Specifically he supervises a class in the College Emile Roux in Cannes.

J.-B. Caillau has given several talks at high-school level in Nice and Sophia on application of mathematics in social choice.

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Project-Team MORPHEME

Morphologie et Images

IN COLLABORATION WITH: Institut de Biologie de Valrose, Laboratoire informatique, signaux systèmes de Sophia Antipolis (I3S)

IN PARTNERSHIP WITH:
CNRS

Université Nice - Sophia Antipolis

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Computational Biology

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Project-Team MORPHEME

Creation of the Team: 2011 September 01, updated into Project-Team: 2013 July 01

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Other Research Topics and Application Domains:

B1.1. - Biology
B1.1.3. - Developmental biology
B2.6. - Biological and medical imaging

1. Team, Visitors, External Collaborators

Research Scientists

Florence Besse [CNRS, Senior Researcher]
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Luca Calatroni [CNRS, Researcher, from Oct 2019]
Eric Debreuve [CNRS, Researcher, HDR]
Xavier Descombes [Team leader, Inria, Senior Researcher, HDR]
Grégoire Malandain [Inria, Senior Researcher, HDR]
Caroline Medioni [CNRS, Researcher]

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Sébastien Schaub [CNRS]

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Somia Rahmoun [Inria, from Oct 2019]

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Anca-Ioana Grapa [Univ de Nice - Sophia Antipolis]
Sarah Laroui [Bayer (cifre)]
Emmanuelle Poulain [GE (cifre) then Inria, until Mar 2019]
Vasiliki Stergiopoulou [CNRS (3IA), from Dec 2019]
Rudan Xiao [Univ Côte d'Azur, from Oct 2019]

Post-Doctoral Fellows
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Somia Rahmoun [Inria, until Sep 2019]

Visiting Scientists
Alin Achim [Bristol University, from Sep 2019]
Rim Rahali [CNRS, from Mar 2019 until May 2019]

2. Overall Objectives

2.1. Overall Objectives

Morpheme is a joint project between Inria, CNRS and the University of Nice-Sophia Antipolis, involving the Computer Science, Signals and Systems Laboratory (I3S) (UMR 6070) and the Institute for Biology of Valrose (iBV) (CNRS/INSERM).

The scientific objectives of MORPHEME are to characterize and model the development and the morphological properties of biological structures from the cell to the supra-cellular scale. Being at the interface between computational science and biology, we plan to understand the morphological changes that occur during development combining in vivo imaging, image processing and computational modeling.

The morphology and topology of mesoscopic structures, indeed, do have a key influence on the functional behavior of organs. Our goal is to characterize different populations or development conditions based on the shape of cellular and supra-cellular structures, including micro-vascular networks and dendrite/axon networks. Using microscopy or tomography images, we plan to extract quantitative parameters to characterize morphometry over time and in different samples. We will then statistically analyze shapes and complex structures to identify relevant markers and define classification tools. Finally, we will propose models explaining the temporal evolution of the observed samples. With this, we hope to better understand the development of normal tissues, but also characterize at the supra-cellular level different pathologies such as the Fragile X Syndrome, Alzheimer or diabetes.

3. Research Program

3.1. Research program

The recent advent of an increasing number of new microscopy techniques giving access to high throughput screenings and micro or nano-metric resolutions provides a means for quantitative imaging of biological structures and phenomena. To conduct quantitative biological studies based on these new data, it is necessary to develop non-standard specific tools. This requires using a multi-disciplinary approach. We need biologists to define experiment protocols and interpret the results, but also physicists to model the sensors, computer scientists to develop algorithms and mathematicians to model the resulting information. These different expertises are combined within the Morpheme team. This generates a fecund frame for exchanging expertise, knowledge, leading to an optimal framework for the different tasks (imaging, image analysis, classification, modeling). We thus aim at providing adapted and robust tools required to describe, explain and model fundamental phenomena underlying the morphogenesis of cellular and supra-cellular biological structures. Combining experimental manipulations, in vivo imaging, image processing and computational modeling, we plan to provide methods for the quantitative analysis of the morphological changes that occur during development. This is of key importance as the morphology and topology of mesoscopic structures govern organ and cell function. Alterations in the genetic programs underlying cellular morphogenesis have been linked to a range of pathologies.

Biological questions we will focus on include:

1. what are the parameters and the factors controlling the establishment of ramified structures? (Are they really organize to ensure maximal coverage? How are genetic and physical constraints limiting their morphology?),
2. how are newly generated cells incorporated into reorganizing tissues during development? (is the relative position of cells governed by the lineage they belong to?)

Our goal is to characterize different populations or development conditions based on the shape of cellular and supra-cellular structures, e.g. micro-vascular networks, dendrite/axon networks, tissues from 2D, 2D+t, 3D or 3D+t images (obtained with confocal microscopy, video-microscopy, photon-microscopy or micro-tomography). We plan to extract shapes or quantitative parameters to characterize the morphometric properties of different samples. On the one hand, we will propose numerical and biological models explaining the temporal evolution of the sample, and on the other hand, we will statistically analyze shapes and complex structures to identify relevant markers for classification purposes. This should contribute to a better understanding of the development of normal tissues but also to a characterization at the supra-cellular scale of different pathologies such as Alzheimer, cancer, diabetes, or the Fragile X Syndrome. In this multidisciplinary context, several challenges have to be faced. The expertise of biologists concerning sample generation, as well as optimization of experimental protocols and imaging conditions, is of course crucial. However, the imaging protocols optimized for a qualitative analysis may be sub-optimal for quantitative biology. Second, sample imaging is only a first step, as we need to extract quantitative information. Achieving quantitative imaging remains an open issue in biology, and requires close interactions between biologists, computer scientists and applied mathematicians. On the one hand, experimental and imaging protocols should integrate constraints from the downstream computer-assisted analysis, yielding to a trade-off between qualitative optimized and quantitative optimized protocols. On the other hand, computer analysis should integrate constraints specific to the biological problem, from acquisition to quantitative information extraction. There is therefore a need of specificity for embedding precise biological information for a given task. Besides, a level of generality is also desirable for addressing data from different teams acquired with different protocols and/or sensors. The mathematical modeling of the physics of the acquisition system will yield higher performance reconstruction/restoration algorithms in terms of accuracy. Therefore, physicists and computer scientists have to work together. Quantitative information extraction also has to deal with both the complexity of the structures of interest (e.g., very dense network, small structure detection in a volume, multiscale behavior, ...) and the unavoidable defects of in vivo imaging (artifacts, missing data, ...). Incorporating biological expertise in model-based segmentation methods provides the required specificity while robustness gained from a methodological analysis increases the generality. Finally, beyond image processing, we aim at quantifying and then statistically analyzing shapes and complex structures (e.g., neuronal or vascular networks), static or in evolution, taking into account variability. In this context, learning methods will be developed for determining (dis)similarity measures between two samples or for determining directly a classification rule using discriminative models, generative models, or hybrid models. Besides, some metrics for comparing, classifying and characterizing objects under study are necessary. We will construct such metrics for biological structures such as neuronal or vascular networks. Attention will be paid to computational cost and scalability of the developed algorithms: biological experimentations generally yield huge data sets resulting from high throughput screenings. The research of Morpheme will be developed along the following axes:

- **Imaging:** this includes i) definition of the studied populations (experimental conditions) and preparation of samples, ii) definition of relevant quantitative characteristics and optimized acquisition protocol (staining, imaging, ...) for the specific biological question, and iii) reconstruction/restoration of native data to improve the image readability and interpretation.
- **Feature extraction:** this consists in detecting and delineating the biological structures of interest from images. Embedding biological properties in the algorithms and models is a key issue. Two main challenges are the variability, both in shape and scale, of biological structures and the huge size of data sets. Following features along time will allow to address morphogenesis and structure development.
- **Classification/Interpretation:** considering a database of images containing different populations, we can infer the parameters associated with a given model on each dataset from which the biological structure under study has been extracted. We plan to define classification schemes for characterizing the different populations based either on the model parameters, or on some specific metric between the extracted structures.
- **Modeling:** two aspects will be considered. This first one consists in modeling biological phenomena such as axon growing or network topology in different contexts. One main advantage of our team is the possibility to use the image information for calibrating and/or validating the biological models. Calibration induces parameter inference as a main challenge. The second aspect consists in using a prior based on biological properties for extracting relevant information from images. Here again, combining biology and computer science expertise is a key point.

4. Highlights of the Year

4.1. Highlights of the Year

Luca Calatroni get a CNRS position as scientist and joined the team in october 2019.

5. New Software and Platforms

5.1. Obj.MPP

KEYWORDS: Object detection - Marked Point Process - Parametric model

FUNCTIONAL DESCRIPTION: Obj.MPP implements the detection of parametric objects using a Marked Point Process (MPP). A parametric object is an n-dimensional piece of signal defined by a finite set of parameters. Detecting an object in a signal amounts to finding a position at which the signal can be described well enough by a specific set of parameters (unknowns of the detection problem). The detection task amounts to finding all such objects. Typically, the signal is a 2-dimensional grayscale image and the parametric objects are bright disks on a dark background. In this case, each object is defined by a single parameter: the disk radius. Note however that the core function of Obj.MPP is not tied to a particular context (2-dimensional imaging is just an example).

- Author: Eric Debreuve
- Contact: Eric Debreuve
- Publications: Stochastic geometry for image analysis - Multiple objects detection in biological images using a marked point process framework - An efficient optimizer for simple point process models - Multiple Birth and Cut Algorithm for Multiple Object Detection
- URL: https://team.inria.fr/morpheme/obj-mpp-object-detection-using-a-marked-point-process/

5.2. ATOLS

Adaptative Threshold Operator based on Level Sets

KEYWORDS: Object detection - Level Set

FUNCTIONAL DESCRIPTION: Atols is a Python script allowing to detect features on images using a contrast scoring. Thus, it's possible to detect features at different levels of intensity unlike a simple threshold which would only keep features above its value.

- Authors: Kevin Giulietti and Guillaume Lavisse
- Contact: Xavier Descombes
- URL: https://team.inria.fr/morpheme/software/

5.3. Small particle detection

KEYWORDS: Image processing - Image segmentation - Object detection - Computational biology - Fluorescence microscopy - Biomedical imaging

FUNCTIONAL DESCRIPTION: An algorithm primarily design to detect objects whose sizes aren't larger a few pixels (particles) on fluorescence microscopy images.

It is an simplified version of marked point process.

- Contact: Nicolas Cedilnik
- Publications: SPADE: A Small Particle Detection Method Using A Dictionary Of Shapes Within The Marked Point Process Framework - SPADE: A Small Particle Detection Method Using A Dictionary Of Shapes Within The Marked Point Process Framework
- URL: https://gitlab.inria.fr/ncedilni/spade

6. New Results

6.1. Exact biconvex reformulation of the $\ell_2 - \ell_0$ minimization problem

Participants: Gilles Aubert, Arne Henrik Bechensteen, Laure Blanc-Féraud.

We focus on the problem of minimizing the least-squares loss function under the constraint that the reconstructed signal is at maximum k-sparse. This is called the ℓ_2-ℓ_0 constrained problem. The ℓ_0 pseudo-norm counts the number of non-zero elements in a vector. The minimization problem is of interest in signal processing, with a wide range of applications as compressed sensing, source separation, and super-resolution imaging, for example.

Based on the results of [31], we reformulate the ℓ_0 pseudo-norm exactly as a convex minimization problem by introducing an auxiliary variable. We then propose an exact biconvex reformulation of the $\ell_2 - \ell_0$ constrained and penalized problems. We give correspondence results between minimizer of the initial function and the reformulated ones. The reformulation is biconvex. This property is used to derive two minimization algorithm, CoBic (Constrained Biconvex) and PeBic (Penalized Biconvex).

We apply the algorithms to the problem of Single-Molecule Localization Microscopy and compare the results with the well-known IHT algorithm [22]. Both visually and numerically the biconvex reformulations perform better. Furthermore, the algorithm has been compared to the IRL1-CEL0 [23] and Deep-STORM [25]. The IRL1-CEL0 minimizes an exact relaxation [29] of the $\ell_2 - \ell_0$ penalized form and Deep-STORM is an algorithm that uses deep-learning and convolutional network to localize the molecules. This work has been presented at the ISBI 2019 conference [6], as well as a more mathematical article was presented as a poster at GRETSI 2019 [12]. A full journal article has been submitted to the Biomedical Optics Express for a feature issue: Superresolution Microscopy on the 25th Anniversary of STED Microscopy and the 20th Anniversary of SIM.

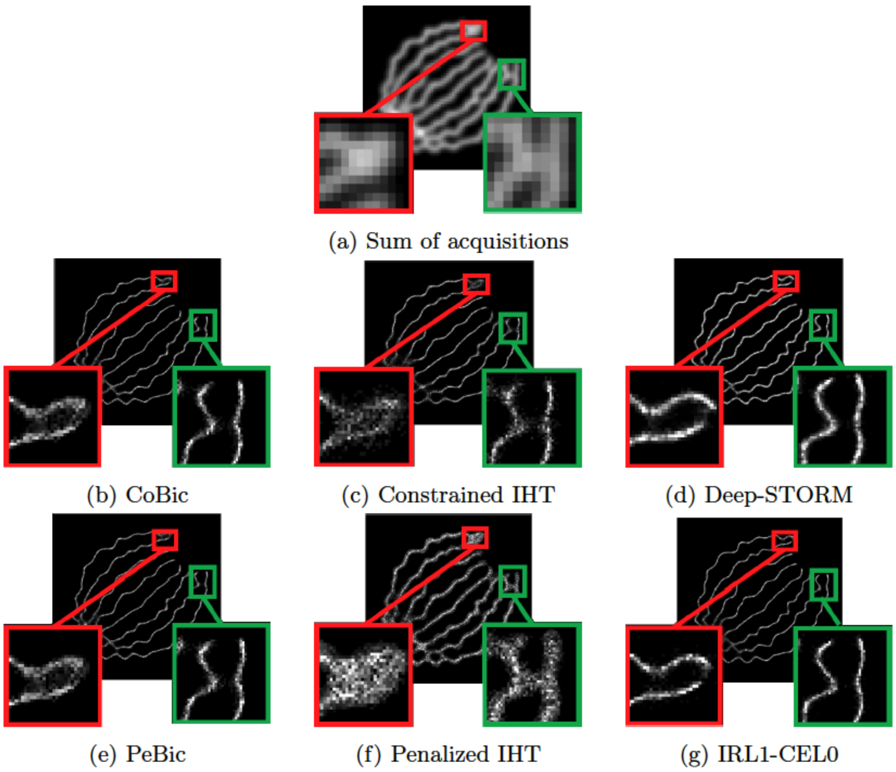

Figure 1. Reconstructed images from the simulated ISBI dataset [28], 99 non-zero pixels on average. Top: Sum of the acquisitions. Middle: From left to right: CoBic, Constrained IHT and Deep-STROM. Bottom: From left to right: PeBic, Penalized IHT and IRL1-CEL0.

6.2. Biological Image Super-resolution Enhanced with Tensor

Participants: Jose Henrique de Morais Goulart, Laure Blanc-Féraud, Eric Debreuve, Sébastien Schaub.

This work is part of the BISET project, funded by the académie 1 RISE (Réseaux, Information et Société numErique) of Idex UCA JEDI.

Fluorescence microscopy imaging has numerous applications in biological sciences, but has limited resolution due to light diffraction. Recently proposed super-resolution techniques acquire an image time series at a high frame rate and exploit independent random fluorophore blinking for reconstruction. This approach holds great potential for observing live-cell sub-cellular phenomena, which is a challenging scenario with strict constraints over the deployed excitation levels and the acquisition time.

The BISET project aimed to develop tensor-based super-resolution fluorescence microscopy algorithms based on this approach. Assuming a known separable PSF $h(x, y) = g(x)g(y)$, a third-order tensor model with two spatial diversities and one temporal diversity was proposed. The model unknowns are high-dimensional fluorophore spatial profiles along x and y directions and temporal fluorophore profiles modeling blinking. Our formulation employs a least-squares loss term and penalty functions promoting spatial profile sparsity (necessary for fluorophore locality) and temporal profile group sparsity (which controls the number of fluorophores).

The formulation is nonconvex but block-convex in the unknown profiles and thus can be solved by alternating minimization. It has a significantly smaller number of unknowns in comparison with a matrix-based convex one (with frames as columns), in consonance with the current trend of employing nonconvex formulations rather than overparameterized convex ones which are often too costly. However, its resolution is numerically challenging for high-density acquisitions. Indeed, even though the proposed algorithm is able to reveal the overall target structure in our simulations, it produces a “dotted” reconstruction. For comparison, we developed a matrix-based formulation with nonconvex group-sparsity regularization, which is more costly to solve but achieves better results. These findings were published in the IEEE CAMSAP 2019 conference [11], and were also presented on October 2019 in a GdR ISIS (Information, Signal, Image et Vision)/MIA (Mathématiques de l'Imagerie et de ses Applications)/ONDES meeting [0] held in Paris and entitled "Co-conception: hybrid sensors and algorithms for innovative systems". An illustration of the results produced by the developed tensor and matrix methods is given in Figure 2, along with outcomes of other state-of-art methods. In conclusion, though our tensor approach is innovative and was shown to be promising, further research is needed to overcome the model estimation difficulties.

6.3. Classification and Modeling of the Fibronectin Networks in Extracellular Matrices

Participants: Anca-Ioana Grapa, Laure Blanc-Féraud, Xavier Descombes.

This work is done in collaboration with Ellen Van Obberghen-Schilling and Georgios Efthymiou (iBV).

We are interested in the numerical analysis and modeling of the Fibronectin (FN) networks, a major extracellular matrix (ECM) molecule, expressed in pathological states (fibrosis, cancer, etc). Our goal is to develop numerical quantitative biomarkers that describe the geometrical organization of the different four variants of the FN fiber networks, from 2D confocal microscopy images. Since the functions of these variants are not well defined in the context of their role within the tumour microenvironment, we hope that a computational model might be able to provide a meaningful description that incorporates the structural differences among the variants.

In a previous work, we have derived a pipeline to classify a given tissue among the four FN variants (cell-derived matrices), based on a decomposition into discrete fast curvelet transform coefficients. We ensured the invariance to rotation of the coefficients and then fed them to a DAG-SVM multiclassifier, in order to prove their discriminative ability in the context of classification of the four FN variants. The results were published in [24] and show that the curvelet coefficients are capable of discerning among the four FN variants with similar performances to those of a human annotator.

[0] Meeting webpage: `http://www.gdr-isis.fr/index.php?page=reunion&idreunion=401`.

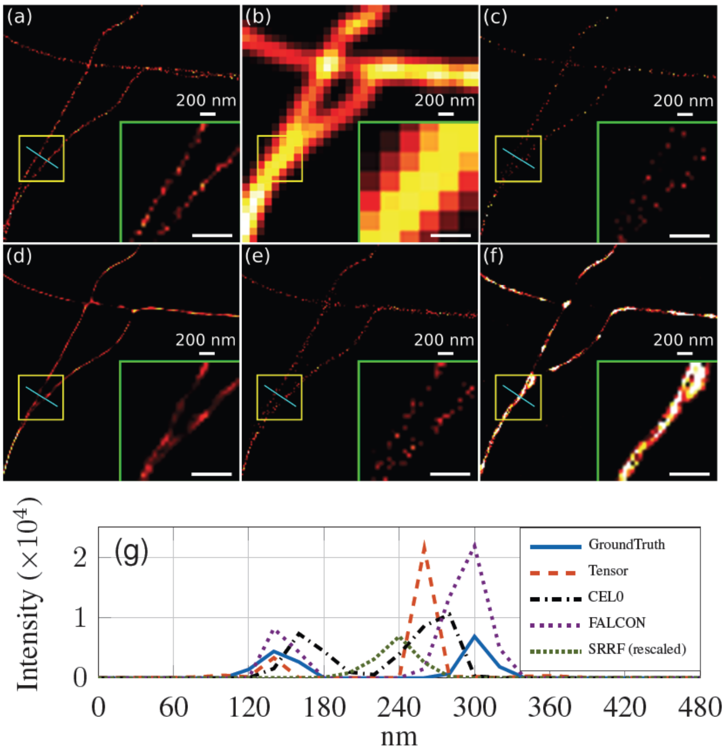

Figure 2. Results for reconstruction of simulated microtubules: (a) integrated ground truth; (b) integrated observed stack (5× zoom); (c) proposed tensor approach; (d) proposed matrix approach; (e) FALCON; (f) SRRF; (g) intensity profiles along the shown blue line. The frame in the bottom right corner shows a $2.66\times$ *zoom of the smaller yellow frame.*

The second step of our work consisted in setting up the modeling of the FN networks starting from a graph-based representation, built on top of Gabor features (fiber scale, orientation, etc). The graph parameters corresponding to the geometrical and topological features of the improved skeletonizations (i.e. median pore circularity, ratio of fiber thinness, fiber thickness kurtosis, fiber connectivity) of the four FN variants, are then classified by a DAG-SVM. It is thus shown through the analysis of the feature distribution over the four variants, features PCA analysis and SVM-based classification, that graph features can discriminate among the FN variants almost as well as our first work. This proves that the graph representation embeds the most relevant information provided by the image.

The next step focused on the development of a metric between graphs that takes into account their topology and geometry. This distance is bound to provide a quantitative but also a qualitative comparison of the four FN variants as well as a differentiation between normal and tumour-like FN fibers. In order to evaluate the distance among graphs, we have referred to graph-matching techniques, which are considered standard problems that deal with graph comparison. The main idea is to obtain an evaluation of the similarity between two graphs, by finding the optimal correspondence between their nodes, such as to align their structure, i.e their adjacency matrices. We expect to obtain invariance with respect to translation, rotation and scale.

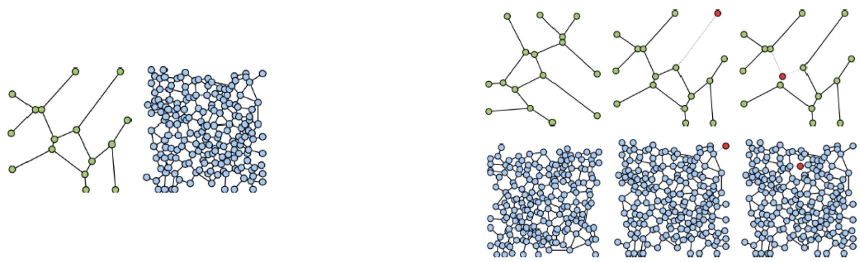

Figure 3. Generated toy-graphs with different dimensions: $16, 181$ *nodes (left side). Right side illustrates the database of toy-graphs derived from the initial ones, but having small modifications in terms of node order (first column) and different number of nodes (second and third column). The purpose is to match the nodes of every pair of graph (initial-modified) using the graph-matching and optimal assignment framework and compare the performances of the two methods.*

More specifically, we are interested in one of the various techniques to perform many-to-many graph matching [32], where the merging of multiple nodes to match another one is allowed, especially in the case of graphs with different dimensions (i.e. different number of total vertices). Alternatively, we considered a different line of work, based on optimal transport for the comparison of structured objects (e.g. graphs) with associated probability distributions. We focus on the work of Peyré et al. [26] that have considered a metric called Gromov-Wasserstein, capable of comparing objects that lie in spaces with different dimensions, by minimizing the cost of mass transport from one discrete distribution to the other. In the context of graph matching techniques, this can be regarded as a probabilistic assignment problem.

In [13], we have compared the two aforementioned approaches from a graph-matching perspective, on randomly generated graphs (Figure 3), in the context of a preliminary study for the future modeling of FN graph-based representations. We have tested different graph scenarios, with various information captured by the adjacency matrix (binary adjacency matrix, shortest path between nodes). Moreover, we have slightly modified the second method by optimal transport, to make it feasible for direct one-to-one matching, by adding dummy masses. We have concluded that the graph matching by many-to-many assignment, captures a meaningful distance between two given graphs with good performances, while the Gromov-Wasserstein discrepancy is computed faster but with lower performances.

One advantage of using graph-matching techniques for comparing fiber networks, comes from the possibility of defining a median graph that will be representative of a FN class. Currently, we are developing methodologies for deriving the representative graph for FN variants, using the metric provided by the many-to-many graph assignment problem. The challenges range from deciding a good technique to perform a meaningful matching among the graphs, to determining the adjacency of the median graph and the corresponding physical localization of the nodes.

A second advantage is given by the possibility of computing various deformation maps between FN fiber networks: the matching serves as a registration between the graphs, and once after having obtained an assignment between the corresponding graph edges, we can compute the differences in terms of fiber length, orientation, etc (see Figure 4 for a example of a deformation map in terms of fiber length - which can be regarded as a local stretching of the fibers that should be applied to first graph in order to obtain the second one)).

The deformation maps can subsequently be analyzed in a test hypothesis framework that decides whether the variation of a certain parameter (e.g. length) is due to the the variance within the same class or not.

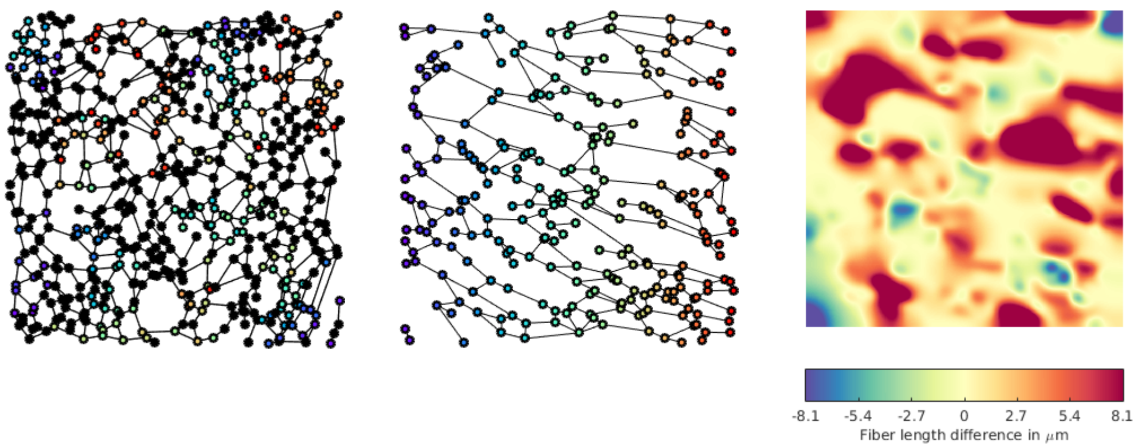

Figure 4. From left to right: graph network FN A+; graph network FN A+ ("tumour-like"); Deformation map between FN A+ and FN A+ (tumour-like)

Once we have derived a meaningful median graph based on graph-matching distances, we might be able to perform classification of the graph networks. Additionally, the fiber properties statistics inferred from the graph local properties, as well as Gabor filters parameters, can be of use to interpret the local differences within a specific class and among FN variants.

Anca Grapa's work is supported by the French Government (National Research Agency, ANR) through the ”Investments for the Future” LABEX SIGNALIFE: program reference ANR-11-LABX-0028-01.

6.4. Classification of the Fibronectin Networks in Extracellular Matrices using CNN and DAG-SVM of confocal and coverslip scanner images

Participants: Ghosh Avrajit, Anca-Ioana Grapa, Laure Blanc-Féraud, Xavier Descombes.

This work is done in collaboration with Ellen Van Obberghen-Schilling and Georgios Efthymiou (iBV).

We are interested in the numerical analysis and modeling of the Fibronectin (FN) networks, a major extracellular matrix (ECM) molecule, expressed in pathological states (fibrosis, cancer, etc).

Firstly, during one experiment, confocal images 3128 × 3128 pixels with a lateral resolution of 0.27μm/pixel were acquired with a Zeiss LSM710 confocal system $10X/0.45$ with the pinhole diameter set to its maximal value. Subsequently, images of FN variants in a different experiment were acquired using a coverslip scanner (Vectra Polaris Automated Quantitative Pathology Imaging System) based on fluorescence whole-slide scanning on a similar resolution to that of the confocal system.

For each of the experiments, 70 images (for every FN variant) corresponding to a representative region of 512×512 pixels were selected for feature extraction and classification.The set of 280 gray-scale images was classified with a DAG-SVM classifier using curvelet features using the parametrization from [24]. Additionally, it was classified with the GoogLeNet [30] pretrained Convolutional Neural Net (CNN) architecture using the MATLAB Deep Learning Toolbox and a 22-layer deep network trained on more than 1 million images for classification into 1000 object categories. A set of 196 images was used for the training of the algorithm, and the remaining 84 for testing it. The training image set was presented to the algorithm 25 times (epochs), in order to improve classification accuracy.

The results (Figures 5, 7, 6, and 8) show that the information in the FN images is relevant enough in a CNN-based classification to distinguish FN variants better than curvelet-based features. Additionally, the coverslip scanner acquired samples are classified with a higher accuracy, underlining the potential benefit of using the scanner for future experiments.

Actual / Predicted	FN B-A+	FN B-A-	FN B+A-	FN B+A+
FN B-A+	85.7	0	28.5	14.3
FN B-A-	0	80.9	14.3	4.8
FN B+A-	0	9.5	90.5	0
FN B+A+	9.5	14.3	0	76.2

Figure 5. Confusion matrix in percentage form of the CNN classification of FN variant confocal images. General mean accuracy of classification is 83.3%.

Actual/ Predicted	FN B-A+	FN B-A-	FB B+A-	FN B+A+
FN B-A+	64.3	2.9	25.7	7.1
FN B-A-	0	90	0	10
FN B+A-	25.7	4.3	45.7	24.3
FN B+A+	0	15.7	8.6	75.7

Figure 6. Confusion matrix in percentage form of the DAG-SVM classification of FN variants, using curvelets features. General mean accuracy of classification is 68.9%.

6.5. Tumor cell tracking for automatic detection of cell death time, and classification of its type

Participants: Deborah Cottais, Eric Debreuve.

This work was made in collaboration with Jérémie Roux (IRCAN, Nice, France).

Actual/ Predicted	FN B-A+	FN B-A-	FB B+A-	FN B+A+
FN B-A+	95.2	0	0	4.7
FN B-A-	0	100	0	0
FN B+A-	0	4.7	62	33
FN B+A+	0	0	0	100

Figure 7. Confusion matrix in percentage form of the CNN classification of FN variant coverslip scanner images. General mean accuracy of classification is 89.3%*.*

Actual/ Predicted	FN B-A+	FN B-A-	FB B+A-	FN B+A+
FN B-A+	72.8	0	0	27.1
FN B-A-	0	85.7	8.5	5.7
FN B+A-	0	10	65.7	24.2
FN B+A+	15.7	0	11.43	72.8

Figure 8. Confusion matrix in percentage form of the DAG-SVM classification of FN variant coverslip scanner images (curvelet features).General mean accuracy of classification is 74.2%*.*

The available data were multi-channel videos acquired in fluorescence microscopy. We first performed cell segmentation on the channel in which the geometrical information was predominant. Then we performed tracking of the segmented cells. More precisely, we refer to tracking as the construction of cell trajectories along the video (see Fig. 9). By *transferring* this cell tracking onto the channel in which the radiometric information of the cells is the richest (mean intensity, variance, texture), we were able to extract characteristics for each cell, and study their temporal evolution to deduce the moment of cell death. Next, we are planning to develop a method of classification of the cell deaths into predefined types.

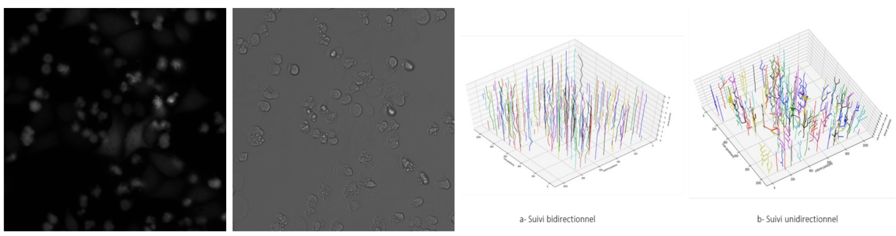

Figure 9. From left to right: two channels of a video frame and tracking trajectories of the segmented cells.

6.6. Cytoplasm segmentation from cells confocal microscopy images

Participants: Somia Rahmoun, Eric Debreuve, Xavier Descombes, Fabienne de Graeve.

As part of the ANR project RNAGRIMP, two series of images have been acquired using fluorescence microscopy: one where the cell cytoplasm has been stained with GFP (Green Fluorescent Protein), the second where the nuclei have been stained with DAPI (4',6-diamidino-2-phenylindole). The first steps are detecting the nuclei on the DAPI images and learning a classification procedure into living cell or dead cell based on morphological and radiometric nuclei properties (average intensity, area, granularity, circularity, ...).

The next step is to segment (i.e., extract automatically the region of) the cell cytoplasms on the GFP images. Indeed, the target RNP-IMP granules appear in that compartment of the cell and are visible through their GFP response. This segmentation problem is particularly difficult due the heterogeneity of the cells intensity. This heterogeneity even appears within a given cell. Besides, cells sometimes form cluster in which there is no clear separation between adjacent cells.

In this context, we have considered a two steps algorithm to segment the cytoplasm. The first step consists of the image segmentation in small areas called superpixels that represent adjacent pixels with similar intensity. An automatic algorithm based on the watershed transform has been chosen after evaluating and comparing different strategies (based on iterative clustering, minimum spanning tree, persistent edge selection ...).

The second step of the proposed approach performs superpixels merging to obtain the final segmentation. Starting from the previously detected nuclei to define cell seeds, the neighboring superpixels are merged iteratively if a radiometric similarity is detected. Ambiguities between neighboring cells are solved by combining radiometric and shape criteria. This cell growth process is considered layer by layer and performed in parallel.

6.7. Adaptative thresholding using persistent diagrams

Participants: Paul Emmanuel Ponsenard, Xavier Descombes.

In this project we have proposed a new algorithm for adaptative thresholding based on persistence diagrams. A common difficulty in binarizing biological images lies in the heterogeneity of the signal. This heterogeneity can be due to the sensor itself but also to variability in the cell response to a given marker. Therefore the binarization can not be adequately performed by using the same threshold on the whole image. In this context, adaptative approaches that estimate a local or regional proper threshold are needed. Last year, we have proposed a solution that embedded both a contrast term and a shape criterion to select the most relevant connected components among the different level sets of the image. In this work we focus on the connected component trajectories along the grey values defining the levels sets. More precisely, the persistent diagram studies the evolution of the different connected components of a binarized image for successive thresholds. The life time of a connected component is thus defined as the timelapse between its birth (gray level for which the component appears) and its death (gray level for which the component is merged with a neighboring one). As a final result for the binarization, we propose to keep the connected components with the longest lifetimes. A result on mitochondrial network binarization is shown on figure 10.

6.8. Graph matching and median graph through simulating annealing

Participants: Zhankeng Zhang, Xavier Descombes.

Graph matching when the number of nodes and edges differs is known as an NP-hard problem. Therefore, sub-optimal optimization algorithms have been proposed to solve this problem. In this work, we evaluate the possibility to reach, at least theoretically, the global optimum by using simulated annealing. We have developed an improved version of the simulating annealing scheme based on a Metropolis sampler. To solve the problem of dimension matching (different number of nodes) we have classically added dummy nodes in the smaller graph. Besides, we have shown that adding dummy nodes in both graphs provides more flexibility in the matching, thus improving the matching result. Finally, within this framework we were able to define and compute "median" graph as shown on figure 11. The algorithm consists in aligning all the graphs in a first step. The median graph is then obtained by considering two types of move in the simulated annealing: adding/removing an edge and switching two nodes. To validate this work we have considered a classification scheme between graphs. The obtained results overcome those obtained with state of the art graph matching algorithms while the computational time remains reasonable.

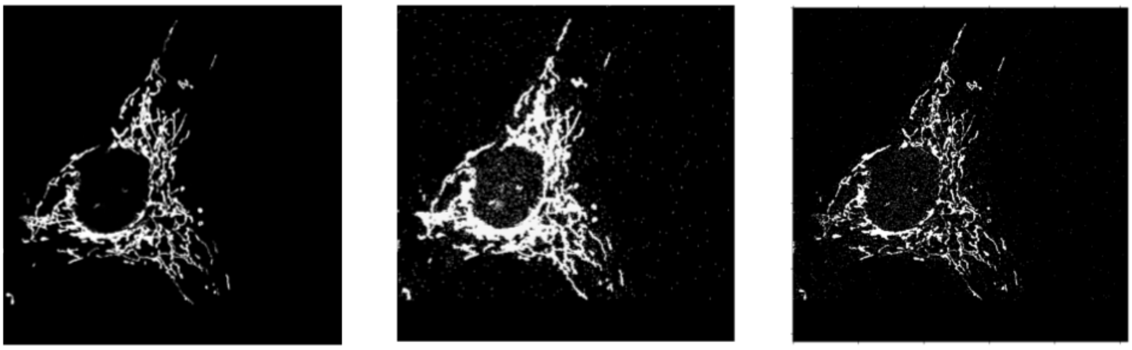

Figure 10. Image of Mitochondria from Bost team at C3M (left), Binarization obtained with a global threshold (middle) and with the persistence diagram approach. (right).

6.9. Botrytis cinerea phenotype recognition and classification: toward the establishment of links between phenotypes and antifungal molecules

Participants: Sarah Laroui, Eric Debreuve, Xavier Descombes.

This work is made in collaboration with Aurelia Vernay and Florent Villiers (Bayer).

Botrytis cinerea is a reference model of filamentous phytopathogen fungi. Some chemical treatments can lead to characteristic morphological changes, or phenotypic signatures. These phenotypes could be associated with the treatment Mode of Action (Figure 12). In order to recognise and characterise different phenotypes and associate them with the different modes of action of the molecules (Figure 13), 24-hour images are taken by transmitted light microscopy. Because of the different dose-response effects, each given molecule is tested at ten concentrations.

We compared the results of classification of these images using two methods: random forests and convolutional neural networks (Deep Learning).

To learn the Random Forest classifier, we developed a robust image analysis and classification framework relying on morphometric and topological characteristics. A number of 16 features are extracted from three representations of the objects (binary mask, skeleton and graph). Some are calculated globally over all the objects of an image (ex: the skeleton length variance) while others are calculated on each object of an image (ex: the number of nodes of the graph). The second method uses a convolutional neural network. It has been implemented using Tensorflow, an open source library for Machine Learning, created by Google to develop applications in Deep Learning.

This method achieves better results than Random Forests, and it proved to be very robust to inter-experiment variations with an average classification accuracy of 88%. In addition, it does not require data pre-processing for feature extraction. However the explanatory aspect that exists with random forests is lost.

6.10. Estimating the volume of a copepod from a single image with Deep Learning

Participants: Cédric Dubois, Eric Debreuve.

This work was made in collaboration with Jean-Olivier Irisson (Laboratoire d'Océanographie de Villefranche).

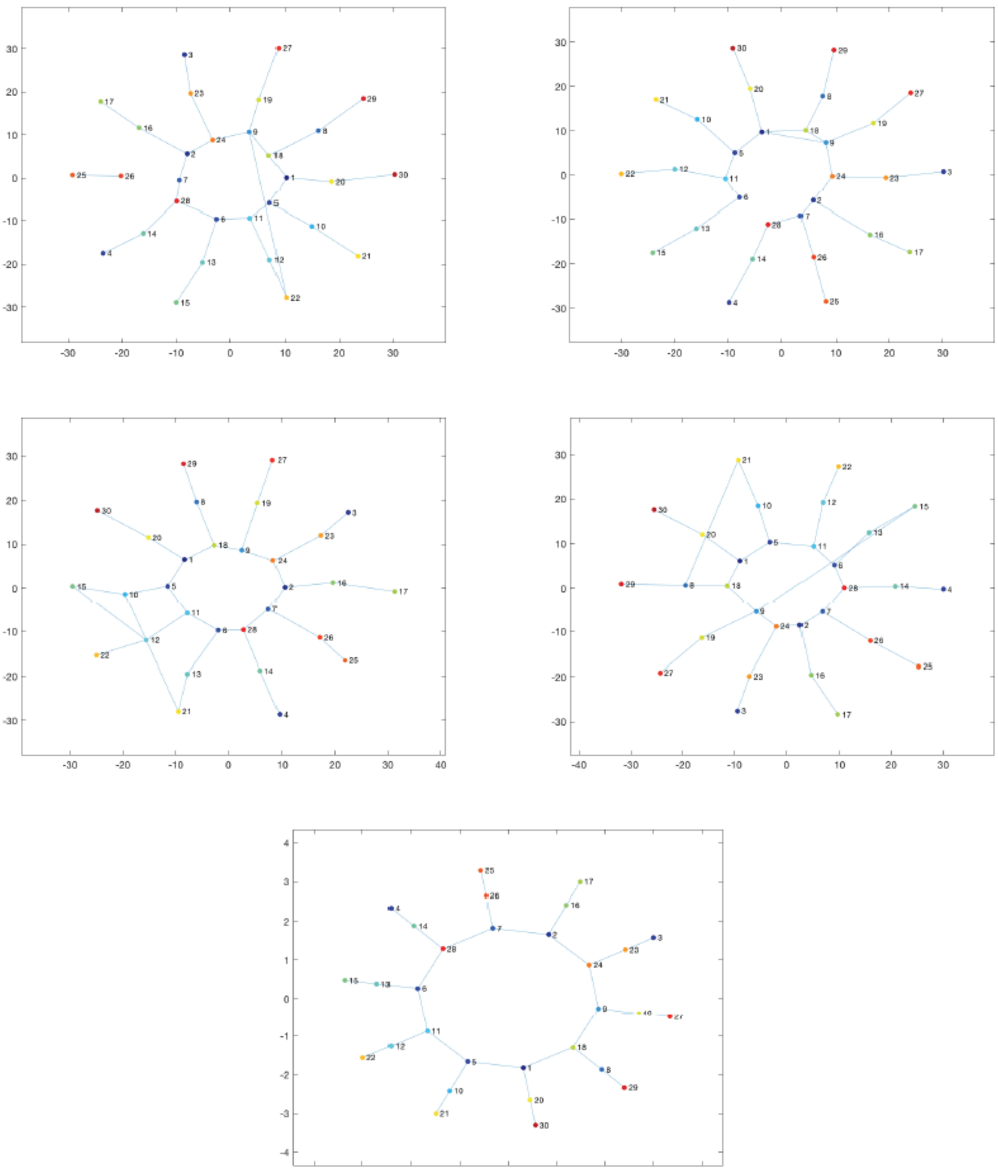

Figure 11. Four samples of noisy SUN graph and computed median graph

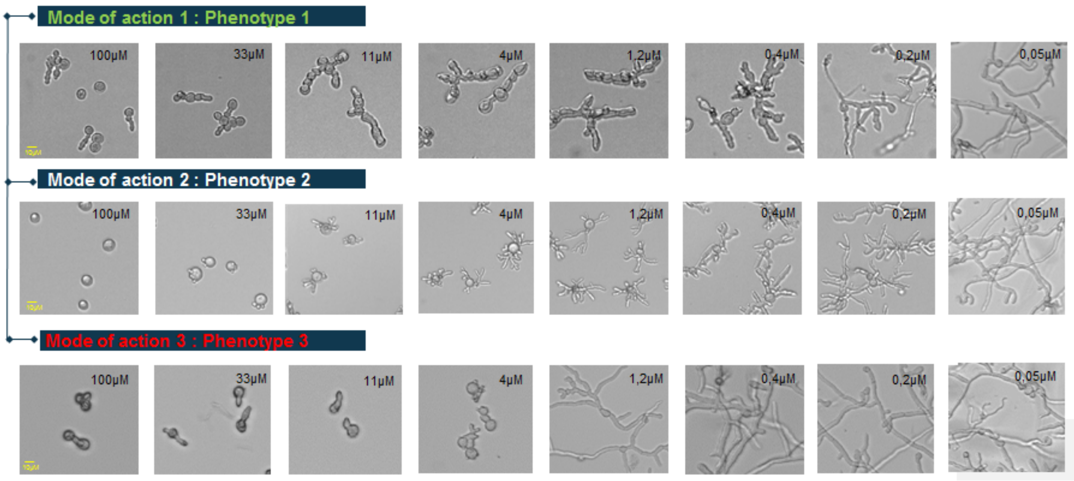

Figure 12. Characteristic phenotypic signatures for different chemical treatments at different concentrations (transmitted light microscopy, ImageXpress microscope, 10x lens).

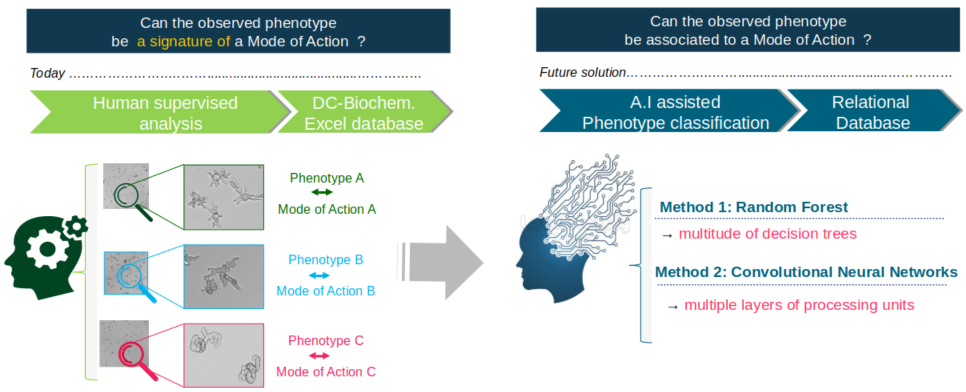

Figure 13. Example of phenotypic signatures obtained with molecules with three different mode of action. Strategy of automatic recognition and characterisation of different phenotypes and associate them with the different modes of action of the molecules.

Ecologists and biogeochemists are interested in estimating the volume of copepods (to then convert it into a biomass), a subclass of zooplankton, in order to estimate how much carbon it can store and how much it will store in the future. Those studies are made thanks to the online database EcoTaxa, which gives access to a large number of plankton images. The standard method used in ecology produces partially incorrect results due to geometric approximations and projection issues (from 3D to the 2D image plane). We first proposed a study of the error made by this method on the volume estimation of copepods. Then we proposed a new method based on the deep learning framework. Its performances have been analyzed on simulated data (Fig. 14) and preliminary tests have been made on a subset of the data of the *UVP5hd GreenEdge 2016* acquisition campaign available on EcoTaxa. Our work pointed out the limitations of both methods, indicating that a broader study is needed to improve the computation of copepod volumes.

This work formed the basis for Cédric Dubois's PhD which began on October 1st 2019 with a Ministère de la Recherche funding.

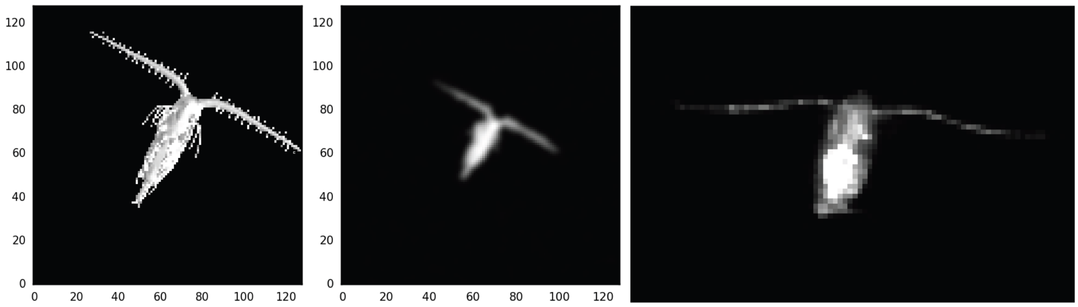

Figure 14. Left: synthetic 3D model of a typical copepod. Middle: a simulated 2D observation of the model. Right: a real observation.

6.11. Cell lineage calculation

Participants: Manuel Petit [Mosaic, Lyon], Christophe Godin [Mosaic, Lyon], Grégoire Malandain.

This work is made within the IPL Naviscope.

In recent years, techniques to image the development of biological organisms have made spectacular progresses. Researchers are now able to observe the trajectories corresponding to the development of 3D- plant tissues or animal embryo with cellular resolution. However, such observations yield a large amount of data, which, in turn, require fast and robust analysis tools to extract information while minimizing user interaction. The goal of M. Petit, which PhD thesis has begun november the 1st, is first to propose new lineage extraction schemes, and then analysis tools over a population of lineages.

6.12. Morphogenesis of the sea urchin embryo

Participants: Angie Moullet, Grégoire Malandain.

This work is made in collaboration with Barthélḿy Delorme and Matteo Rauzi (iBV, Nice).

The goal of the project is to understand how biophysical forces are generated and how they work to produce exquisitely precise and controlled tissue shape changes in embryo development. Tissue morphogenesis is a process by which the embryo is reshaped into the final form of a developed animal. Tissues are constituted by cells that are interconnected one another: local changes of cell mechanical properties and shape drive consequent tissue shape change. Nevertheless, the knowledge per se of the mechanisms and mechanics at the cell level which drive cell shape changes is insufficient to explain how tissues change their shape. Emerging properties arise at higher scales resulting from the interaction of cells within tissues and of tissues coordinating and interacting with one another.

To study the embryo evolution at a cellular scale, temporal series will be acquired by a multi-view light-sheet microscope. We will use the Mediterranean sea urchin embryo species Paracentrotus lividus as a model system and focus on the process of tissue folding, that will process that is vital since folding defects can impair neurulation in vertebrates and gastrulation in all animals which are organized into the three germ layers. From the technological perspective, new tools are needed to be able to visualize cells and to provide quantifiable data at high temporal and spatial resolution over large regions and across the entire embryo.

The goal of A. Moullet's internship (that begins dec. the 1st) is to measure and study the archenteron length evolution over a population of sea urchin embryos.

6.13. 3D Coronary vessel tracking in x-ray projections

Participants: Emmanuelle Poulain, Grégoire Malandain.

This work is made in collaboration with Régis Vaillant (GE-Healthcare, Buc, France) and Nicholas Ayache (Inria Epione team).

Percutaneous Coronary Intervention (PCI) is a minimally procedure which is used to treat coronary artery narrowing. The physician intervenes on the patient under the guidance of an x-ray imaging system. This system is not able to display a visual assessment of the coronary wall, contrary to the pre-operative Computed Tomography Angiography (CTA). To help physician to exploit this information during the course of the procedure, registering these two modalities would be useful. To this aim, we first proposed in a previous work a method of 3D coronary tracking of the main vessel in x-ray projections [27]. This approach is only applicable when the operator has avoided vessel superimposition over the vessel of interest. To further extend the concept, we explore the benefit of doing the deformable registration over the whole coronary tree. This benefit is illustrated in Fig. 15 and through tracking videos presented in https://3dvttracking.github.io/.

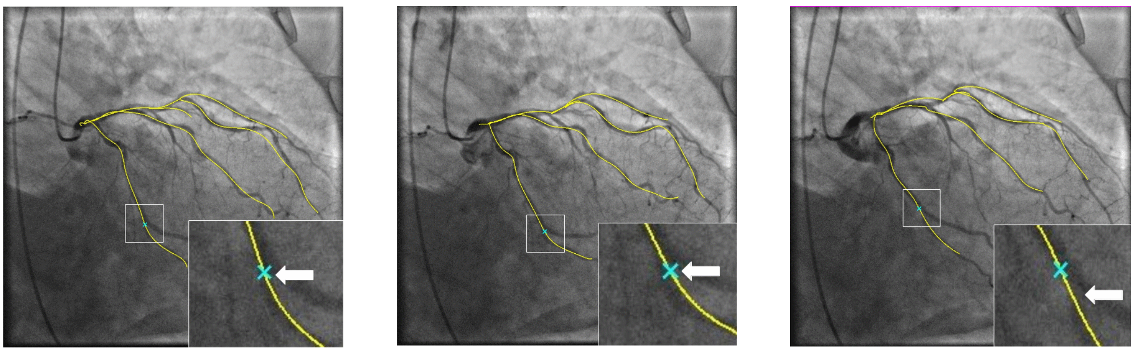

Figure 15. Tracking results for one patient over one cardiac cycle. The yellow curve represents the projected 3D vessel, the blue cross represents the point tracked as the bifurcation, and the white arrow points to the bifurcation. Those images come from a 15 frames sequence. This figure shows the frames 1, 6, 15, from left to right.

The proposed approach involves several algorithmic steps: a rigid registration of the tree to an iso-cardiac phase projection followed by a deformation of the tree represented as a tree-spline.

Indeed, a tree-spline i.e. a tree with a spline attached to each edge and shared control points between these points describes a 3D coronary tree and is able to represent its deformation along the time. We combine this description with a registration algorithm operating between the tree-spline and the angiographic projection of the coronary tree. It starts by the estimation of a rigid transformation for the iso cardiac phase time followed by a non-rigid deformation of the tree driven by the pairings formed between the projection of the edges of the tree-spline and the observed x-ray projection of the coronary arteries. The pairings are built taking into account the tree topology consistency. Anatomical constraints of length preservation is enforced when deforming the arteries.

This work has been published in FIMH [9].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

General Electric Healthcare: a 2 months (from feb. 2019 to mar. 2019) for the end of the thesis of E. Poulain.

Bayer, Lyon: a 36 months (from aug. 2018 to jul. 2021) companion contract for the Cifre thesis of S. Laroui.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. Labex Signalife

The MORPHEME team is member of the SIGNALIFE Laboratory of Excellence.

Florence Besse and Xavier Descombes are members of the Scientific Committee.

8.1.2. Idex UCA Jedi

Luca Calatroni is responsible of the project "Action 2, DEP attractivité du territoire du IDEX JEDI, Académie 2 ’Systemes complexes’".

Xavier Descombes is co-PI of the MOORPHEUS project funded by the Academy 4 of IDEX-JEDI ("Modélisation computationnelle de la croissance et de l’organisation spatiale dynamique des organoides/tumoroides de prostate"), in collaboration with C3M.

Biological Image Super-resolution Enhanced with Tensor (Biset) supported by Académie 1 RISE. Participants : E. Debreuve, L. Blanc-Féraud, S. Schaub.

Multiscale Tomography : imaging and modelling ancient materials, technical traditions and transfers, (ToMaT), supported by Idex UCA JEDI structuring Project, Participants: L. Blanc-Féraud, Vanna-Lisa Coli, Juliette Leblond, Didier Binder, Louise Gomart, Serge Cohen.

The PhD grant of Clara Sanchez is funded by the IDEX EUR DS4H. Participants: E. Debreuve, C. Rovère (IPMC).

8.1.3. 3AI Côte d’Azur

Laure Blanc-Féraud and Grégoire Malandain are chair holders of the 3AI Côte d’Azur, in the "Computational Biology and Bio-Inspired AI" axis.

The PhD grant of Vasiliki Stergiopoulou is funded by the 3AI Côte d’Azur.

8.2. National Initiatives

8.2.1. ANR RNAGRIMP

Participants: Florence Besse [PI], Fabienne de Graeve, Xavier Descombes, Eric Debreuve, Somia Rahmoun.

Here, we propose to study the molecular bases underlying the assembly and regulation of RNA granules, using the highly conserved IMP-containing granules as a paradigm. Specifically, we propose to perform an unbiased genome-wide RNAi screen on Drosophila cultured cells to identify mutant conditions in which the organization and/or distribution of IMP-containing granules is altered. To quantitatively and statistically analyze mutant conditions, and to define precise and coherent classes of mutants, we will combine high throughput microscopy with the development of a computational pipeline optimized for automatic analysis and classification of images. The function of positive hits isolated in the screen will then be validated in vivo in Drosophila neurons using fly genetics and imaging techniques, and characterized at the molecular and cellular levels using biochemical assays, in vitro phase transition experiments and live-imaging. Finally, the functional conservation of identified regulators will be tested in zebrafish embryos combining gene inactivation and live-imaging techniques. This integrative study will provide the first comprehensive analysis of the functional network that regulates the properties of the conserved IMP RNA granules. Our characterization of the identified regulators in vivo in neuronal cells will be of particular significance in the light of recent evidence linking the progression of several degenerative human diseases to the accumulation of non-functional RNA/protein aggregates.

This 4-years project started january, 2016 and is leaded by F. Besse (iBV, Nice). Participants are iBV, institut de biologie Paris Seine (IBPS, Paris), and Morpheme.

8.2.2. ANR HMOVE

Participants: Xavier Descombes, Eric Debreuve, Somia Rahmoun.

Among the signaling molecules involved in animal morphogenesis are the Hedgehog (Hh) family proteins which act at distance to direct cell fate decisions in invertebrate and vertebrate tissues. To study the underlying process we will develop accurate tracking algorithm to compare trajectories of different Hh pools transportation in live animals. This will allow us to analyze the contribution of the different carriers in the establishment of the Hh gradient. Moreover, we will develop new methods to modify the spatio-temporal and dynamical properties of the extra-cellular Hh gradient and separate the contribution of the apical versus basal Hh pools. We will complete this study with a genome-wide screen to identify genes and related cellular processes responsible for Hh release. The particular interest of this collaboration lies in the combination of development of tracking algorithm to analyze Hh distribution and trajectories with extremely powerful genetics, ease of in vivo manipulation and lack of genetic redundancy of Drosophila.

This 4-years project started january, 2016 and is leaded by P. Thérond (iBV, Nice). Participants are iBV and Morpheme.

8.2.3. ANR Cell Whisper

Participant: Grégoire Malandain.

Successful embryogenesis requires the differentiation of the correct cell types, in defined numbers and in appropriate positions. In most cases, decisions taken by individual cells are instructed by signals emitted by their neighbours. A surprisingly small set of signalling pathways is used for this purpose. The FGF/Ras/ERK pathway is one of these and mutations in some of its individual components cause a class of human developmental syndromes, the RASopathies. Our current knowledge of this pathway is, however, mostly static. We lack an integrated understanding of its spatio-temporal dynamics and we can imperfectly explain its highly non-linear response to a graded increase in input stimulus.

This systems biology project combines advanced quantitative live imaging, pharmacological/optogenetics perturbations and computational modelling to address 3 major unanswered questions, each corresponding to a specific aim:

- Aim 1: What is the spatio-temporal dynamic of intracellular signal transduction in response to FGF?
- Aim 2: What is the molecular basis of the switch-like response to graded extracellular signals?
- Aim 3: Can the results be integrated into a predictive computational model of the pathway?

Through this approach, in a simplified model system, we hope to gain an integrated view of the pathway's dynamics.

This 4-years project started october the 1st, 2019 and is leaded by P. Lemaire (CRBM, Montpellier). Participants are CRBM (Montpellier), LIRMM (Montpellier), MOSAIC (Inria Grenoble) and Morpheme.

8.2.4. Inria Large-scale initiative Naviscope

Participant: Grégoire Malandain.

This action gathers the expertise of seven Inria research teams (Aviz, Beagle, Hybrid, Morpheme, Parietal, Serpico and Mosaic) and other groups (MaIAGE, INRA, Jouy-en-Josas and UMR 144, Institut Curie Paris) and aimed at developing original and cutting-edge visualization and navigation methods to assist scientists, enabling semi-automatic analysis, manipulation, and investigation of temporal series of multi-valued volumetric images, with a strong focus on live cell imaging and microscopy application domains. More precisely, the three following challenges will be addressed:

- Novel machine learning methods able to detect the main regions of interest, and automatic quantification of sparse sets of molecular interactions and cell processes during navigation to save memory and computational resources.
- Novel visualization methods able to encode 3D motion/deformation vectors and dynamics features with color/texture-based and non-sub-resolved representations, abstractions, and discretization, as used to show 2D motion and deformation vectors and patterns.
- Effective machine learning-driven navigation and interaction techniques for complex functional 3D+Time data enabling the analysis of sparse sets of localized intra-cellular events and cell processes (migration, division, etc.).

8.3. International Research Visitors

8.3.1. Visits of International Scientists

Alin Achim, professor at Bristol university, is an invited professor in Morpheme since september 2019 for a ten months period (Leverhulme grant).

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events: Selection

9.1.1.1. Member of the Conference Program Committees

Laure Blanc-Féraud was member of the Conference Program Committees of NCMIP (New Computational methods for Inverse Problems), OSA Applied Optics Congress Mathematics in imaging, Workshop SPARS (Signal processing with Adaptive Sparse Structured Representation).

Luca Calatroni was the co-organiser of the workshop Regularisation methods for inverse problems and machine learning (Jussieu, Paris), 19 November 2019.

9.1.1.2. Reviewer

Laure Blanc-Féraud was a reviewer for the conferences IEEE ISBI, ICIP and ICASSP.

Xavier Descombes was a reviewer for for the conferences ISBI, ICIP, ICASSP.

Grégoire Malandain was a reviewer for the conference ISBI.

9.1.2. Journal

9.1.2.1. Member of the Editorial Boards

Laure Blanc-Féraud was Associated Editor for the journals SIAM Imaging Sciences. She was also responsible of the editorial field "Image" of the SCIENCES new editorial project of ISTE/WILEY Group which concerns the publication of collections of multi-authored titles in the fields of pure and applied sciences, health and humanities.

Luca Calatroni is a guest-editor of the Journal of Mathematical Neuroscience for the special issue on Colour representation and Cortical-inspired image processing

Xavier Descombes is Associated Editor for the journal Digital Signal Processing.

9.1.2.2. Reviewer - Reviewing Activities

Florence Besse was a reviewer for the journals Nature, Development, RNA, LifeStarAlliance, Front.mol.biol.

Luca Calatroni was a reviewer for the Journal of Mathematical Imaging and Vision, Applied Mathematics and Computation and SIAM Journal of Imaging Sciences.

Xavier Descombes was a reviewer for the Journal of the American Statistical Association.

9.1.3. Invited Talks

Laure Blanc-Féraud was invited to give a talk at to give a talk during the Sparsity4PSL International Summer School.

Luca Calatroni was invited to give a talk at the GdR Vision 2019 (Marseille), 10 October 2019, at the Statistical and Computational Learning seminars (Università di Genova, IIT, LCSL), 29 November 2019, and a BaD seminar (University of Bologna), December 3 2019.

Xavier Descombes was invited to give a talk at the Institut Henro Poincaré (Paris) for the workshop "Statistical Modeling for Shapes and Imaging", march 11-15.

9.1.4. Leadership within the Scientific Community

Laure Blanc-Féraud is member of IEEE BISP (Biomedical Imaging Signal Processing) Technical Committee.

Xavier Descombes is member of IEEE BISP (Biomedical Imaging Signal Processing) Technical Committee.

Grégoire Malandain is member of the IEEE/EMB Technical Committee on Biomedical Imaging and Image Processing (BIIP). He is an member of the Scientific Committee of the MIA department of INRA.

9.1.5. Scientific Expertise

Laure Blanc-Féraud is a member of the ANR scientific evaluation committee ASTRID.

Luca Calatroni was in the committee for the evaluation of PhD allocation for the Region Normandie.

Xavier Descombes is a member of the ANR scientific evaluation committee CE45.

Xavier Descombes is an expert of the French Research Ministry for evaluating companies CIR and JEI.

9.1.6. Research Administration

Laure Blanc-Féraud is a member of the "Commission Administrative Paritaire" for "chargé de recherche" of CNRS. She is a member of the Conseil Scientifique et Pédagogique de l'EUR DS4H, and of the Academic Council of the 3IA Côte d'Azur project, in charge of the biological axis.

Eric Debreuve is member of the Comité Permanent des Ressources Humaines (CPRH), UNS, section 61.

Xavier Descombes is member of the "comité des projets" of Inria CRISAM, of the Comité Permanent des Ressources Humaines (CPRH), UNS, section 61, of the ANR evaluation committee CE45, of the Labex Signalife Scientific Council.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence : Arne Bechensteen, Outils pour la physique, 42h, L1, Polytech Nice Sophia, France

Licence : Arne Bechensteen, Programmation impérative PeiP1, 13h30, L1, Polytech Nice Sophia, France

Master : Arne Bechensteen, Traitement Numérique des Images, 8h, M2, Polytech Nice Sophia, France

Master : Arne Bechensteen, Compression, analyse et visualisation de contenus multimédia, 2h, M2, Polytech Nice Sophia, France

Licence: Florence Besse, RNA localization, 3h, L3, ENS Ulm, France

Master: Florence Besse, Neuron cell biology and circuits, 6h, M1/2, Université Côte d'Azur, France

Master: Florence Besse, RNA localization and neuron morphology, 4h, M1/2, Université Côte d'Azur, France

Master: Laure Blanc-Féraud, Traitement avancé des images, master STIMM, 8h Eq. TD, Niveau M2, Université Côte d'Azur, France.

Master: Eric Debreuve, scientific image processing, 9h EqTD, M1 + M2, Université Côte d'Azur, France

Master: Xavier Descombes, Traitement d'images, Analyse de données, Techniques avancées de traitement d'images, 10h Eq. TD, Niveau M2, ISAE, France.

Master: Xavier Descombes, Traitement d'images, master, 9h Eq. TD, Niveau M2, Université Côte d'Azur, France.

Master: Xavier Descombes, Bio-imagerie, master IRIV, 6h Eq. TD, Niveau M2, Université de Strasbourg, France

Master: Xavier Descombes, Analyse d'images, master GBM, 9h Eq. TD, Niveau M2, Université Côte d'Azur, France.

Master: Xavier Descombes, Traitement d'images scientifiques, master SVS, 15h Eq. TD Niveau M2, Université Côte d'Azur.

Licence: Henrique Goulart, Automatique, 30h, niveau L3, École Polytechnique Universitaire de Nice Sophia-Antipolis, France

Licence: Henrique Goulart, Traitement Numérique du Signal, 48h, niveau L3, École Polytechnique Universitaire de Nice Sophia-Antipolis, France

Master: Sarah Laroui, Analyse d'images, master GBM, 10h Eq. TD, Niveau M2, Université Côte d'Azur, France.

Master/Ingénieur: Sarah Laroui, Data Science, M2/Ingénieur 5, Niveau 5eme année ingénieur, 4h Eq. TD, Polytech Nice Sophia, France.

IUT 1ere année: Sarah Laroui, Acquisition et codage de l'information, niveau 1ère Année DUT RT, 13h30 Eq. TD, Institut Universitaire de Technologie (IUT) Sophia, France.

DUT: Somia Rahmoun, Acquisition et Codage de l'Information, 8h Eq.TD, Bac+1, IUT Réseaux et Télécommunications de Nice Côte d'Azur, France

9.2.2. Supervision

PhD: Emmanuelle Poulain, Recalage déformable entre angioscanner cardiaque 3D statique et angiographie coronaire dynamique 2D+t, université Côte d'Azur, october 10th, 2019, Grégoire Malandain.

PhD in progress: Arne Bechensteen, TIRF-MA and super-resolution by sparse estimation method, october 2nd, 2017, Laure Blanc-Féraud, Gilles Aubert, Sébastien Schaub.

PhD in progress: Cédric Dubois, Classification du plancton conjointe en espèce et traits morphologiques et fonctionnels avec contrainte de relations espèces-traits et de hiérarchie des espèces en taxonomie génétique, october 1st, 2019, Eric Debreuve, Jean-Olivier Irisson (LOV, Villefranche-sur-mer).

PhD in progress: Anca-Ioana Grapa, Characterization of the organization of the Extracellular Matrix (ECM) by Image Processing, 19 September 2016, Laure Blanc-Féraud, Xavier Descombes, E. van Obberghen, (iBV).

PhD in progress: Sarah Laroui, Classification and modelling of botrytis cinerea fungi growth from microscope images: toward the establishment of links between phenotypes and antifongic molecules, 1st August 2018, Eric Debreuve, Xavier Descombes

PhD in progress: Manuel Petit, Quantifying and modeling trajectories of living form development, 1st November 2019, Grégoire Malandain, Christophe Godin (EPI Mosaic, Inria, Lyon).

PhD in progress: Clara Sanchez, Lipides nutritionnels et neuroinflammation : dévelopement d'outil de morphométrie cellulaire, 1st october 2019, Carole Rovère (IPMC), Eric Debreuve.

PhD in progress: Vasiliki Stergiopoulou, Learning and optimization for 3D+T super-resolution in fluorescent microscopy, January 1st 2020, Laure Blanc-Féraud, Luca Calatroni, Sébastien Schaub.

PhD in progress: Rudan Xiao, Analysis and classification of cellular and vascular markers in histological images: application to kidney cancer, 1st october 2019, Xavier Descombes, Eric Debreuve.

9.2.3. Post-doctorates

Post-doc: Vanna Lisa Coli, Image processing for ancient pottery, co-supervised by Laure Blanc-Féraud and Juliette Leblond EPI Factas.

Post-doc: Henrique Goulart, Superresolution microscopy by blinking molecules, supervised by Laure Blanc-Féraud, Eric Debreuve and Sébastien Schaub.

9.2.4. Internships

Amina Achaibou, Détection, caractérisation et clustering de cellules gliales dans le cadre d'une étude des lipides nutritionnels, Eric Debreuve

Ghosh Avrajit, Deep Learning for ExtraCellular Matrix classification, Laure Blanc-Féraud, Xavier Descombes

Deborah Cottais, Tumor cell tracking for automatic detection of cell death time, and classification of its type, Eric Debreuve

Paul-Emmanuel Ponsenard, Image binarization using persistence diagram, Xavier Descombes

Pat Vatiwutipong, Master of mathematics, "Properties of the d-Radon transform and application to imaging issues in archeology , co-supervised by Juliette Leblond EPI FACTAS and Laure Blanc-Féraud.

Zhankeng Zhang, Graph matching and classification using simulated annealing, Xavier Descombes

9.2.5. Juries

Florence Besse particpated to 4 PhD defense committees (UCA (2) and University of Montpellier (2)) and 2 HDR defense committees (UCA and Paris Descartes)

Laure Blanc-Féraud was part of 3 PhD defense committees (Megane Boudineau IRIT Toulouse, Aleix Boquet Pasteur Institute Paris as reviewer, Jabrane Karkouri CReatis Lyon) and one HDR committee (Mathieu Aucejo CNAM Paris). She was part of 2 "comités de suivi de thèse".

Xavier Descombes participated as a reviewer to the PhD thesis committee of Lamees Nasser (Paris Sorbonne University) and Kim Jonkhoon (Paul Sabatier University, Toulouse).

Grégoire Malandain participated as reviewer to the PhD thesis committee of Carlos Tor Diez (COMUE Bretagne Loire) and as supervisor to the PhD thesis committee of Emmanuelle Poulain (université Côte d'Azur)

9.3. Popularization

9.3.1. Education

Luca Calatroni participates to the Italian project “Penne amiche della scienza” to promote scientific research in Primary Schools.

9.3.2. Interventions

Laure Blanc-Féraud gave a conference in high school CIV during "la fête de la science".

National events: Village des Sciences et de l'Innovation d'Antibes Juan les Pins 2019.

The Morpheme team took part in "La fête de la Science” during the "Village de la Science” in Juan-Les-Pins. Somia Rahnmoun, Cedric Dubois and Arne Bechensteen were present at the Inria stand for this event.

10. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journal

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[3] J. DICHAMP, C. BARREAU, C. GUISSARD, A. CARRIÈRE, Y. MARTINEZ, X. DESCOMBES, L. PENICAUD, J. ROUQUETTE, L. CASTEILLA, F. PLOURABOUÉ, A. LORSIGNOL.*3D analysis of the whole subcutaneous adipose tissue reveals a complex spatial network of interconnected lobules with heterogeneous browning ability*, in "Scientific Reports", December 2019, vol. 9, n^{o} 1 [*DOI :* 10.1038/S41598-019-43130-9], https://hal.archives-ouvertes.fr/hal-02136531

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[12] A. BECHENSTEEN, L. BLANC-FÉRAUD, G. AUBERT.*Exact biconvex reformulation of the $L2-L0$ minimization problem*, in "GRETSI 2019", Lille, France, August 2019, https://hal.inria.fr/hal-02382369

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Project-Team NACHOS

Numerical modeling and high performance computing for evolution problems in complex domains and heterogeneous media

IN COLLABORATION WITH: Laboratoire Jean-Alexandre Dieudonné (JAD)

IN PARTNERSHIP WITH:
CNRS

Université Nice - Sophia Antipolis

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Numerical schemes and simulations

Table of contents

Project-Team NACHOS

Creation of the Project-Team: 2007 July 01

Keywords:

Computer Science and Digital Science:
A6.1.4. - Multiscale modeling
A6.2.1. - Numerical analysis of PDE and ODE
A6.2.6. - Optimization
A6.2.7. - High performance computing

Other Research Topics and Application Domains:
B4.3. - Renewable energy production
B4.3.4. - Solar Energy
B5.3. - Nanotechnology
B5.5. - Materials

1. Team, Visitors, External Collaborators

Research Scientists
Stephane Lanteri [Team leader, Inria, Senior Researcher, HDR]
Théophile Chaumont-Frelet [Inria, Researcher]
Frédéric Valentin [Inria, International Chair, Advanced Research Position]

Faculty Members
Stéphane Descombes [Univ Côte d'Azur, Professor, HDR]
Claire Scheid [Univ Côte d'Azur, Associate Professor]
Yves d'Angelo [Univ Côte d'Azur, Professor, HDR]

Technical Staff
Guillaume Leroy [Inria, Engineer, from Nov 2019]
Massimiliano Montone [Inria, Engineer, from May 2019 until Nov 2019]

PhD Students
Alexis Gobé [Inria, PhD Student]
Zakaria Kassali [Inria, PhD Student, from Nov 2019]
Massimiliano Montone [Inria, PhD Student, from Dec 2019]
Georges Nehmetallah [Inria, PhD Student]

Post-Doctoral Fellows
Mahmoud Elsawy [Inria, Post-Doctoral Fellow]
Mostafa Javadzadeh Moghtader [Inria, Post-Doctoral Fellow, until Mar 2019]
Patrick Vega [Inria, Post-Doctoral Fellow, from Dec 2019]

Visiting Scientist
Kun Li [UESTC, Chengdu, China, until Mar 2019]

Administrative Assistant
Montserrat Argente [Inria, Administrative Assistant]

2. Overall Objectives

2.1. Overall objectives

The overall objectives of the NACHOS project-team are the design, mathematical analysis and actual leveraging of numerical methods for the solution of first order linear systems of partial differential equations (PDEs) with variable coefficients modeling wave propagation problems. The two main physical contexts considered by the team are electrodynamics and elastodynamics. The corresponding applications lead to the simulation of electromagnetic or seismic wave interaction with media exhibiting space and time heterogeneities. Moreover, in most of the situations of practical relevance, the propagation settings involve structures or/and material interfaces with complex shapes. Both the heterogeneity of the media and the complex geometrical features of the propagation domains motivate the use of numerical methods that can deal with non-uniform discretization meshes. In this context, the research efforts of the team concentrate on numerical methods formulated on unstructured or hybrid structured/unstructured meshes for the solution of the systems of PDEs of electrodynamics and elastodynamics. Our activities include the implementation of these numerical methods in advanced 3D simulation software that efficiently exploit the capabilities of modern high performance computing platforms. In this respect, our research efforts are also concerned with algorithmic issues related to the design of numerical algorithms that perfectly fit to the hardware characteristics of petascale class supercomputers.

In the case of electrodynamics, the mathematical model of interest is the full system of unsteady Maxwell equations [55] which is a first-order hyperbolic linear system of PDEs (if the underlying propagation media is assumed to be linear). This system can be numerically solved using so-called time-domain methods among which the Finite Difference Time-Domain (FDTD) method introduced by K.S. Yee [61] in 1996 is the most popular and which often serves as a reference method for the works of the team. For certain types of problems, a time-harmonic evolution can be assumed leading to the formulation of the frequency-domain Maxwell equations whose numerical resolution requires the solution of a linear system of equations (i.e in that case, the numerical method is naturally implicit). Heterogeneity of the propagation media is taken into account in the Maxwell equations through the electrical permittivity, the magnetic permeability and the electric conductivity coefficients. In the general case, the electrical permittivity and the magnetic permeability are tensors whose entries depend on space (i.e heterogeneity in space) and frequency. In the latter case, the time-domain numerical modeling of such materials requires specific techniques in order to switch from the frequency evolution of the electromagnetic coefficients to a time dependency. Moreover, there exist several mathematical models for the frequency evolution of these coefficients (Debye model, Drude model, Drude-Lorentz model, etc.).

In the case of elastodynamics, the mathematical model of interest is the system of elastodynamic equations [50] for which several formulations can be considered such as the velocity-stress system. For this system, as with Yee's scheme for time-domain electromagnetics, one of the most popular numerical method is the finite difference method proposed by J. Virieux [59] in 1986. Heterogeneity of the propagation media is taken into account in the elastodynamic equations through the Lamé and mass density coefficients. A frequency dependence of the Lamé coefficients allows to take into account physical attenuation of the wave fields and characterizes a viscoelastic material. Again, several mathematical models are available for expressing the frequency evolution of the Lamé coefficients.

3. Research Program

3.1. Scientific foundations

The research activities undertaken by the team aim at developing innovative numerical methodologies putting the emphasis on several features:

- **Accuracy**. The foreseen numerical methods should rely on discretization techniques that best fit to the geometrical characteristics of the problems at hand. Methods based on unstructured, locally refined, even non-conforming, simplicial meshes are particularly attractive in this regard. In addition, the proposed numerical methods should also be capable to accurately describe the underlying physical phenomena that may involve highly variable space and time scales. Both objectives are generally addressed by studying so-called hp-adaptive solution strategies which combine h-adaptivity using local refinement/coarsening of the mesh and p-adaptivity using adaptive local variation of the interpolation order for approximating the solution variables. However, for physical problems involving strongly heterogeneous or high contrast propagation media, such a solution strategy may not be sufficient. Then, for dealing accurately with these situations, one has to design numerical methods that specifically address the multiscale nature of the underlying physical phenomena.
- **Numerical efficiency**. The simulation of unsteady problems most often relies on explicit time integration schemes. Such schemes are constrained by a stability criterion, linking some space and time discretization parameters, that can be very restrictive when the underlying mesh is highly non-uniform (especially for locally refined meshes). For realistic 3D problems, this can represent a severe limitation with regards to the overall computing time. One possible overcoming solution consists in resorting to an implicit time scheme in regions of the computational domain where the underlying mesh size is very small, while an explicit time scheme is applied elsewhere in the computational domain. The resulting hybrid explicit-implicit time integration strategy raises several challenging questions concerning both the mathematical analysis (stability and accuracy, especially for what concern numerical dispersion), and the computer implementation on modern high performance systems (data structures, parallel computing aspects). A second, often considered approach is to devise a local time stepping strategy. Beside, when considering time-harmonic (frequency-domain) wave propagation problems, numerical efficiency is mainly linked to the solution of the system of algebraic equations resulting from the discretization in space of the underlying PDE model. Various strategies exist ranging from the more robust and efficient sparse direct solvers to the more flexible and cheaper (in terms of memory resources) iterative methods. Current trends tend to show that the ideal candidate will be a judicious mix of both approaches by relying on domain decomposition principles.
- **Computational efficiency**. Realistic 3D wave propagation problems involve the processing of very large volumes of data. The latter results from two combined parameters: the size of the mesh i.e the number of mesh elements, and the number of degrees of freedom per mesh element which is itself linked to the degree of interpolation and to the number of physical variables (for systems of partial differential equations). Hence, numerical methods must be adapted to the characteristics of modern parallel computing platforms taking into account their hierarchical nature (e.g multiple processors and multiple core systems with complex cache and memory hierarchies). In addition, appropriate parallelization strategies need to be designed that combine SIMD and MIMD programming paradigms.

From the methodological point of view, the research activities of the team are concerned with four main topics: (1) high order finite element type methods on unstructured or hybrid structured/unstructured meshes for the discretization of the considered systems of PDEs, (2) efficient time integration strategies for dealing with grid induced stiffness when using non-uniform (locally refined) meshes, (3) numerical treatment of complex propagation media models (e.g. physical dispersion models), (4) algorithmic adaptation to modern high performance computing platforms.

3.2. High order discretization methods

3.2.1. The Discontinuous Galerkin method

The Discontinuous Galerkin method (DG) was introduced in 1973 by Reed and Hill to solve the neutron transport equation. From this time to the 90's a review on the DG methods would likely fit into one page. In the meantime, the Finite Volume approach (FV) has been widely adopted by computational fluid dynamics scientists and has now nearly supplanted classical finite difference and finite element methods in solving problems of non-linear convection and conservation law systems. The success of the FV method is due to its ability to capture discontinuous solutions which may occur when solving non-linear equations or more simply, when convecting discontinuous initial data in the linear case. Let us first remark that DG methods share with FV methods this property since a first order FV scheme may be viewed as a 0th order DG scheme. However a DG method may also be considered as a Finite Element (FE) one where the continuity constraint at an element interface is released. While keeping almost all the advantages of the FE method (large spectrum of applications, complex geometries, etc.), the DG method has other nice properties which explain the renewed interest it gains in various domains in scientific computing as witnessed by books or special issues of journals dedicated to this method [47]- [48]- [49]- [54]:

- It is naturally adapted to a high order approximation of the unknown field. Moreover, one may increase the degree of the approximation in the whole mesh as easily as for spectral methods but, with a DG method, this can also be done very locally. In most cases, the approximation relies on a polynomial interpolation method but the DG method also offers the flexibility of applying local approximation strategies that best fit to the intrinsic features of the modeled physical phenomena.
- When the space discretization is coupled to an explicit time integration scheme, the DG method leads to a block diagonal mass matrix whatever the form of the local approximation (e.g. the type of polynomial interpolation). This is a striking difference with classical, continuous FE formulations. Moreover, the mass matrix may be diagonal if the basis functions are orthogonal.
- It easily handles complex meshes. The grid may be a classical conforming FE mesh, a non-conforming one or even a hybrid mesh made of various elements (tetrahedra, prisms, hexahedra, etc.). The DG method has been proven to work well with highly locally refined meshes. This property makes the DG method more suitable (and flexible) to the design of some hp-adaptive solution strategy.
- It is also flexible with regards to the choice of the time stepping scheme. One may combine the DG spatial discretization with any global or local explicit time integration scheme, or even implicit, provided the resulting scheme is stable.
- It is naturally adapted to parallel computing. As long as an explicit time integration scheme is used, the DG method is easily parallelized. Moreover, the compact nature of DG discretization schemes is in favor of high computation to communication ratio especially when the interpolation order is increased.

As with standard FE methods, a DG method relies on a variational formulation of the continuous problem at hand. However, due to the discontinuity of the global approximation, this variational formulation has to be defined locally, at the element level. Then, a degree of freedom in the design of a DG method stems from the approximation of the boundary integral term resulting from the application of an integration by parts to the element-wise variational form. In the spirit of FV methods, the approximation of this boundary integral term calls for a numerical flux function which can be based on either a centered scheme or an upwind scheme, or a blending between these two schemes.

3.2.2. High order DG methods for wave propagation models

DG methods are at the heart of the activities of the team regarding the development of high order discretization schemes for the PDE systems modeling electromagnetic and elatsodynamic wave propagation.

- **Nodal DG methods for time-domain problems**. For the numerical solution of the time-domain Maxwell equations, we have first proposed a non-dissipative high order DGTD (Discontinuous Galerkin Time-Domain) method working on unstructured conforming simplicial meshes [9]. This DG method combines a central numerical flux function for the approximation of the integral term at the interface of two neighboring elements with a second order leap-frog time integration scheme. Moreover, the local approximation of the electromagnetic field relies on a nodal (Lagrange type) polynomial interpolation method. Recent achievements by the team deal with the extension of these methods towards non-conforming unstructured [6]-[7] and hybrid structured/unstructured meshes [4], their coupling with hybrid explicit/implicit time integration schemes in order to improve their efficiency in the context of locally refined meshes [3]-[14]-[13]. A high order DG method has also been proposed for the numerical resolution of the elastodynamic equations modeling the propagation of seismic waves [2].

- **Hybridizable DG (HDG) method for time-domain and time-harmonic problems**. For the numerical treatment of the time-harmonic Maxwell equations, nodal DG methods can also be considered [5]. However, such DG formulations are highly expensive, especially for the discretization of 3D problems, because they lead to a large sparse and undefinite linear system of equations coupling all the degrees of freedom of the unknown physical fields. Different attempts have been made in the recent past to improve this situation and one promising strategy has been recently proposed by Cockburn *et al.*[52] in the form of so-called hybridizable DG formulations. The distinctive feature of these methods is that the only globally coupled degrees of freedom are those of an approximation of the solution defined only on the boundaries of the elements. This work is concerned with the study of such Hybridizable Discontinuous Galerkin (HDG) methods for the solution of the system of Maxwell equations in the time-domain when the time integration relies on an implicit scheme, or in the frequency-domain. The team has been a precursor in the development of HDG methods for the frequency-domain Maxwell equations[12].
- **Multiscale DG methods for time-domain problems**. More recently, in collaboration with LNCC in Petropolis (Frédéric Valentin) the framework of the HOMAR assoacite team, we are investigating a family of methods specifically designed for an accurate and efficient numerical treatment of multiscale wave propagation problems. These methods, referred to as Multiscale Hybrid Mixed (MHM) methods, are currently studied in the team for both time-domain electromagnetic and elastodynamic PDE models. They consist in reformulating the mixed variational form of each system into a global (arbitrarily coarse) problem related to a weak formulation of the boundary condition (carried by a Lagrange multiplier that represents e.g. the normal stress tensor in elastodynamic sytems), and a series of small, element-wise, fully decoupled problems resembling to the initial one and related to some well chosen partition of the solution variables on each element. By construction, that methodology is fully parallelizable and recursivity may be used in each local problem as well, making MHM methods belonging to multi-level highly parallelizable methods. Each local problem may be solved using DG or classical Galerkin FE approximations combined with some appropriate time integration scheme (θ-scheme or leap-frog scheme).

3.3. Efficient time integration strategies

The use of unstructured meshes (based on triangles in two space dimensions and tetrahedra in three space dimensions) is an important feature of the DGTD methods developed in the team which can thus easily deal with complex geometries and heterogeneous propagation media. Moreover, DG discretization methods are naturally adapted to local, conforming as well as non-conforming, refinement of the underlying mesh. Most of the existing DGTD methods rely on explicit time integration schemes and lead to block diagonal mass matrices which is often recognized as one of the main advantages with regards to continuous finite element methods. However, explicit DGTD methods are also constrained by a stability condition that can be very restrictive on highly refined meshes and when the local approximation relies on high order polynomial interpolation. There are basically three strategies that can be considered to cure this computational efficiency problem. The first approach is to use an unconditionally stable implicit time integration scheme to overcome the restrictive constraint on the time step for locally refined meshes. In a second approach, a local time stepping strategy is combined with an explicit time integration scheme. In the third approach, the time step size restriction is overcome by using a hybrid explicit-implicit procedure. In this case, one blends a time implicit and a time explicit schemes where only the solution variables defined on the smallest elements are treated implicitly. The first and third options are considered in the team in the framework of DG [3]-[14]-[13] and HDG discretization methods.

3.4. Numerical treatment of complex material models

Towards the general aim of being able to consider concrete physical situations, we are interested in taking into account in the numerical methodologies that we study, a better description of the propagation of waves in realistic media. In the case of electromagnetics, a typical physical phenomenon that one has to consider is *dispersion*. It is present in almost all media and expresses the way the material reacts to an electromagnetic field. In the presence of an electric field a medium does not react instantaneously and thus presents an electric polarization of the molecules or electrons that itself influences the electric displacement. In the case of a linear homogeneous isotropic media, there is a linear relation between the applied electric field and the polarization. However, above some range of frequencies (depending on the considered material), the dispersion phenomenon cannot be neglected and the relation between the polarization and the applied electric field becomes complex. This is rendered via a frequency-dependent complex permittivity. Several models of complex permittivity exist. Concerning biological media, the Debye model is commonly adopted in the presence of water, biological tissues and polymers, so that it already covers a wide range of applications [11]. In the context of nanoplasmonics, one is interested in modeling the dispersion effects on metals on the nanometer scale and at optical frequencies. In this case, the Drude or the Drude-Lorentz models are generally chosen [17]. In the context of seismic wave propagation, we are interested by the intrinsic attenuation of the medium [15]. In realistic configurations, for instance in sedimentary basins where the waves are trapped, we can observe site effects due to local geological and geotechnical conditions which result in a strong increase in amplification and duration of the ground motion at some particular locations. During the wave propagation in such media, a part of the seismic energy is dissipated because of anelastic losses relied to the internal friction of the medium. For these reasons, numerical simulations based on the basic assumption of linear elasticity are no more valid since this assumption results in a severe overestimation of amplitude and duration of the ground motion, even when we are not in presence of a site effect, since intrinsic attenuation is not taken into account.

3.5. High performance numerical computing

Beside basic research activities related to the design of numerical methods and resolution algorithms for the wave propagation models at hand, the team is also committed to demonstrate the benefits of the proposed numerical methodologies in the simulation of challenging three-dimensional problems pertaining to computational electromagnetics and computational geoseismics. For such applications, parallel computing is a mandatory path. Nowadays, modern parallel computers most often take the form of clusters of heterogeneous multiprocessor systems, combining multiple core CPUs with accelerator cards (e.g Graphical Processing Units - GPUs), with complex hierarchical distributed-shared memory systems. Developing numerical algorithms that efficiently exploit such high performance computing architectures raises several challenges, especially in the context of a massive parallelism. In this context, current efforts of the team are towards the exploitation of multiple levels of parallelism (computing systems combining CPUs and GPUs) through the study of hierarchical SPMD (Single Program Multiple Data) strategies for the parallelization of unstructured mesh based solvers.

4. Application Domains

4.1. Electromagnetic wave propagation

Electromagnetic devices are ubiquitous in present day technology. Indeed, electromagnetism has found and continues to find applications in a wide array of areas, encompassing both industrial and societal purposes. Applications of current interest include (among others) those related to communications (e.g transmission through optical fiber lines), to biomedical devices (e.g microwave imaging, micro-antenna design for telemedecine, etc.), to circuit or magnetic storage design (electromagnetic compatibility, hard disc operation), to geophysical prospecting, and to non-destructive evaluation (e.g crack detection), to name but just a few. Equally notable and motivating are applications in defence which include the design of military hardware with decreased signatures, automatic target recognition (e.g bunkers, mines and buried ordnance, etc.) propagation effects on communication and radar systems, etc. Although the principles of electromagnetics are well understood, their application to practical configurations of current interest, such as those that arise in connection with the examples above, is significantly complicated and far beyond manual calculation in all but the simplest cases. These complications typically arise from the geometrical characteristics of the propagation medium (irregular shapes, geometrical singularities), the physical characteristics of the propagation medium (heterogeneity, physical dispersion and dissipation) and the characteristics of the sources (wires, etc.).

Although many of the above-mentioned application contexts can potentially benefit from numerical modeling studies, the team currently concentrates its efforts on two physical situations.

4.1.1. Microwave interaction with biological tissues

Two main reasons motivate our commitment to consider this type of problem for the application of the numerical methodologies developed in the NACHOS project-team:

- First, from the numerical modeling point of view, the interaction between electromagnetic waves and biological tissues exhibit the three sources of complexity identified previously and are thus particularly challenging for pushing one step forward the state-of-the art of numerical methods for computational electromagnetics. The propagation media is strongly heterogeneous and the electromagnetic characteristics of the tissues are frequency dependent. Interfaces between tissues have rather complicated shapes that cannot be accurately discretized using cartesian meshes. Finally, the source of the signal often takes the form of a complicated device (e.g a mobile phone or an antenna array).
- Second, the study of the interaction between electromagnetic waves and living tissues is of interest to several applications of societal relevance such as the assessment of potential adverse effects of electromagnetic fields or the utilization of electromagnetic waves for therapeutic or diagnostic purposes. It is widely recognized nowadays that numerical modeling and computer simulation of electromagnetic wave propagation in biological tissues is a mandatory path for improving the scientific knowledge of the complex physical mechanisms that characterize these applications.

Despite the high complexity both in terms of heterogeneity and geometrical features of tissues, the great majority of numerical studies so far have been conducted using variants of the widely known FDTD method due to Yee [61]. In this method, the whole computational domain is discretized using a structured (cartesian) grid. Due to the possible straightforward implementation of the algorithm and the availability of computational power, FDTD is currently the leading method for numerical assessment of human exposure to electromagnetic waves. However, limitations are still seen, due to the rather difficult departure from the commonly used rectilinear grid and cell size limitations regarding very detailed structures of human tissues. In this context, the general objective of the contributions of the NACHOS project-team is to demonstrate the benefits of high order unstructured mesh based Maxwell solvers for a realistic numerical modeling of the interaction of electromagnetic waves and biological tissues with emphasis on applications related to numerical dosimetry. Since the creation of the team, our works on this topic have mainly been focussed on the study of the exposure of humans to radiations from mobile phones or wireless communication systems (see Fig. 1). This activity has been conducted in close collaboration with the team of Joe Wiart at Orange Labs/Whist Laboratory (http://whist.institut-telecom.fr/en/index.html) (formerly, France Telecom Research & Development) in Issy-les-Moulineaux [8].

4.1.2. Light-matter interaction on the nanoscale

Nanostructuring of materials has opened up a number of new possibilities for manipulating and enhancing light-matter interactions, thereby improving fundamental device properties. Low-dimensional semiconductors, like quantum dots, enable one to catch the electrons and control the electronic properties of a material, while photonic crystal structures allow to synthesize the electromagnetic properties. These technologies may, e.g., be employed to make smaller and better lasers, sources that generate only one photon at a time, for applications in quantum information technology, or miniature sensors with high sensitivity. The incorporation of metallic structures into the medium add further possibilities for manipulating the propagation of electromagnetic waves. In particular, this allows subwavelength localisation of the electromagnetic field and, by subwavelength

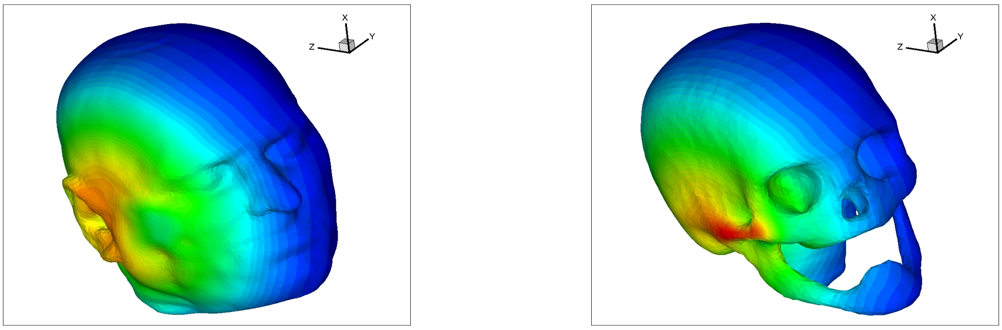


Figure 1. Exposure of head tissues to an electromagnetic wave emitted by a localized source. Top figures: surface triangulations of the skin and the skull. Bottom figures: contour lines of the amplitude of the electric field.

structuring of the material, novel effects like negative refraction, e.g. enabling super lenses, may be realized. Nanophotonics is the recently emerged, but already well defined, field of science and technology aimed at establishing and using the peculiar properties of light and light-matter interaction in various nanostructures. Nanophotonics includes all the phenomena that are used in optical sciences for the development of optical devices. Therefore, nanophotonics finds numerous applications such as in optical microscopy, the design of optical switches and electromagnetic chips circuits, transistor filaments, etc. Because of its numerous scientific and technological applications (e.g. in relation to telecommunication, energy production and biomedicine), nanophotonics represents an active field of research increasingly relying on numerical modeling beside experimental studies.

Plasmonics is a related field to nanophotonics. Metallic nanostructures whose optical scattering is dominated by the response of the conduction electrons are considered as plasmomic media. If the structure presents an interface with e.g. a dielectric with a positive permittivity, collective oscillations of surface electrons create surface-plasmons-polaritons (SPPs) that propagate along the interface. SPPs are guided along metal-dielectric interfaces much in the same way light can be guided by an optical fiber, with the unique characteristic of subwavelength-scale confinement perpendicular to the interface. Nanofabricated systems that exploit SPPs offer fascinating opportunities for crafting and controlling the propagation of light in matter. In particular, SPPs can be used to channel light efficiently into nanometer-scale volumes, leading to direct modification of mode dispersion properties (substantially shrinking the wavelength of light and the speed of light pulses for example), as well as huge field enhancements suitable for enabling strong interactions with non-linear materials. The resulting enhanced sensitivity of light to external parameters (for example, an applied electric field or the dielectric constant of an adsorbed molecular layer) shows great promise for applications in sensing and switching. In particular, very promising applications are foreseen in the medical domain [53]- [62].

Numerical modeling of electromagnetic wave propagation in interaction with metallic nanostructures at optical frequencies requires to solve the system of Maxwell equations coupled to appropriate models of physical dispersion in the metal, such as the Drude and Drude-Lorentz models. Here again, the FDTD method is a widely used approach for solving the resulting system of PDEs [58]. However, for nanophotonic applications, the space and time scales, in addition to the geometrical characteristics of the considered nanostructures (or structured layouts of the latter), are particularly challenging for an accurate and efficient application of the FDTD method. Recently, unstructured mesh based methods have been developed and have demonstrated their potentialities for being considered as viable alternatives to the FDTD method [56]- [57]- [51]. Since the end of 2012, nanophotonics/plasmonics is increasingly becoming a focused application domain in the research activities of the team in close collaboration with physicists from CNRS laboratories, and also with researchers from international institutions.

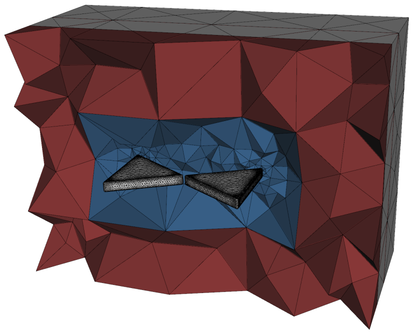


Figure 2. Simulation of the field enhancement at the tip of a gold bowtie nanoantenna (PhD thesis of Jonathan Viquerat).

4.2. Elastodynamic wave propagation

Elastic wave propagation in interaction with solids are encountered in a lot of scientific and engineering contexts. One typical example is geoseismic wave propagation for earthquake dynamics or resource prospection.

4.2.1. Earthquake dynamics

To understand the basic science of earthquakes and to help engineers better prepare for such an event, scientists want to identify which regions are likely to experience the most intense shaking, particularly in populated sediment-filled basins. This understanding can be used to improve buildings in high hazard areas and to help engineers design safer structures, potentially saving lives and property. In the absence of deterministic earthquake prediction, forecasting of earthquake ground motion based on simulation of scenarios is one of the most promising tools to mitigate earthquake related hazard. This requires intense modeling that meets the spatial and temporal resolution scales of the continuously increasing density and resolution of the seismic instrumentation, which record dynamic shaking at the surface, as well as of the basin models. Another important issue is to improve the physical understanding of the earthquake rupture processes and seismic wave propagation. Large-scale simulations of earthquake rupture dynamics and wave propagation are currently the only means to investigate these multiscale physics together with data assimilation and inversion. High resolution models are also required to develop and assess fast operational analysis tools for real time seismology and early warning systems.

Numerical methods for the propagation of seismic waves have been studied for many years. Most of existing numerical software rely on finite difference type methods. Among the most popular schemes, one can cite the staggered grid finite difference scheme proposed by Virieux [59] and based on the first order velocity-stress hyperbolic system of elastic waves equations, which is an extension of the scheme derived by Yee [61] for the solution of the Maxwell equations. Many improvements of this method have been proposed, in particular, higher order schemes in space or rotated staggered-grids allowing strong fluctuations of the elastic parameters. Despite these improvements, the use of cartesian grids is a limitation for such numerical methods especially when it is necessary to incorporate surface topography or curved interface. Moreover, in presence of a non planar topography, the free surface condition needs very fine grids (about 60 points by minimal Rayleigh wavelength) to be approximated. In this context, our objective is to develop high order unstructured mesh based methods for the numerical solution of the system of elastodynamic equations for elastic media in a first step, and then to extend these methods to a more accurate treatment of the heterogeneities of the medium or to more complex propagation materials such as viscoelastic media which take into account the intrinsic attenuation. Initially, the team has considered in detail the necessary methodological developments for the large-scale simulation of earthquake dynamics [1]. More recently, the team has collaborated with CETE

Méditerranée which is a regional technical and engineering centre whose activities are concerned with seismic hazard assessment studies, and IFSTTAR (https://www.ifsttar.fr/en/welcome/) which is the French institute of science and technology for transport, development and networks, conducting research studies on control over aging, risks and nuisances.

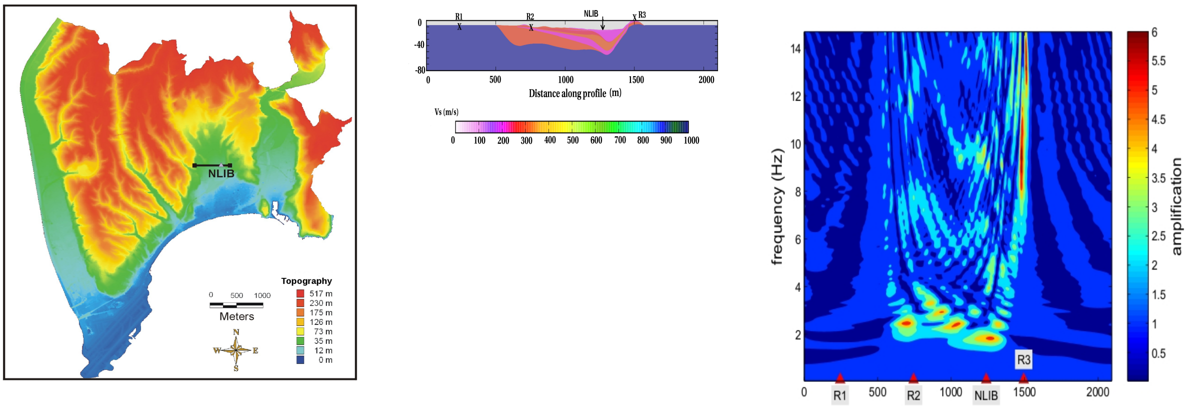


Figure 3. Propagation of a plane wave in a heterogeneous model of Nice area (provided by CETE Méditerranée). Left figure: topography of Nice and location of the cross-section used for numerical simulations (black line). Middle figure: S-wave velocity distribution along the cross-section in the Nice basin. Right figure: transfer functions (amplification) for a vertically incident plane wave ; receivers every 5 m at the surface. This numerical simulation was performed using a numerical method for the solution of the elastodynamics equations coupled to a Generalized Maxwell Body (GMB) model of viscoelasticity (PhD thesis of Fabien Peyrusse).

4.2.2. Seismic exploration

This application topic is considered in close collaboration with the MAGIQUE-3D project-team at Inria Bordeaux - Sud-Ouest which is coordinating the Depth Imaging Partnership (DIP -http://dip.inria.fr) between Inria and TOTAL. The research program of DIP includes different aspects of the modeling and numerical simulation of sesimic wave propagation that must be considered to construct an efficient software suites for producing accurate images of the subsurface. Our common objective with the MAGIQUE-3D project-team is to design high order unstructured mesh based methods for the numerical solution of the system of elastodynamic equations in the time-domain and in the frequency-domain, that will be used as forward modelers in appropriate inversion procedures.

5. New Software and Platforms

5.1. DIOGENeS

DIscOntinuous GalErkin Nanoscale Solvers

KEYWORDS: High-Performance Computing - Computational electromagnetics - Discontinuous Galerkin - Computational nanophotonics

FUNCTIONAL DESCRIPTION: The DIOGENeS software suite provides several tools and solvers for the numerical resolution of light-matter interactions at nanometer scales. A choice can be made between time-domain (DGTD solver) and frequency-domain (HDGFD solver) depending on the problem. The available sources, material laws and observables are very well suited to nano-optics and nano-plasmonics (interaction with metals). A parallel implementation allows to consider large problems on dedicated cluster-like architectures.

- Authors: Stéphane Lanteri, Nikolai Schmitt, Alexis Gobé and Jonathan Viquerat
- Contact: Stéphane Lanteri
- URL: https://diogenes.inria.fr/

5.2. GERShWIN

discontinuous GalERkin Solver for microWave INteraction with biological tissues

KEYWORDS: High-Performance Computing - Computational electromagnetics - Discontinuous Galerkin - Computational bioelectromagnetics

FUNCTIONAL DESCRIPTION: GERShWIN is based on a high order DG method formulated on unstructured tetrahedral meshes for solving the 3D system of time-domain Maxwell equations coupled to a Debye dispersion model.

- Contact: Stéphane Lanteri
- URL: http://www-sop.inria.fr/nachos/index.php/Software/GERShWIN

5.3. HORSE

High Order solver for Radar cross Section Evaluation

KEYWORDS: High-Performance Computing - Computational electromagnetics - Discontinuous Galerkin

FUNCTIONAL DESCRIPTION: HORSE is based on a high order HDG (Hybridizable Discontinuous Galerkin) method formulated on unstructured tetrahedral and hybrid structured/unstructured (cubic/tetrahedral) meshes for the discretization of the 3D system of frequency-domain Maxwell equations, coupled to domain decomposition solvers.

- Authors: Ludovic Moya and Alexis Gobé
- Contact: Stéphane Lanteri
- URL: http://www-sop.inria.fr/nachos/index.php/Software/HORSE

6. New Results

6.1. Electromagnetic wave propagation

6.1.1. POD-based reduced-order DGTD method

Participants: Stéphane Lanteri, Kun Li [UESTC, Chengdu, China], Liang Li [UESTC, Chengdu, China].

This study is concerned with reduced-order modeling for time-domain electromagnetics and nanophotonics. More precisely, we consider the applicability of the proper orthogonal decomposition (POD) technique for the system of 3D time-domain Maxwell equations, possibly coupled to a Drude dispersion model, which is employed to describe the interaction of light with nanometer scale metallic structures. We introduce a discontinuous Galerkin (DG) approach for the discretization of the problem in space based on an unstructured tetrahedral mesh. A reduced subspace with a significantly smaller dimension is constructed by a set of POD basis vectors extracted offline from snapshots that are obtained by the global DGTD scheme with a second order leap-frog method for time integration at a number of time levels. POD-based ROM is established by projecting (Galerkin projection) the global semi-discrete DG scheme onto the low-dimensional space. The stability of the POD-based ROM equipped with the second order leap-frog time scheme has been analysed through an energy method. Numerical experiments have allowed to verify the accuracy, and demonstrate the capabilities of the POD-based ROM. These very promising preliminary results are currently consolidated by assessing the efficiency of the proposed POD-based ROM when applied to the simulation of 3D nanophotonic problems.

6.1.2. Study of 3D periodic structures at oblique incidences

Participants: Claire Scheid, Nikolai Schmitt, Jonathan Viquerat.

In this work, we focus on the development of the use of periodic boundary conditions with sources at oblique incidence in a DGTD framework. Whereas in the context of the Finite Difference Time Domain (FDTD) methods, an abundant literature can be found, for DGTD, the amount of contributions reporting on such methods is remarkably low. In this work, we supplement the existing references using the field transform technique with an analysis of the continuous system using the method of characteristics and provide an energy estimate. Furthermore, we also study the numerical stability of the resulting DGTD scheme. After numerical validations, two realistic test problems have been considered in the context of nanophotonics with our DIOGENeS DGTD solver. This work has been accepted for publication in 2019.

6.1.3. Stability and asymptotic properties of the linearized Hydrodynamic Drude model

Participants: Serge Nicaise [Université de Valenciennes], Claire Scheid.

We go a step further toward a better understanding of the fundamental properties of the linearized hydrodynamical model studied in the PhD of Nikolai Schmitt [16]. This model is especially relevant for small nanoplasmonic structures (below 10nm). Using a hydrodynamical description of the electron cloud, both retardation effects and non local spatial response are taken into account. This results in a coupled PDE system for which we study the linear response. In [45] (submitted, under revision), we concentrate on establishing well posedness results combined to a theoretical and numerical stability analysis. We especially prove polynomial stability and provide optimal energy decay rate. Finally, we investigate the question of numerical stability of several explicit time integration strategies combined to a Discontinuous Galerkin spatial discretization.

6.1.4. Toward thermoplasmonics

Participants: Yves d'Angelo, Stéphane Lanteri, Claire Scheid.

Although losses in metal is viewed as a serious drawback in many plasmonics experiments, thermoplasmonics is the field of physics that tries to take advantage of the latter. Indeed, the strong field enhancement obtained in nanometallic structures lead to a localized raise of the temperature in its vicinity leading to interesting photothermal effects. Therefore, metallic nanoparticles may be used as heat sources that can be easily integrated in various environments. This is especially appealing in the field of nanomedecine and can for example be used for diagnosis purposes or nanosurgery to cite but just a few. This year, we initiated a preliminary work towards this new field in collaboration with Y. D'Angelo (Université Côte d'Azur) and G. Baffou (Fresnel Institute, Marseille) who is an expert in this field. Due to the various scales and phenomena that come into play, the numerical modeling present great challenges. The laser illumination first excite a plasmon oscillation (reaction of the electrons of the metal) that relaxes in a thermal equilibrium and in turn excite the metal lattice (phonons). The latter is then responsible for heating the environment. A relevant modeling approach thus consists in describing the electron-phonon coupling through the evolution of their respective temperature. Maxwell's equations is then coupled to a set of coupled nonlinear hyperbolic equations describing the evolution of the temperatures of electrons, phonons and environment. The nonlinearities and the different time scales at which each thermalization occurs make the numerical approximation of these equations quite challenging.

6.1.5. Corner effects in nanoplasmonics

Participants: Camille Carvalho [Applied Mathematics Department, University of California Merced, USA], Claire Scheid.

In this work, we study nanoplasmonic structures with corners (typically a diedral/triangular structure); a situation that raises a lot of issues. We focus on a lossles Drude dispersion model and propose to investigate the range of validity of the amplitude limit principle. The latter predicts the asymptotic harmonic regime of a structure that is monochromatically illuminated, which makes a frequency domain approach relevant. However, in frequency domain, several well posedness problems arise due to the presence of corners (addressed in the PhD thesis of Camille Carvalho). This should impact the validity of the limit amplitude principle and has not yet been addressed in the literature in this precise setting. Here, we combine frequency-domain and time-domain viewpoints to give a numerical answer to this question in two dimensions. We show that the limit amplitude principle does not hold for whole interval of frequencies, that are explicited using the well-posedness analysis. This work is now being finalized.

6.1.6. MHM methods for the time-domain Maxwell equations

Participants: Alexis Gobé, Stéphane Lanteri, Diego Paredes Concha [Instituto de Matemáticas, Universidad Católica de Valparaiso, Chile], Claire Scheid, Frédéric Valentin [LNCC, Petropolis, Brazil].

Although the DGTD method has already been successfully applied to complex electromagnetic wave propagation problems, its accuracy may seriously deteriorate on coarse meshes when the solution presents multiscale or high contrast features. In other physical contexts, such an issue has led to the concept of multiscale basis functions as a way to overcome such a drawback and allow numerical methods to be accurate on coarse meshes. The present work, which is conducted in the context of the HOMAR Associate Team, is concerned with the study of a particular family of multiscale methods, named Multiscale Hybrid-Mixed (MHM) methods. Initially proposed for fluid flow problems, MHM methods are a consequence of a hybridization procedure which caracterize the unknowns as a direct sum of a coarse (global) solution and the solutions to (local) problems with Neumann boundary conditions driven by the purposely introduced hybrid (dual) variable. As a result, the MHM method becomes a strategy that naturally incorporates multiple scales while providing solutions with high order accuracy for the primal and dual variables. The completely independent local problems are embedded in the upscaling procedure, and computational approximations may be naturally obtained in a parallel computing environment. In this study, a family of MHM methods is proposed for the solution of the time-domain Maxwell equations where the local problems are discretized either with a continuous FE method or a DG method (that can be viewed as a multiscale DGTD method). Preliminary results have been obtained in the two-dimensional case.

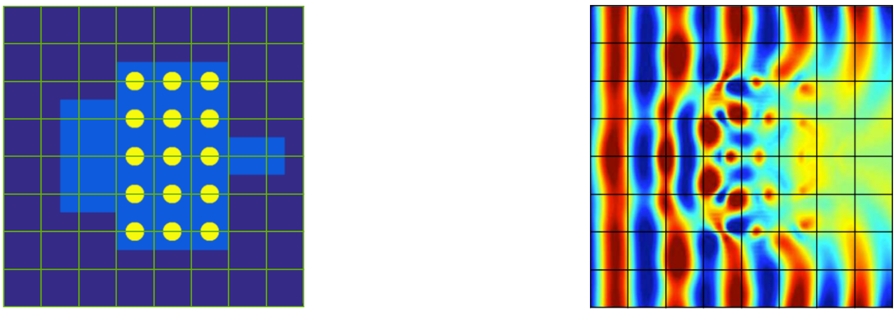


Figure 4. Light propagation in a photonic crystal structure using a MHM-DGTD method for solving the 2D Maxwell's equations. Left: quadrangular mesh. Right: contour lines of the amplitude of the electric field.

6.1.7. HDG methods for the time-domain Maxwell equations

Participants: Théophile Chaumont-Frelet, Stéphane Descombes, Stéphane Lanteri, Georges Nehmetallah.

Hybridizable discontinuous Galerkin (HDG) methods have been investigated in the team since 2012. This family of method employs face-based degrees of freedom that can be viewed as a fine grain domain decomposition technique. We originally focused on frequency-domain applications, for which HDG methods enable the use of static condensation, leading to drastic reduction in computational time and memory consumption. More recently, we have investigated the use of HDG discretization to solve time-dependent problems. Specifically, in the context of the PhD thesis of Georges Nehmetallah, we focused on two particular aspects. On the one hand, HDG methods exhibit a superconvergence property that allows, by means of local postprocessing, to obtain new improved approximations of the unknowns. Our first contribution is to apply this methodology to time-dependent Maxwell's equations, where the post-processed approximation converges with order $k+1$ instead of k in the $H(curl)$-norm, when using polynomial of degree $k \geq 1$. The proposed method has been implemented for dealing with general 3D problems. Fig. 5 highlights the improved accuracy of the post-processed approximation on a cavity benchmark.

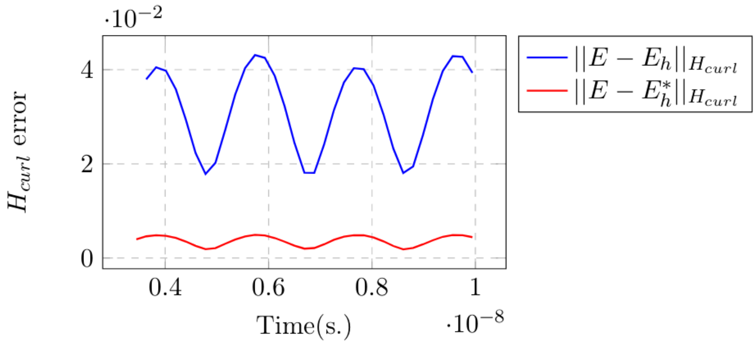


Figure 5. Time evolution of the $H(curl)$-error before and after postprocessing for P_2 interpolation and a fixed mesh constituted by 3072 elements

Another interesting aspect of the HDG method is that it can be conveniently employed to blend different time-integration schemes in different regions of the mesh. This is especially useful to efficiently handle locally refined space grids, that are required to take into account geometrical details. These ideas have already been explored for standard discontinuous Galerkin discretization in the context of the PhD thesis of Ludovic Moya [13], [14]. Here, we focused on HDG methods and we introduced a family of coupled implicit-explicit (IMEX) time integration methods for solving time-dependent Maxwell's equations. We established stability conditions that are independent of the size of the small elements in the mesh, and are only constrained by the coarse part. Numerical experiments on two-dimensional benchmarks illustrate the theory and the usefulness of the approach.

6.1.8. *A posteriori error estimators*

Participants: Théophile Chaumont-Frelet, Alexandre Ern [SERENA project-team], Patrick Vega, Martin Vohralík [SERENA project-team].

The development of *a posteriori* error estimators and is a new topic of interest for the team. Concerning *a posteriori* estimators, a collaboration with the SERENA project-team has been initiated. We mainly focus on a technique called equilibrated fluxes, which has the advantage to produce p-robust error estimators together with guaranteed error estimates. This means in particular that these estimators are particularly suited for high-order discretization schemes. Our first results deal with the Helmholtz equation, and have been recently submitted [39] and presented at the Enumath international conference [29]. Fig. 6 depicts the ability of the estimators to accurately describe the error distribution in a realistic application. Future works in this line will include the treatment of Maxwell's equations. The recently hired postdoctoral fellow Patrick Vega will actively participate in these developments.

6.1.9. hp-*adaptivity*

Participants: Théophile Chaumont-Frelet, David Pardo [Basque Center for Applied Mathematics, Bilbao, Spain].

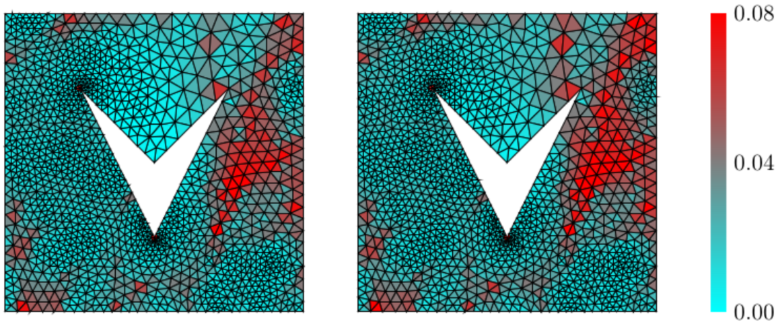


Figure 6. Estimators η_K (left) and elementwise errors $\|u-u_h\|_K$ (right) for a scattering problem discretized with $\mathcal{P}_3$ elements

Together with the development of a posteriori estimators, a novel activity in the team is the design of efficient hp-adpative strategy. In this regard, we propose a multi-level hierarchical data structure imposing Dirichlet nodes to manage the so-called hanging nodes. Our hp-adaptive strategy is based on performing quasi-optimal unrefinements. Taking advantage of the hierarchical structure of the basis functions both in terms of the element size h and the polynomial order of approximation p, we mark those with the lowest contributions to the energy of the solution and remove them. This straightforward unrefinement strategy does not require from a fine grid or complex data structures, making the algorithm flexible to many practical situations and existing implementations. Our first contribution has been recently submitted [42], and deals with the Poisson equation. Fig. 7 shows how the algorithm is able to correctly refine the computational grid to capture a shock wave.

6.1.10. Multiscale methods for frequency-domain wave propagation

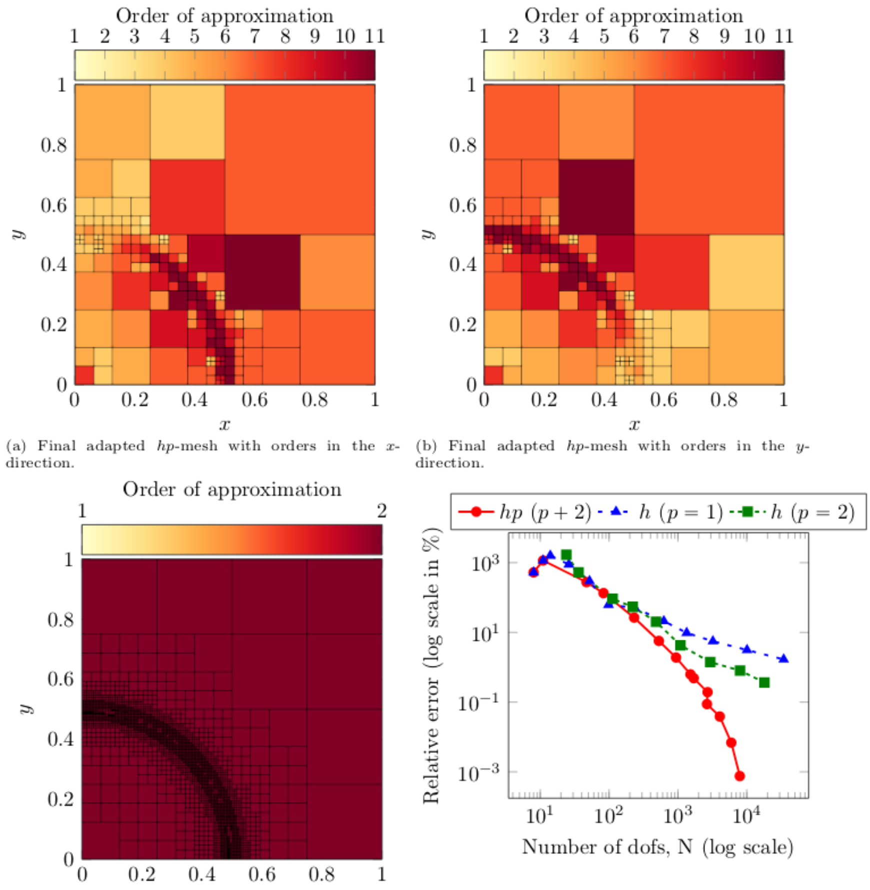
Participants: Théophile Chaumont-Frelet, Zakaria Kassali, Stéphane Lanteri, Frédéric Valentin.

The design and analysis of multiscale methods for wave propagation is an important research line for team. The team actually mainly specializes in one family of multiscale methods, called multiscale hybrid-mixed (MHM). These developments started thanks to the close collaboration with Frédéric Valentin, who has recently been awarded an Inria international chair. Previous investigations in the context of this collaboration focused on time-dependent Maxwell's equations [10]. Recent efforts have been guided towards the realization of a MHM method for time-harmonic Maxwell's equations. We first focused on the Helmholtz equation, that modelizes the particular case of polarized waves. Our first results include the implementation of the method for two-dimensional problems as well as rigorous, frequency-explicit, stability and convergence analysis. These findings have recently been accepted for publication [40]. In the context of the internship of Zakaria Kassali, the method has been further adapted for the propagation of polarized waves in solar cells. Specifically, it is required in this case to take into account "quasi-periodic" boundary conditions that deserve a special treatment. We are currently undertaking further developments guided toward full three-dimensional Maxwell's equations with the PhD of Zakaria Kassali, which started in November 2019.

6.2. High performance numerical computing

6.2.1. High order HDG schemes and domain decomposition solvers for frequency-domain electromagnetics

Participants: Emmanuel Agullo [HIEPACS project-team, Inria Bordeaux - Sud-Ouest], Théophile Chaumont-Frelet, Luc Giraud [HIEPACS project-team, Inria Bordeaux - Sud-Ouest], Stéphane Lanteri.



(a) Final adapted hp-mesh with orders in the x-direction.

(b) Final adapted hp-mesh with orders in the y-direction.

(c) Final adapted h-mesh, $p = 2$.

(d) Evolution of the error in H^1 semi-norm.

Figure 7. Different hp-adptive strategies for capturing a shock wave

This work is undertaken in the context of PRACE 6IP project and aims at the development of scalable frequency-domain electromagnetic wave propagation solvers, in the framework of the DIOGENeS software suite. This solver is based on a high order HDG scheme formulated on an unstructured tetrahedral grid for the discretization of the system of three-dimensional Maxwell equations in dispersive media, leading to the formulation of large sparse undefinite linear system for the hybrid variable unknowns. This system is solved with domain decomposition strategies that can be either a purely algebraic algorithm working at the matrix operator level (i.e. a black-box solver), or a tailored algorithm designed at the continuous PDE level (i.e. a PDE-based solver). In the former case, we collaborate with the HIEPACS project-team at Inria Bordeaux - Sud-Ouest in view of adapting and exploiting the MaPHyS (Massively Parallel Hybrid Solver - https://gitlab.inria.fr/solverstack/maphys) algebraic hybrid iterative-direct domain decomposition solver. More precisely, this collaboration is concerned with two topics: one one hand,= the improvement of the iterative convergence of MaPHyS for the HDG hybrid variable linear system.

6.3. Applications

6.3.1. Inverse design of metasurfaces using statistical learning methods

Participants: Régis Duvigneau [ACUMES project-team, Inria Sophia Antipolis-Méditerranée], Mahmoud Elsawy, Patrice Genevet [CRHEA laboratory, Sophia Antipolis], Stéphane Lanteri.

Metasurfaces are flat optical nanocomponents, that are the basis of several more complicated optical devices. The optimization of their performance is thus a crucial concern, as they impact a wide range of applications. Yet, current design techniques are mostly based on *engineering knowledge*, and may potentially be improved by a rigorous analysis based on accurate simulation of Maxwell's equations. The goal of this study is to optimize phase gradient metasurfaces by taking advantage of our fullwave high order Discontinuous Galerkin time-Domain solver implemented in DIOGENeS, coupled with two advanced optimization techniques based on statistical learning and evolutionary strategies. Our key findings are novel designs for Gan semiconductor phase gradient metasurfaces operating at visible wavelengths. Our numerical results reveal that rectangular and cylindrical nanopillar arrays can achieve more than respectively 88% and 85% of diffraction efficiency for TM polarization and both TM and TE polarization respectively, using only 150 fullwave simulations. To the best of our knowledge, this is the highest blazed diffraction efficiency reported so far at visible wavelength using such metasurface architectures. Fig. 8 depicts the superiority of the proposed statistical learning approaches over standard gradient-based optimization strategies. This work has been recently published [22].

6.3.2. Optimization of light-trapping in nanocone gratings

Participants: Stéphane Collin [Sunlit team, C2N-CNRS, Marcoussi], Alexis Gobé, Julie Goffard [Sunlit team, C2N-CNRS, Marcoussi], Stéphane Lanteri.

There is significant recent interest in designing ultrathin crystalline silicon solar cells with active layer thickness of a few micrometers. Efficient light absorption in such thin films requires both broadband antireflection coatings and effective light trapping techniques, which often have different design considerations. In collaboration with physicists from the Sunlit team at C2N-CNRS, we conduct a numerical study of solar cells based on nanocone gratings. Indeed, it has been previously shown that by employing a double-sided grating design, one can separately optimize the geometries for antireflection and light trapping purposes to achieve broadband light absorption enhancement [60]. In the present study, we adopt the nanocone grating considered in [60]. This structure contains a crystalline silicon thin film with nanocone gratings also made of silicon. The circular nanocones form two-dimensional square lattices on both the front and the back surfaces. The film is placed on a perfect electric conductor (PEC) mirror. The ultimate objective of this study is to devise a numerical optimization strategy to infer optimal values of the geometrical characteristics of the nanocone grating on each side of the crystalline silicon thin film. Absorption characteristics are here evaluated using the high order DGTD solver from the DIOGENeS software suite. We use two efficient global optimization techniques based on statistical learning to adpat the geometrical characteristics of the nanocones in order the maximize the light absorption properties of this type of solr cells.

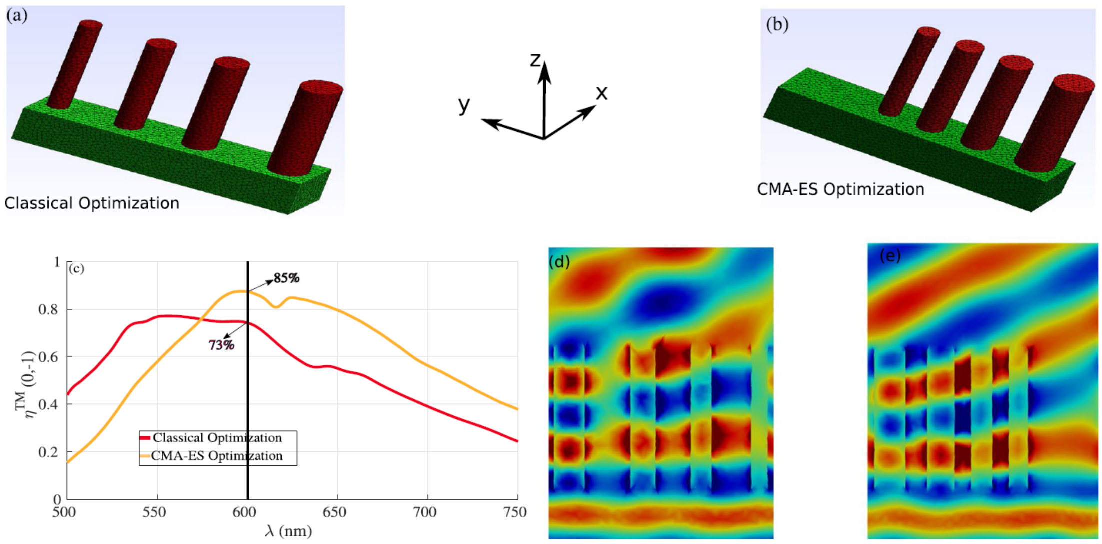


Figure 8. Comparison between the classical approach to phase gradient metasurface design and our optimized geometries for the cylindrical nanopillars with $h = 800$ nm. (a,b) The geometry obtained using the classical approach in which each nanopillar is optimized manually by changing the diameter and finally placed together in order to obtain the desired phase shift needed to maximize the light deflection for the first order mode at $\lambda = 600$ nm with period 1500 nm in y-direction. (c) Results obtained using the CMA-ES for the cylindrical nanopillars (see Table 3) for the corresponding parameters. (c) Comparison between the deflection efficiency for the first order mode obtained using the classical (red curve) and the CMA-ES (orange curve). (d,e) Represent field maps of $Re(E_y)$ obtained using the classical optimization design and the CMA-ES results, respectively

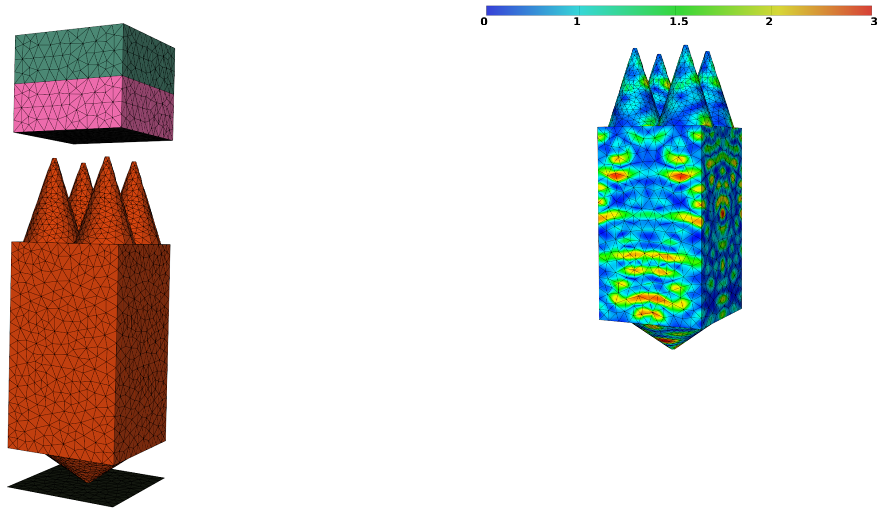


Figure 9. Simulation of light trapping in a solar cell based on nanocone gratings. Geometrical model (left) and contour lines of the module of the DFT of $\mathbf{E}$ *for a wavelength* $\lambda = 857$ *nm (right).*

6.3.3. Influence of spatial dispersion on surface plasmons and grating couplers

Participants: Stéphane Lanteri, Antoine Moreau [Institut Pascal, Université Blaise Pascal], Armel Pitelet [Institut Pascal, Université Blaise Pascal], Claire Scheid, Nikolai Schmitt, Jonathan Viquerat.

Recent experiments have shown that spatial dispersion may have a conspicuous impact on the response of plasmonic structures. This suggests that in some cases the Drude model should be replaced by more advanced descriptions that take spatial dispersion into account, like the hydrodynamic model. Here we show that nonlocality in the metallic response affects surface plasmons propagating at the interface between a metal and a dielectric with high permittivity. As a direct consequence, any nanoparticle with a radius larger than 20 nm can be expected to be sensitive to spatial dispersion whatever its size. The same behavior is expected for a simple metallic grating allowing the excitation of surface plasmons, just as in Woods famous experiment. Finally, we carefully set up a procedure to measure the signature of spatial dispersion precisely, leading the way for future experiments. Importantly, our work suggests that for any plasmonic structure in a high permittivity dielectric, nonlocality should be taken into account.

6.3.4. Optimization and uncertainty quantification of gradient index metasurfaces

Participants: Gauthier Brière [CRHEA laboratory, Sophia Antipolis], Herbert de Gersem [TEMF institute, TU Darmstadt, Germany], Patrice Genevet [CRHEA laboratory, Sophia Antipolis], Niklas Georg [TEMF institute, TU Darmstadt, Germany], Stéphane Lanteri, Dimitrios Loukrezis [TEMF institute, TU Darmstadt, Germany], Ulrich Römer [TEMF institute, TU Darmstadt, Germany], Nikolai Schmitt.

The design of intrinsically flat two-dimensional optical components, i.e., metasurfaces, generally requires an extensive parameter search to target the appropriate scattering properties of their constituting building blocks. Such design methodologies neglect important near-field interaction effects, playing an essential role in limiting the device performance. Optimization of transmission, phase-addressing and broadband performances of metasurfaces require new numerical tools. Additionally, uncertainties and systematic fabrication errors should be analysed. These estimations, of critical importance in the case of large production of metaoptics components, are useful to further project their deployment in industrial applications. Here, we report on a computational methodology to optimize metasurface designs. We complement this computational methodology by quantifying the impact of fabrication uncertainties on the experimentally characterized components. This analysis provides general perspectives on the overall metaoptics performances, giving an idea of the expected average behavior of a large number of devices.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. DGTD solver for time-domain elecromagnetics with application to geoseismics

Participants: Andreas Atle [TOTAL], Henri Calandra [TOTAL], Karim El Maarouf [TOTAL], Alexis Gobé, Stéphane Lanteri, Michael Sekachev [TOTAL].

This contract with TOTAL CSE (Computational Science and Engineering) division in Houston, Texas, is concerned with the development of a DGTD solver for applications in geoseismics. The R&D division of the EP (Oil, Gas Exploration & Production) branch of TOTAL has been interested in DG type methods since many years. It acquired a know-how on these methods and developed internally software tools integrating DG methods as solvers of the direct problem (forward propagators) in different seismic imaging processes (RTM - Reverse Time Migration, and FWI - Full Waveform Inversion). These solvers are concerned with the numerical resolution of PDE systems of acoustics and elastodynamics. TOTAL is now interested in having a similar DGTD solver for the numerical resolution of the system of time-domain Maxwell equations, in view of the development of an electromagnetic imaging process to identify conductivity of a medium. This electromagnetic imaging process would then be coupled to the existing seismic imaging ones.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR project

8.1.1.1. OPERA (Adpative planar optics)

Participants: Emmanuel Agullo [HIEPACS project-team, Inria Bordeaux - Sud-Ouest], Régis Duvigneau [ACUMES project-team], Mahmoud Elsawy, Patrice Genevet [CRHEA laboratory, Sophia Antipolis], Luc Giraud [HIEPACS project-team, Inria Bordeaux - Sud-Ouest], Stéphane Lanteri.

Type: ANR ASTRID Maturation

See also: http://www-sop.inria.fr/nachos/opera/

Duration: Avril 2019 - March 2022

Coordinator: Inria

Partner: CRHEA laboratory in Sophia Antipolis and NAPA Technologies in Archamps

Inria contact: Stéphane Lanteri

Abstract: In the OPERA project, we are investigating and optimizing the properties of planar photonic devices based on metasurfaces using numerical modelling. The scientific and technical activities that constitute the project work programme are organized around 4 main workpackages. The numerical characterization of the optical properties of planar devices based on metasurfaces, as well as their optimization are at the heart of the activities and objectives of two horizontal (transversal) workpackages. These numerical methodologies will be integrated into the DIOGENeS software framework that will eventually integrates (1) discontinuous Galerkin-type methods that have been tested over the past 10 years for the discretization of Maxwell equations in time and frequency regimes, mainly for applications in the microwave band, (2) parallel resolution algorithms for sparse linear systems based on the latest developments in numerical linear algebra, (3) modern optimization techniques based on learning and metamodeling methods and (4) software components adapted to modern high performance computing architectures. Two vertical workpackages complete this program. One of them aims to demonstrate the contributions of methodological developments and numerical tools resulting from transversal workpackages through their application to diffusion/radiation control by passive planar devices. The other, more prospective, concerns the study of basic building blocks for the realization of adaptive planar devices.

8.2. European Initiatives

8.2.1. H2020 Projects

8.2.1.1. PRACE 6IP

Title: PRACE Sixth Implementation Phase (PRACE-6IP) project

See also: https://cordis.europa.eu/project/id/823767

Duration: May 2019 - December 2021

Partners: see https://cordis.europa.eu/project/id/823767

Inria contact: Luc Giraud

PRACE, the Partnership for Advanced Computing is the permanent pan-European High Performance Computing service providing world-class systems for world-class science. Systems at the highest performance level (Tier-0) are deployed by Germany, France, Italy, Spain and Switzerland, providing researchers with more than 17 billion core hours of compute time. HPC experts from 25 member states enabled users from academia and industry to ascertain leadership and remain competitive in the Global Race. Currently PRACE is finalizing the transition to PRACE 2, the successor of the initial five year period. The objectives of PRACE-6IP are to build on and seamlessly continue the successes of PRACE and start new innovative and collaborative activities proposed by the consortium. These include: assisting the development of PRACE 2; strengthening the internationally recognised PRACE brand; continuing and extend advanced training which so far provided more than 36 400 person·training days; preparing strategies and best practices towards Exascale computing, work on forward-looking SW solutions; coordinating and enhancing the operation of the multi-tier HPC systems and services; and supporting users to exploit massively parallel systems and novel architectures. A high level Service Catalogue is provided. The proven project structure will be used to achieve each of the objectives in 7 dedicated work packages. The activities are designed to increase Europe's research and innovation potential especially through: seamless and efficient Tier-0 services and a pan-European HPC ecosystem including national capabilities; promoting take-up by industry and new communities and special offers to SMEs; assistance to PRACE 2 development; proposing strategies for deployment of leadership systems; collaborating with the ETP4HPC, CoEs and other European and international organisations on future architectures, training, application support and policies. This will be monitored through a set of KPIs.

8.2.1.2. EPEEC

Title: European joint effort toward a highly productive programming environment for heterogeneous exascale computing

Program: H2020

See also: https://epeec-project.eu

Duration: October 2018 - September 2021

Coordinator: Barcelona Supercomputing Center

Partner: Barcelona Supercomputing Center (Spain)

Coordinator: CEA

Partners:

Fraunhofer–Gesellschaft (Germany)
CINECA (Italy)
IMEC (Blegium)
INESC ID (Portugal)
Appentra Solutions (Spain)
Eta Scale (Sweden)
Uppsala University (Sweden)
Inria (France)
Cerfacs (France)

Inria contact: Stéphane Lanteri

EPEEC's main goal is to develop and deploy a production-ready parallel programming environment that turns upcoming overwhelmingly-heterogeneous exascale supercomputers into manageable platforms for domain application developers. The consortium will significantly advance and integrate existing state-of-the-art components based on European technology (programming models, runtime systems, and tools) with key features enabling 3 overarching objectives: high coding productivity, high performance, and energy awareness. An automatic generator of compiler directives will provide outstanding coding productivity from the very beginning of the application developing/porting process. Developers will be able to leverage either shared memory or distributed-shared memory programming flavours, and code in their preferred language: C, Fortran, or C++. EPEEC will ensure the composability and interoperability of its programming models and runtimes, which will incorporate specific features to handle data-intensive and extreme-data applications. Enhanced leading-edge performance tools will offer integral profiling, performance prediction, and visualisation of traces. Five applications representative of different relevant scientific domains will serve as part of a strong inter-disciplinary co-design approach and as technology demonstrators. EPEEC exploits results from past FET projects that led to the cutting-edge software components it builds upon, and pursues influencing the most relevant parallel programming standardisation bodies.

8.3. International Initiatives

8.3.1. Participation in Other International Programs

8.3.1.1. International Initiatives

PHOTOM

Title: PHOTOvoltaic solar devices in Multiscale computational simulations

International Partners:

Center for Research in Mathematical Engineering, Universidad de Concepcion (Chile), Rodolfo Araya

Laboratório Nacional de Computação Científica (Brazil), Frédéric Valentin

Instito de Matemáticas, PUCV (Chile), Diego Paredes

Duration: 2018 - 2020

Start year: 2018

See also: http:////www.photom.lncc.br

The work consists of devising, analyzing and implementing new multiscale finite element methods, called Multiscale Hybrid-Mixed (MHM) method, for the Helmholtz and the Maxwell equations in the frequency domain. The physical coefficients involved in the models contain highly heterogeneous and/or high contrast features. The goal is to propose numerical algorithms to simulate wave propagation in complex geometries as found in photovoltaic devices, which are naturally prompt to be used in massively parallel computers. We demonstrate the well-posedness and establish the optimal convergence of the MHM methods. Also, the MHM methods are shown to induce a new face-based a posteriori error estimator to drive space adaptivity. An efficient parallel implementation of the new multiscale algorithm assesses theoretical results and is shown to scale on a petaflop parallel computer through academic and realistic two and three-dimensional solar cells problems.

8.3.1.2. Informal International Partners

Prof. Kurt Busch, Humboldt-Universität zu Berlin, Institut für Physik, Theoretical Optics & Photonics

8.3.1.3. Inria International Chairs

IIC VALENTIN Frédéric

Title: Innovative multiscale numerical algorithms for wave-matter interaction models at the nanoscale

International Partner (Institution - Laboratory - Researcher):

Laboratório Nacional de Computação Científica (Brazil), Frédéric Valentin

Duration: 2018 - 2022

Start year: 2018

See also: https://www.lncc.br/~valentin/

The project addresses complex three-dimensional nanoscale wave-matter interaction models, which are relevant to the nanophotonics and nanophononics fields, and aims at devising innovative multiscale numerical methods, named Multiscale Hybrid-Mixed methods (MHM for short), to solve them with high accuracy and high performance.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

- David Pardo (Basque Center for Applied Mathematics, Spain) at Inria, France, April 2-5, 2019.
- Christophe Geuzaine (University of Liège, Belgium) at Inria, France, April 29-30, 2019.
- Jean-Francois Remacle (Ecole Polytechnique de Louvain, Belgium) at Inria, France, April 29-30, 2019.
- Jay Gopalakrishnan (University of Portland, USA) at Inria, France, June 4-5, 2019.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events: Organisation

9.1.1.1. General Chair, Scientific Chair

- Stéphane Lanteri has chaired the second workshop of the PHOTOM (PHOTOvoltaic solar devices in Multiscale computational simulations) project that took place at Inria Sophia Antipolis-Méditerranée, France, Jan 28-Feb 01, 2019.
- Stéphane Lanteri has chaired the third workshop of the CLIPhTON (advanCed numericaL modelIng for multiscale and multiphysics nanoPhoTONics) network that took place ati Inria Sophia Antipolis-Méditerranée, France, October 24-25, 2019.

9.1.2. Journal

9.1.2.1. Reviewer - Reviewing Activities

- Théophile Chaumont-Frelet: ESAIM Math. Model. Numer. Anal., NUMA, NME
- Yves D'Angelo: Nanotechnology, Journal of Geophysical & Astrophysical Fluid Dynamics
- Claire Scheid: SIAM J. Numer. Anal., SIAM J. Sci. Comput.
- Stéphane Lanteri: J. Comput. Phys., Comp. Meth. Appl. Mech. Engrg.

9.1.3. Invited Talks

- Théophile Chaumont-Frelet, Journées Ondes Sud-Ouest, MIOS, France , January 2019.
- Théophile Chaumont-Frelet, Séminaire LJAD, Nice, France , November 2019.
- Théophile Chaumont-Frelet at University of Basel, Switzerland, December 11-13, 2019.
- Théophile Chaumont-Frelet at University of Bath, UK, November 11-15, 2019.
- Théophile Chaumont-Frelet at the Basque Center for Applied Mathematics, Spain, May 1-3, 2019.

9.1.4. Scientific Expertise

Stéphane Lanteri is a member of the Scientific Committee of CERFACS.

9.1.5. Research Administration

- Yves D'Angelo is the head of the "Laboratoire J.A. Dieudonné" (LJAD, UMR 7351).
- Stéphane Descombes is the head of the "Maison de la Modélisation, de la Simulation et des Interactions" (MSI) of Université Côte d'Azur
- Stéphane Lanteri is a member of the Project-team Committee's Bureau of the Inria Sophia Antipolis-Méditerranée research center.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

License: Yves D'Angelo, *Analyse des Séries de Fourier* , 30 h, L3, Univ. Côte d'Azur

Lisence: Claire Scheid, *Fondements 2* , 24 h, L1, Univ. Côte d'Azur

Master: Yves D'Angelo, *Modélisation et Simulation Numérique* , 48 h, M1, Univ. Côte d'Azur

Master: Yves D'Angelo, *Modélisation de la Turbulence fluid* , 30 h, M2, Univ. Côte d'Azur

Master: Claire Scheid, *Analyse, Lecture and practical works* , 27 h, M2, Univ. Côte d'Azur

Master: Claire Scheid, *Méthodes numériques en EDP, Lectures and practical works* , 63 h, M1, Univ. Côte d'Azur

Master: Claire Scheid, *Option Modélisation, Lectures and practical works* , 48 h, M2, Univ. Côte d'Azur

Master: Claire Scheid, *Soutien Analyse Fonctionnelle et Esepacde de Hilbert* , 18 h, M1, Univ. Côte d'Azur

Master: Stéphane Descombes, *Introduction aux EDP* , 30 h, M1, Univ. Côte d'Azur

Master: Stéphane Descombes, *ACP et reconnaissance de caractères* , 9 h, M2, Univ. Côte d'Azur

License: Stéphane Descombes, *Travaux dirigés de mathématiques pour l'économie*, 18 h, L1, Univ. Côte d'Azur

Engineering: Stéphane Lanteri, *High performance scientific computing*, , 24 h, MAM5, Polytech Nice Sophia

9.2.2. Supervision

PhD in progress: Alexis Gobé, Multiscale hybrid-mixed methods for time-domain nanophotonics, vNovember 2016, Stéphane Lanteri

PhD in progress: Georges Nehmetallah, Efficient finite element type solvers for the numerical modeling of light transmission in nanostructured waveguides and cavities, November 2017, Stéphane Descombes and Stéphane Lanteri

PhD in progress: Zakaria Kassali, Multiscale finite element simulations applied to the design of photovoltaic cells, November 2019, Théophile Chaumont-Frelet and Stéphane Lanteri

PhD in progress: Massimiliano Montone, High order finite element type solvers for the coupled Maxwell-semiconductor equations in the time-domain, December 2019, Stéphane Lanteri and Claire Scheid

9.2.3. Juries

Yves D'Angelo: Basile Radisson, IRPHE Marseille, France, Avril 2019, Rapporteur.

Claire Scheid: Pierre Mennuni, Lille, France, November 2019, Examinatrice.

Claire Scheid: Weslley Da Silva Peireira, LNCC, Petropolis, Brazil, September 2019, Examinatrice.

Stéphane Lanteri: Aurélien Citrain, Inria Pau, December 2019, Rapporteur.

Stéphane Lanteri: Nicolas Lebbe, CEA LETI, Grenoble, Novembre 2019, Examinateur.

Stéphane Lanteri: Matthieu Patrizio, ISAE, Toulouse, Mai 2019: Examinateur.

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Project-Team NEO

Network Engineering and Operations

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Networks and Telecommunications

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Project-Team NEO

Creation of the Team: 2017 January 01, updated into Project-Team: 2017 December 01

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1. Team, Visitors, External Collaborators

Research Scientists
Alain Jean-Marie [Team leader, Inria, Senior Researcher]
Sara Alouf [Inria, Researcher, HDR]
Eitan Altman [Inria, Senior Researcher, HDR]
Konstantin Avrachenkov [Inria, Senior Researcher, HDR]
Giovanni Neglia [Inria, Researcher, HDR]

External Collaborator
Patrick Brown [Inria, Nov 2019]

Technical Staff
Omar Mohamed [Inria, Engineer, from Jun 2019 until Sep 2019]
Cedric Richier [Inria, Engineer, from Mar 2019 until May 2019]

PhD Students
Zaid Allybokus [Huawei, until Jun 2019]
Abhishek Bose [Inria, until Sep 2019]
Mandar Datar [Inria]
Maximilien Dreveton [Inria]
Guilherme Iecker Ricardo [Institut Telecom ex GET Groupe des Ecoles des Télécommunications]
Mikhail Kamalov [Inria, from Jun 2019]
Marie Masson [Orange]
Dimitra Politaki [Univ Côte d'Azur - Sophia Antipolis, until Mar 2019]
Tareq Si Salem [Univ Côte d'Azur, from Oct 2019]

Post-Doctoral Fellows
Nicolas Allegra [Inria, until Aug 2019]
Andrei Bobu [Inria, from May 2019]
Swapnil Dhamal [Inria, until Feb 2019]
Kishor Yashavant Patil [Inria, from Oct 2019]
Chuan Xu [Inria, from Oct 2018]

Visiting Scientists
Vladimir Gaitsgory [Macquarie University, Australia, from Sep 2019 until Oct 2019]
Witold Szczechla [Warsaw University, Poland, from Oct 2019 until Dec 2019]

Administrative Assistant
Laurie Vermeersch [Inria]

2. Overall Objectives

2.1. Overall Objectives

NEO is an Inria project-team whose members are located in Sophia Antipolis (S. Alouf, K. Avrachenkov, G. Neglia), in Avignon (E. Altman) at LIA (Lab. of Informatics of Avignon) and in Montpellier (A. Jean-Marie) at LIRMM (Lab. Informatics, Robotics and Microelectronics of Montpellier). The team is positioned at the intersection of Operations Research and Network Science. By using the tools of Stochastic Operations Research, we model situations arising in several application domains, involving networking in one way or the other. The aim is to understand the rules and the effects in order to influence and control them so as to engineer the creation and the evolution of complex networks.

3. Research Program

3.1. Stochastic Operations Research

Stochastic Operations Research is a collection of modeling, optimization and numerical computation techniques, aimed at assessing the behavior of man-made systems driven by random phenomena, and at helping to make decisions in such a context.

The discipline is based on applied probability and focuses on effective computations and algorithms. Its core theory is that of Markov chains over discrete state spaces. This family of stochastic processes has, at the same time, a very large modeling capability and the potential of efficient solutions. By "solution" is meant the calculation of some *performance metric*, usually the distribution of some random variable of interest, or its average, variance, etc. This solution is obtained either through exact "analytic" formulas, or numerically through linear algebra methods. Even when not analytically or numerically tractable, Markovian models are always amenable to "Monte-Carlo" simulations with which the metrics can be statistically measured.

An example of this is the success of classical Queueing Theory, with its numerous analytical formulas. Another important derived theory is that of the Markov Decision Processes, which allows to formalize *optimal* decision problems in a random environment. This theory allows to characterize the optimal decisions, and provides algorithms for calculating them.

Strong trends of Operations Research are: a) an increasing importance of multi-criteria multi-agent optimization, and the correlated introduction of Game Theory in the standard methodology; b) an increasing concern of (deterministic) Operations Research with randomness and risk, and the consequent introduction of topics like Chance Constrained Programming and Stochastic Optimization. Data analysis is also more and more present in Operations Research: techniques from statistics, like filtering and estimation, or Artificial Intelligence like clustering, are coupled with modeling in Machine Learning techniques like Q-Learning.

4. Application Domains

4.1. Network Science

Network Science is a multidisciplinary body of knowledge, principally concerned with the emergence of global properties in a network of individual agents, from the "local" properties of this network, namely, the way agents interact with each other. The central model of "networks" is the graph (of Graph Theory/Operations Research), with nodes representing the different entities managing information and taking decisions, and the links representing the fact that entities interact, or not. Links are usually equipped with a "weight" that measures the intensity of interaction. Adding evolution rules to this quite elementary representation leads to dynamic network models, the properties of which Network Science tries to analyze.

A classical example of properties sought in networks is the famous “six degrees of separation” (or “small world”) property: how and why does it happen so frequently? Another ubiquitous property of real-life networks is the Zipf or “scale-free” distribution for degrees. Some of these properties, when properly exploited, lead to successful business opportunities: just consider the PageRank algorithm of Google, which miraculously connects the relevance of some Web information with the relevance of the other information that points to it.

4.2. Network Engineering

In its primary acceptation, Network Science involves little or no engineering: phenomena are assumed to be “natural” and emerge without intervention. However, the idea comes fast to intervene in order to modify the outcome of the phenomenon. This is where NEO is positioned. Beyond the mostly descriptive approach of Network Science, we aim at using the techniques of Operations Research so as to engineer complex networks.

To quote just two examples: controlling the spread of diseases through a “network” of people is of primarily interest for mankind. Similarly, controlling the spread of information or reputation through a social network is of great interest in the Internet. Precisely: given the impact of web visibility on business income, it is tempting (and quite common) to manipulate the graph of the web by adding links so as to drive the PageRank algorithm to a desired outcome.

Another interesting example is the engineering of community structures. Recently, thousands of papers have been written on the topic of community *detection* problem. In most of the works, the researchers propose methods, most of the time, heuristics, for detecting communities or dense subgraphs inside a large network. Much less effort has been put in the understanding of community formation process and even much less effort has been dedicated to the question of how one can influence the process of community formation, e.g. in order to increase overlap among communities and reverse the fragmentation of the society.

Our ambition for the medium term is to reach an understanding of the behavior of complex networks that will make us capable of influencing or producing a certain property in said network. For this purpose, we will develop families of models to capture the essential structure, dynamics, and uncertainty of complex networks. The “solution” of these models will provide the correspondence between metrics of interest and model parameters, thus opening the way to the synthesis of effective control techniques.

In the process of tackling real, very large size networks, we increasingly deal with large graph data analysis and the development of decision techniques with low algorithmic complexity, apt at providing answers from large datasets in reasonable time.

5. Highlights of the Year

5.1. Highlights of the Year

Maximilien Dreveton, PhD student in NEO, has co-authored a book: *Leçons pour l’agrégation de mathématiques* [61].

The members of NEO have edited three collections: [64], [65], [66]. One collection is a result of the very successful EU Project CONGAS: Multilevel Strategic Interaction Game Models for Complex Networks.

Sara Alouf has been elected member of the Board of Directors of the ACM SIGMETRICS.

A workshop in the honor of Eitan Altman, at the occasion of his 60th birthday, took place at the University of Avignon on June, 3rd, 2019. Recordings of the presentations are available, see https://www.canal-u.tv/producteurs/universite_d_avignon_et_des_pays_de_vaucluse/colloque/wiopt_2019.

6. New Software and Platforms

6.1. marmoteCore

Markov Modeling Tools and Environments - the Core

KEYWORDS: Modeling - Stochastic models - Markov model

FUNCTIONAL DESCRIPTION: marmoteCore is a C++ environment for modeling with Markov chains. It consists in a reduced set of high-level abstractions for constructing state spaces, transition structures and Markov chains (discrete-time and continuous-time). It provides the ability of constructing hierarchies of Markov models, from the most general to the particular, and equip each level with specifically optimized solution methods.

This software is developed within the ANR MARMOTE project: ANR-12-MONU-00019.

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- Publications: marmoteCore: a Markov Modeling Platform - marmoteCore: a software platform for Markov modeling
- URL: http://marmotecore.gforge.inria.fr/

7. New Results

7.1. Stochastic Modeling

Participants: Sara Alouf, Eitan Altman, Konstantin Avrachenkov, Alain Jean-Marie, Giovanni Neglia.

7.1.1. Network growth models

Network growth models that embody principles such as preferential attachment and local attachment rules have received much attention over the last decade. Among various approaches, random walks have been leveraged to capture such principles. In the framework of joint team with Brazil (Thanes), G. Neglia, together with G. Iacobelli and D. Figueiredo (both from UFRJ, Brazil), has studied a simple model where network growth and a random walker are coupled [23]. In particular, they consider the No Restart Random Walk model where a walker builds its graph (tree) while moving around. The walker takes s steps (a parameter) on the current graph. A new node with degree one is added to the graph and connected to the node currently occupied by the walker. The walker then resumes, taking another s steps, and the process repeats. They have analyzed this process from the perspective of the walker and the network, showing a fundamental dichotomy between transience and recurrence for the walker as well as power law and exponential degree distribution for the network.

7.1.2. Controlled Markov chains

E. Altman in collaboration with D. Josselin and S. Boularouk (CERI/LIA, Univ Avignon) study in [26] a multiobjective dynamic program where all the criteria are in the form of total expected sum of costs till absorption in some set of states. They assume that instantaneous costs are strictly positive and make no assumption on the ergodic structure of the Markov Decision Process. Their main result is to extend the linear program solution approach that was previously derived for transient Constrained Markov Decision Processes to the general ergodic structure. Several (additive) cost metrics are defined and (possibly randomized) routing policies are sought which minimize one of the costs subject to constraints over the other objectives.

7.1.3. Escape probability estimation in large graphs

Consider large graphs as the object of study and specifically the problem of escape probability estimation. Generally, this characteristic cannot be calculated analytically nor even numerically due to the complexity and large size of the investigation object. In [32], K. Avrachenkov and A. Borodina (Karelian Institute of Applied Mathematical Research, Russia) have presented an effective method for estimating the probability that the random walk on graph first enters a node b before returning into the starting node a. Regenerative properties of the random walk allow the use of an accelerated method for the simulation of cycles based on the splitting technique. The results of numerical experiments confirm the advantages of the proposed method.

7.1.4. Random surfers and prefetching

Prefetching is a basic technique used to reduce the latency of diverse computer services. Deciding what to prefetch amounts to make a compromise between latency and the waste of resources (network bandwidth, storage, energy) if contents is mistakenly prefetched. Modeling the problem in case of web/video/gaming navigation, is done by identifying a graph of "documents" connected by links representing the possible chaining. A surfer, either random or strategic, browses this graph. The prefetching controller must make it sure that the documents browsed are always available locally. In the case where the surfer is random and/or the graph is not completely known in advance, the question is largely unexplored. Q. Petitjean, under the supervision of S. Alouf and A. Jean-Marie, has determined through extensive simulations that when the graph is a tree, neither the greedy strategy, nor the one optimal when the tree is completely known, are optimal when the tree is discovered progressively.

7.1.5. The marmoteCore platform

The development of marmoteCore (see Section 6.1) has been pursued. Its numerical features for computing stationary distributions, average hitting times and absorption probabilities have been used in a joint work with F. Cazals, D. Mazauric and G. Santa Cruz (ABS team) and J. Roux (Univ Cote d'Azur) [52]. The software has been presented to young researchers in networking at the ResCom 2019 summer school.

7.2. Random Graph and Matrix Models

Participants: Konstantin Avrachenkov, Andrei Bobu.

7.2.1. Random geometric graphs

Random geometric graphs are good examples of random graphs with a tendency to demonstrate community structure. Vertices of such a graph are represented by points in Euclid space R^d, and edge appearance depends on the distance between the points. Random geometric graphs were extensively explored and many of their basic properties are revealed. However, in the case of growing dimension $d \to \infty$ practically nothing is known; this regime corresponds to the case of data with many features, a case commonly appearing in practice. In [30], K. Avrachenkov and A. Bobu focus on the cliques of these graphs in the situation when average vertex degree grows significantly slower than the number of vertices n with $n \to \infty$ and $d \to \infty$. They show that under these conditions random geometric graphs do not contain cliques of size 4 a.s. As for the size 3, they present new bounds on the expected number of triangles in the case $\log^2(n) \ll d \ll \log^3(n)$ that improve previously known results.

Network geometries are typically characterized by having a finite spectral dimension (SD), that characterizes the return time distribution of a random walk on a graph. The main purpose of this work is to determine the SD of random geometric graphs (RGGs) in the thermodynamic regime, in which the average vertex degree is constant. The spectral dimension depends on the eigenvalue density (ED) of the RGG normalized Laplacian in the neighborhood of the minimum eigenvalues. In fact, the behavior of the ED in such a neighborhood characterizes the random walk. Therefore, in [33] K. Avrachenkov together with L. Cottatellucci (FAU, Germany and Eurecom) and M. Hamidouche (Eurecom) first provide an analytical approximation for the eigenvalues of the regularized normalized Laplacian matrix of RGGs in the thermodynamic regime. Then, we show that the smallest non zero eigenvalue converges to zero in the large graph limit. Based on the analytical expression of the eigenvalues, they show that the eigenvalue distribution in a neighborhood of the minimum value follows a power-law tail. Using this result, they find that the SD of RGGs is approximated by the space dimension d in the thermodynamic regime.

In [42] K. Avrachenkov together with L. Cottatellucci (FAU, Germany and Eurecom) and M. Hamidouche (Eurecom) have analyzed the limiting eigenvalue distribution (LED) of random geometric graphs. In particular, they study the LED of the adjacency matrix of RGGs in the connectivity regime, in which the average vertex degree scales as $\log(n)$ or faster. In the connectivity regime and under some conditions on the radius r, they show that the LED of the adjacency matrix of RGGs converges to the LED of the adjacency matrix of a deterministic geometric graph (DGG) with nodes in a grid as the size of the graph n goes to infinity. Then, for

n finite, they use the structure of the DGG to approximate the eigenvalues of the adjacency matrix of the RGG and provide an upper bound for the approximation error.

7.3. Data Analysis and Learning

Participants: Konstantin Avrachenkov, Maximilien Dreveton, Giovanni Neglia, Chuan Xu.

7.3.1. Almost exact recovery in label spreading

In semi-supervised graph clustering setting, an expert provides cluster membership of few nodes. This little amount of information allows one to achieve high accuracy clustering using efficient computational procedures. Our main goal is to provide a theoretical justification why the graph-based semi-supervised learning works very well. Specifically, for the Stochastic Block Model in the moderately sparse regime, in [34] K. Avrachenkov and M. Dreveton have proved that popular semi-supervised clustering methods like Label Spreading achieve asymptotically almost exact recovery as long as the fraction of labeled nodes does not go to zero and the average degree goes to infinity.

7.3.2. Similarities, kernels and proximity measures on graphs

In [13], K. Avrachenkov together with P. Chebotarev (RAS Trapeznikov Institute of Control Sciences, Russia) and D. Rubanov (Google) have analytically studied proximity and distance properties of various kernels and similarity measures on graphs. This helps to understand the mathematical nature of such measures and can potentially be useful for recommending the adoption of specific similarity measures in data analysis.

7.3.3. The effect of communication topology on learning speed

Many learning problems are formulated as minimization of some loss function on a training set of examples. Distributed gradient methods on a cluster are often used for this purpose. In [47], G. Neglia, together with G. Calbi (Univ Côte d'Azur), D. Towsley, and G. Vardoyan (UMass at Amherst, USA), has studied how the variability of task execution times at cluster nodes affects the system throughput. In particular, a simple but accurate model allows them to quantify how the time to solve the minimization problem depends on the network of information exchanges among the nodes. Interestingly, they show that, even when communication overhead may be neglected, the clique is not necessarily the most effective topology, as commonly assumed in previous works.

In [48] G. Neglia and C. Xu, together with D. Towsley (UMass at Amherst, USA) and G. Calbi (Univ Côte d'Azur) have investigated why the effect of the communication topology on the number of epochs needed for machine learning training to converge appears experimentally much smaller than what predicted by theory.

7.4. Game Theory

Participants: Eitan Altman, Konstantin Avrachenkov, Mandar Datar, Swapnil Dhamal, Alain Jean-Marie.

7.4.1. Resource allocation: Kelly mechanism and Tullock game

The price-anticipating Kelly mechanism (PAKM) is one of the most extensively used strategies to allocate divisible resources for strategic users in communication networks and computing systems. It is known in other communities as the Tullock game. The users are deemed as selfish and also benign, each of which maximizes his individual utility of the allocated resources minus his payment to the network operator. E. Altman, A. Reiffers-Masson (IISc Bangalore, India), D. Sadoc-Menasche (UFJR, Brazil), M. Datar, S. Dhamal, C. Touati (Inria Grenoble-Rhone-Alpes) and R. El-Azouzi (CERI/LIA, Univ Avignon) have first applied this type of games to competition in crypto-currency protocols between miners in blockchain [11]. Blockchain is a distributed synchronized secure database containing validated blocks of transactions. A block is validated by special nodes called miners and the validation of each new block is done via the solution of a computationally difficult problem, which is called the proof-of-work puzzle. The miners compete against each other and the first to solve the problem announces it, the block is then verified by the majority of miners in this network, trying to reach consensus. After the propagated block reaches the consensus, it is successfully added to the distributed database. The miner who found the solution receives a reward either in the form of crypto-currencies or in the form of a transaction reward. The authors show that the discrete version of the game is equivalent to a congestion game and thus has an equilibrium in pure strategies.

E. Altman, M. Datar, C. Touati (Inria Grenoble-Rhone-Alpes) and G. Burnside (Nokia Bell Labs) then introduce further constraints on the total amount of resources used and study pricing issues in this constrained game. They show that a normalized equilibrium (in the sense of Rosen) exists which implies that pricing can be done in a scalable way, i.e; prices can be chosen to be independent of the player. A possible way to prove this structure is to show that the utilities are strict diagonal concave (which is an extension to game setting of concavity) which they did in [27].

In [25], Y. Xu, Z. Xiao, T. Ni, X. Wang (all from Fudan Univ, China), J. H. Wang (Tsinghua Univ, China) and E. Altman formulate a non-cooperative Tullock game consisting of a finite amount of benign users and one misbehaving user. The maliciousness of this misbehaving user is captured by his willingness to pay to trade for unit degradation in the utilities of benign users. The network operator allocates resources to all the users via the price-anticipating Kelly mechanism. They present six important performance metrics with regard to the total utility and the total net utility of benign users, and the revenue of network operator under three different scenarios: with and without the misbehaving user, and the maximum. We quantify the robustness of PAKM against the misbehaving actions by deriving the upper and lower bounds of these metrics.

7.4.2. A stochastic game with non-classical information structure

In [44], V. Kavitha, M. Maheshwari (both from IIT Bombay, India) and E. Altman introduce a stochastic game with partial, asymmetric and non-classical information. They obtain relevant equilibrium policies using a new approach which allows managing the belief updates in a structured manner. Agents have access only to partial information updates, and their approach is to consider optimal open loop control until the information update. The agents continuously control the rates of their Poisson search clocks to acquire the locks, the agent to get all the locks before others would get reward one. However, the agents have no information about the acquisition status of others and will incur a cost proportional to their rate process. The authors solved the problem for the case with two agents and two locks and conjectured the results for a general number of agents. They showed that a pair of (partial) state-dependent time-threshold policies form a Nash equilibrium.

7.4.3. Zero-Sum stochastic games over the field of real algebraic numbers

In [14], K. Avrachenkov together with V. Ejov (Flinders Univ, Australia), J. Filar and A. Moghaddam (both from Univ of Queensland, Australia) have considered a finite state, finite action, zero-sum stochastic games with data defining the game lying in the ordered field of real algebraic numbers. In both the discounted and the limiting average versions of these games, they prove that the value vector also lies in the same field of real algebraic numbers. Their method supplies finite construction of univariate polynomials whose roots contain these value vectors. In the case where the data of the game are rational, the method also provides a way of checking whether the entries of the value vectors are also rational.

7.4.4. Evolutionary Markov games

I. Brunetti (CIRED), Y. Hayel (CERI/LIA, Univ Avignon) and E. Altman extend in [59] evolutionary game theory by introducing the concept of individual state. They analyze a particular simple case, in which they associate a state to each player, and suppose that this state determines the set of available actions. They consider deterministic stationary policies and suppose that the choice of a policy determines the fitness of the player and it impacts the evolution of the state. They define the interdependent dynamics of states and policies and introduce the State Policy coupled Dynamics in order to study the evolution of the population profile. They prove the relation between the rest points of the system and the equilibria of the game. Then they assume that the processes of states and policies move with different velocities: this assumption allows them to solve the system and then find the equilibria of the game with two different methods: the singular perturbation method and a matrix approach.

7.4.5. Stochastic replicator dynamics

In [12], K. Avrachenkov and V.S. Borkar (IIT Bombay, India) have considered a novel model of stochastic replicator dynamics for potential games that converts to a Langevin equation on a sphere after a change of variables. This is distinct from the models of stochastic replicator dynamics studied earlier. In particular, it is ill-posed due to non-uniqueness of solutions, but is amenable to the Kolmogorov selection principle that picks a unique solution. The model allows us to make specific statements regarding metastable states such as small noise asymptotics for mean exit times from their domain of attraction, and quasi-stationary measures. We illustrate the general results by specializing them to replicator dynamics on graphs and demonstrate that the numerical experiments support theoretical predictions.

7.4.6. *Stochastic coalitional better-response dynamics for finite games with application to network formation games*

In [57], K. Avrachenkov and V.V. Sing (IIT Delhi, India) have considered coalition formation among players in n-player finite strategic game over infinite horizon. At each time a randomly formed coalition makes a joint deviation from a current action profile such that at new action profile all the players from the coalition are strictly benefited. Such deviations define a coalitional better-response (CBR) dynamics that is in general stochastic. The CBR dynamics either converges to a $\mathcal{K}$-stable equilibrium or becomes stuck in a closed cycle. The authors also assume that at each time a selected coalition makes mistake in deviation with small probability that add mutations (perturbations) into CBR dynamics. They prove that all $\mathcal{K}$-stable equilibria and all action profiles from closed cycles, that have minimum stochastic potential, are stochastically stable. A similar statement holds for strict $\mathcal{K}$-stable equilibrium. They apply the CBR dynamics to study the dynamic formation of the networks in the presence of mutations. Under the CBR dynamics all strongly stable networks and closed cycles of networks are stochastically stable.

7.4.7. *Strong Stackelberg equilibria in stochastic games*

In a joint work with V. Bucarey López (Univ Libre de Bruxelles, Belgium and Inria team INOCS), E. Della Vecchia (Univ Nacional de Rosario, Argentina), and F. Ordóñez (Univ de Chile, Chile), A. Jean-Marie has considered Stackelberg equilibria for discounted stochastic games. The motivation originates in applications of Game Theory to security issues, but the question is of general theoretical and practical relevance. The solution concept of interest is that of Stationary Strong Stackelberg Equlibrium (SSSE) policies: both players apply state feedback policies; the leader announces her strategy and the follower plays a best response to it. Tie breaks are resolved in favor of the leader. The authors provide classes of games where the SSSE exists, and we prove via counterexamples that SSSE does not exist in the general case. They define suitable dynamic programming operators whose fixed points are referred to as Fixed Point Equilibrium (FPE). They show that the FPE and SSSE coincide for a class of games with Myopic Follower Strategy. Numerical examples shed light on the relationship between SSSE and FPE and the behavior of Value Iteration, Policy Iteration and Mathematical programming formulations for this problem. A security application illustrates the solution concepts and the efficiency of the algorithms introduced. The results are presented in [67], [50], [51].

7.4.8. *Routing on a ring network*

R. Burra, C. Singh and J. Kuri (IISc Bangalore, India), study in [60] with E. Altman routing on a ring network in which traffic originates from nodes on the ring and is destined to the center. The users can take direct paths from originating nodes to the center and also multihop paths via other nodes. The authors show that routing games with only one and two hop paths and linear costs are potential games. They give explicit expressions of Nash equilibrium flows for networks with any generic cost function and symmetric loads. They also consider a ring network with random number of users at nodes, all of them having same demand, and linear routing costs. They give explicit characterization of Nash equilibria for two cases: (i) General i.i.d. loads and one and two hop paths, (ii) Bernoulli distributed loads. They also analyze optimal routing in each of these cases.

7.4.9. *Routing games applied to the network neutrality debate*

The Network Neutrality issue has been at the center of debate worldwide lately. Some countries have established laws so that principles of network neutrality are respected. Among the questions that have been discussed in these debates there is whether to allow agreements between service and content providers, i.e. to allow some preferential treatment by an operator to traffic from some providers (identity-based discrimination). In [63], A. Reiffers-Masson (IISc Bangalore), Y. Hayel, T. Jimenez (CERI/LIA, Univ Avignon) and E. Altman, study this question using models from routing games.

7.4.10. Peering vs transit: A game theoretical model for autonomous systems connectivity

G. Accongiagioco (IMT, Italy), E. Altman, E. Gregori (Institute of Informatics and Telematics, Univ Pisa) and Luciano Lenzini (Dipartimento di Informatica, Univ Pisa) propose a model for network optimization in a non-cooperative game setting with specific reference to the Internet connectivity. The model describes the decisions taken by an Autonomous System when joining the Internet. They first define a realistic model for the interconnection costs incurred; then they use this cost model to perform a game theoretic analysis of the decisions related to link creation and traffic routing, keeping into account the peering/transit dichotomy. The proposed model does not fall into the standard category of routing games, hence they devise new tools to solve it by exploiting specific properties of the game. They prove analytically the existence of multiple equilibria.

7.4.11. Altruistic behavior and evolutionary games

Within some species like bees or ants, the one who interacts is not the one who reproduces. This implies that the Darwinian fitness is related to the entire swarm and not to a single individual and thus, standard Evolutionary Game models do not apply to these species. Furthermore, in many species, one finds altruistic behaviors, which favors the group to which the playing individual belongs, but which may hurt the single individual. In [58], [62], I. Brunetti (CIRED), R. El-Azouzi, M. Haddad, H. Gaiech, Y. Hayel (LIA/CERI, Univ Avignon) and E. Altman define evolutionary games between group of players and study the equilibrium behavior as well as convergence to equilibrium.

7.5. Applications in Telecommunications

Participants: Eitan Altman, Konstantin Avrachenkov, Giovanni Neglia.

7.5.1. Elastic cloud caching services

In [37], G. Neglia, together with D. Carra (Univ of Verona, Italy) and P. Michiardi (Eurecom), has considered in-memory key-value stores used as caches, and their elastic provisioning in the cloud. The cost associated to such caches not only includes the storage cost, but also the cost due to misses: in fact, the cache miss ratio has a direct impact on the performance perceived by end users, and this directly affects the overall revenues for content providers. The goal of their work is to adapt dynamically the number of caches based on the traffic pattern, to minimize the overall costs. They present a dynamic algorithm for TTL caches whose goal is to obtain close-to-minimal costs and propose a practical implementation with limited computational complexity: their scheme requires constant overhead per request independently from the cache size. Using real-world traces collected from the Akamai content delivery network, they show that their solution achieves significant cost savings specially in highly dynamic settings that are likely to require elastic cloud services.

7.5.2. Neural networks for caching

In [19] G. Neglia, together with V. Fedchenko (Univ Côte d'Azur) and B. Ribeiro (Purdue Univ, USA), has proposed a caching policy that uses a feedforward neural network (FNN) to predict content popularity. This scheme outperforms popular eviction policies like LRU or ARC, but also a new policy relying on the more complex recurrent neural networks. At the same time, replacing the FNN predictor with a naive linear estimator does not degrade caching performance significantly, questioning then the role of neural networks for these applications.

7.5.3. Similarity caching

In similarity caching systems, a user request for an object o that is not in the cache can be (partially) satisfied by a similar stored object o', at the cost of a loss of user utility. Similarity caching systems can be effectively employed in several application areas, like multimedia retrieval, recommender systems, genome study, and machine learning training/serving. However, despite their relevance, the behavior of such systems is far from being well understood. In [41], G. Neglia, together with M. Garetto (Univ of Turin, Italy) and E. Leonardi (Politechnic of Turin, Italy), provides a first comprehensive analysis of similarity caching in the offline, adversarial, and stochastic settings. They show that similarity caching raises significant new challenges, for which they propose the first dynamic policies with some optimality guarantees. They evaluate the performance of the proposed schemes under both synthetic and real request traces.

7.5.4. Performance evaluation and optimization of 5G wireless networks

In small cell networks, high mobility of users results in frequent handoff and thus severely restricts the data rate for mobile users. To alleviate this problem, one idea is to use heterogeneous, two-tier network structure where static users are served by both macro and micro base stations, whereas the mobile (i.e., moving) users are served only by macro base stations having larger cells; the idea is to prevent frequent data outage for mobile users due to handoff. In [16], A. Chattopadhyay and B. Błaszczyszyn (Inria DYOGENE team) in collaboration with E. Altman use the classical two-tier Poisson network model with different transmit powers, assume independent Poisson process of static users and doubly stochastic Poisson process of mobile users moving at a constant speed along infinite straight lines generated by a Poisson line process. Using stochastic geometry, they calculate the average downlink data rate of the typical static and mobile (i.e., moving) users, the latter accounted for handoff outage periods. They consider also the average throughput of these two types of users.

In [15], the same authors consider location-dependent opportunistic bandwidth sharing between static and mobile downlink users in a cellular network. Each cell has some fixed number of static users. Mobile users enter the cell, move inside the cell for some time and then leave the cell. In order to provide higher data rate to mobile users, the authors propose to provide higher bandwidth to the mobile users at favourable times and locations, and provide higher bandwidth to the static users in other times. They formulate the problem as a long run average reward Markov decision process (MDP) where the per-step reward is a linear combination of instantaneous data volumes received by static and mobile users, and find the optimal policy. The transition structure of this MDP is not known in general. To alleviate this issue, they propose a learning algorithm based on single timescale stochastic approximation. Also, noting that the unconstrained MDP can be used to solve a constrained problem, they provide a learning algorithm based on multi-timescale stochastic approximation. The results are extended to address the issue of fair bandwidth sharing between the two classes of users. Numerical results demonstrate performance improvement by their scheme, and also the trade-off between performance gain and fairness.

7.5.5. The age of information

Two decades after the seminal paper on software aging and rejuvenation appeared in 1995, a new concept and metric referred to as the age of information (AoI) has been gaining attention from practitioners and the research community. In the vision paper [46], D.S. Menasche (UFRJ, Brazil), K. Trivedi (Duke Univ, USA) and E. Altman show the similarities and differences between software aging and information aging. In particular, modeling frameworks that have been applied to software aging, such as the semi Markov approach can be immediately applied in the realm of age of information. Conversely, they indicate that questions pertaining to sampling costs associated with the age of information can be useful to assess the optimal rejuvenation trigger interval for software systems.

The demand for Internet services that require frequent updates through small messages has tremendously grown in the past few years. Although the use of such applications by domestic users is usually free, their access from mobile devices is subject to fees and consumes energy from limited batteries. If a user activates his mobile device and is in the range of a publisher, an update is received at the expense of monetary and energy costs. Thus, users face a tradeoff between such costs and their messages aging. It is then natural to ask how to cope with such a tradeoff, by devising aging control policies. An aging control policy consists of deciding, based on the utility of the owned content, whether to activate the mobile device, and if so, which technology to use (WiFi or cellular). In [28] E. Altman, R. El-Azouzi (CERI/LIA, Univ Avignon), D.S. Menasche (UFRJ, Brazil) and Y. Xu (Fudan Univ, China) show the existence of an optimal strategy in the class of threshold strategies, wherein users activate their mobile devices if the age of their poadcasts surpasses a given threshold and remain inactive otherwise. The accuracy of their model is validated against traces from the UMass DieselNet bus network. The first version of this paper, among the first to introduce the age of information, appeared already in arXiv on 2010.

7.5.6. Wireless transmission vehicle routing

The Wireless Transmission Vehicle Routing Problem (WT-VRP) consists of searching for a route for a vehicle responsible for collecting information from stations. The new feature w.r.t. classical vehicle routing is the possibility of picking up information via wireless transmission, without visiting physically the stations of the network. The WT-VRP has applications in underwater surveillance and environmental monitoring. In [53], L. Flores Luyo and E. Ocaña Anaya (IMCA, Brazil), A. Agra (Univ Aveiro, Brazil), R. Figueiredo (CERI/LIA, Univ Avignon) and E. Altman, study three criteria for measuring the efficiency of a solution and propose a mixed integer linear programming formulation to solve the problem. Computational experiments were done to access the numerical complexity of the problem and to compare solutions under the three criteria proposed.

7.5.7. Video streaming in 5G cellular networks

Dynamic Adaptive Streaming over HTTP (DASH) has become the standard choice for live events and on-demand video services. In fact, by performing bitrate adaptation at the client side, DASH operates to deliver the highest possible Quality of Experience (QoE) under given network conditions. In cellular networks, in particular, video streaming services are affected by mobility and cell load variation. In this context, DASH video clients continually adapt the streaming quality to cope with channel variability. However, since they operate in a greedy manner, adaptive video clients can overload cellular network resources, degrading the QoE of other users and suffer persistent bitrate oscillations. In [40] R. El-Azouzi (CERI/LIA, Univ Avignon), A. Sunny (IIT Palakkad, India), L. Zhao (Huazhong Agricultural Univ, China), E. Altman, D. Tsilimantos (Huawei Technologies, France), F. De Pellegrini (CERI/LIA Univ Avignon), and S. Valentin (Darmstadt Univ, Germany) tackle this problem using a new scheduler at base stations, named Shadow-Enforcer, which ensures minimal number of quality switches as well as efficient and fair utilization of network resources.

While most modern-day video clients continually adapt quality of the video stream, they neither coordinate with the network elements nor among each other. Consequently, a streaming client may quickly overload the cellular network, leading to poor Quality of Experience (QoE) for the users in the network. Motivated by this problem, A. Sunny (IIT Palakkad, India), R. El-Azouzi, A. Arfaoui (both from CERI/LIA, Univ Avignon), E. Altman, S. Poojary (BITS, India), D. Tsilimantos (Huawei Technologies, France) and S. Valentin (Darmstadt Univ, Germany) introduce in [24] D-VIEWS — a scheduling paradigm that assures video bitrate stability of adaptive video streams while ensuring better system utilization. The performance of D-views is then evaluated through simulations.

In [39], R. El-Azouzi, K.V. Acharya (ENS Lyon), M. Haddad (CERI/LIA, Univ Avignon), S. Poojary (BITS, India), A. Sunny (IIT Palakkad, India), D. Tsilimantos (Huawei Technologies, France), S. Valentin (Darmstadt Univ, Germany) and E. Altman, develop an analytical framework to compute the Quality-of-Experience (QoE) metrics of video streaming in wireless networks. Their framework takes into account the system dynamics that arises due to the arrival and departure of flows. They also consider the possibility of users abandoning the system on account of poor QoE. Considering the coexistence of multiple services such as video streaming and elastic flows, they use a Markov chain based analysis to compute the user QoE metrics: probability of starvation, prefetching delay, average video quality and bitrate switching. The simulation results validate the accuracy of their model and describe the impact of the scheduler at the base station on the QoE metrics.

7.5.8. A learning algorithm for the Whittle index policy for scheduling web crawlers

In [31] K. Avrachenkov and V.S. Borkar (IIT Bombay, India) have revisited the Whittle index policy for scheduling web crawlers for ephemeral content and developed a reinforcement learning scheme for it based on LSPE(0). The scheme leverages the known structural properties of the Whittle index policy.

7.5.9. Distributed cooperative caching for VoD with geographic constraints

Consider the caching of video streams in a cellular network in which each base station is equipped with a cache. Video streams are partitioned into multiple substreams and the goal is to place substreams in caches such that the residual backhaul load is minimized. In [36] K. Avrachenkov together with J. Goseling (UTwente, The Netherlands) and B. Serbetci (Eurecom) have studied two coding mechanisms for the substreams: Layered coding (LC) mechanism and multiple description coding (MDC). They develop a distributed asynchronous algorithm for deciding which files to store in which cache to minimize the residual bandwidth, i.e., the cost for downloading the missing substreams of the user's requested video with a certain video quality from the gateway (i.e., the main server). They show that their algorithm converges rapidly. Finally, they show that MDC partitioning is better than the LC mechanism when the most popular content is stored in caches; however, their algorithm enables to use the LC mechanism as well without any performance loss.

Further, in [35], K. Avrachenkov together with J. Goseling (UTwente, The Netherlands) and B. Serbetci (Eurecom), have considered the same setting as above but maximized the expected utility. The utility depends on the quality at which a user is requesting a file and the chunks that are available. They impose alpha-fairness across files and qualities. Similarly to [36] they have developed a distributed asynchronous algorithm for deciding which chunks to store in which cache.

7.6. Applications in Social Networks

Participants: Eitan Altman, Swapnil Dhamal, Giovanni Neglia.

7.6.1. Utility from accessing an online social network

The retention of users on online social networks has important implications, encompassing economic, psychological and infrastructure aspects. In the framework of our joint team with Brazil (Thanes), G. Neglia, together with E. Hargreaves and D. Menasche (both from UFRJ, Brazil) investigated the following question: what is the optimal rate at which users should access a social network? To answer this question, they have proposed an analytical model to determine the value of an access (VoA) to the social network. In the simple setting they considered, VoA is defined as the chance of a user accessing the network and obtaining new content. Clearly, VoA depends on the rate at which sources generate content and on the filtering imposed by the social network. Then, they have posed an optimization problem wherein the utility of users grows with respect to VoA but is penalized by costs incurred to access the network. Using the proposed framework, they provide insights on the optimal access rate. Their results are parameterized using Facebook data, indicating the predictive power of the approach. This research activity led to two publications in 2019 [49], [43].

Last year, the same researchers, together with E. Altman, A. Reiffers-Masson (IISc, India), and the journalist C. Agosti (Univ of Amsterdam, Netherlands), have worked on Facebook News Feed personalization algorithm. The publication [21] complete that line of work described in NEO's 2018 technical report.

7.6.2. Optimal investment strategies for competing camps in a social network

S. Dhamal, W. Ben-Ameur (Telecom SudParis), T. Chahed (Telecom SudParis), and E. Altman have studied the problem of optimally investing in nodes of a social network in [17], wherein two camps attempt to maximize adoption of their respective opinions by the population. Several settings are analyzed, namely, when the influence of a camp on a node is a concave function of its investment on that node, when one of the camps has uncertain information regarding the values of the network parameters, when a camp aims at maximizing competitor's investment required to drive the overall opinion of the population in its favor, and when there exist common coupled constraints concerning the combined investment of the two camps on each node. Extensive simulations are conducted on real-world social networks for all the considered settings.

S. Dhamal, W. Ben-Ameur (Telecom SudParis), T. Chahed (Telecom SudParis), and E. Altman have studied a two-phase investment game for competitive opinion dynamics in social networks, in [18]. The existence of Nash equilibrium and its polynomial time computability is shown under reasonable assumptions. A simulation study is conducted on real-world social networks to quantify the effects of the initial biases and the weigh attributed by nodes to their initial biases, as well as that of a camp deviating from its equilibrium strategy. The study concludes that, if nodes attribute high weight to their initial biases, it is advantageous to have a high investment in the first phase, so as to effectively influence the biases to be harnessed in the second phase.

7.6.3. Extending the linear threshold model

S. Dhamal has proposed a generalization of the linear threshold model to account for multiple product features, in [38]. An integrated framework is presented for product marketing using multiple channels: mass media advertisement, recommendations using social advertisement, and viral marketing using social networks. An approach for allocating budget among these channels is proposed.

7.6.4. Public retention in Youtube

There exist many aspects involved in a video turning viral on YouTube. These include properties of the video such as the attractiveness of its title and thumbnail, the recommendation policy of YouTube, marketing and advertising policies and the influence that the video's creator or owner has in social networks. E. Altman and T. Jimenez (CERI/LIA, Univ Avignon), study in [29] audience retention measurements provided by YouTube to video creators, which may provide valuable information for improving the videos and for better understanding the viewers' potential interests in them. They then study the question of when is a video too long and can gain from being shortened. They examine consistency between several existing audience retention measures. They end in a proposal for a new audience retention measure and identify its advantages.

7.6.5. The medium selection game

F. Lebeau (ENS Lyon), C. Touati (Inria Grenoble-Rhone-Alpes), E. Altman and N. Abuzainab (Virginia Tech, USA) consider in [45] competition of content creators in routing their content through various media. The routing decisions may correspond to the selection of a social network (e.g. twitter versus facebook or linkedin) or of a group within a given social network. The utility for a player to send its content to some medium is given as the difference between the dissemination utility at this medium and some transmission cost. The authors model this game as a congestion game and compute the pure potential of the game. In contrast to the continuous case, they show that there may be various equilibria. They show that the potential is M-concave which allows them to characterize the equilibria and to propose an algorithm for computing it. They then introduce a learning mechanism which allows them to give an efficient algorithm to determine an equilibrium. They finally determine the asymptotic form of the equilibrium and discuss the implications on the social medium selection problem.

7.7. Applications to Environmental Issues

Participant: Alain Jean-Marie.

7.7.1. Sustainable management of water consumption

Continuing a series of game-theoretic studies on sustainable management of water resources, A. Jean-Marie, jointly with T. Jimenez (CERI/LIA, Univ Avignon) and M. Tidball (INRA), consider in [54] the basic groundwater exploitation problem, in the case where agents (farmers) have incomplete information about other agents' profit functions and about pumping cost functions. Farmers behave more or less myopically. The authors analyze two models where they assume that each agent relies on simple beliefs about the other agents' behavior. In a first model, a variation of their own extraction has a first order linear effect on the extractions of others. In a second model, agents consider that extraction of the others players is a proportion of the available water. Farmers' beliefs are updated through observations of the resource level over time. The paper also considers two models with a myopic feature and no learning. In the first one, agents do not know the profit function of the other agents and cost is announced before extraction. In the second one agents know the profit function of the other player and cost is announced after extraction. In this last case agents play a Nash equilibrium. The four behaviors are compared from the economic and environmental points of view.

7.7.2. Pollution permit trading

In a joint work with K. Fredj (Univ of Northern British Columbia, Canada), G. Martín-Herrán (Univ Valladolid, Spain) and Mabel Tidball (INRA), A. Jean-Marie investigated in [20] the strategic behaviour of two countries or firms that minimize costs facing emission standards. Emission standards can be reached through emission reduction, banking or borrowing, and emission trading in a given and fixed planning horizon. The authors extend classical models with: the introduction of transaction costs in tradeable emission markets on the one hand, and using a dynamic game setting, on the other hand. They analyze the case with and without transaction costs and the case with and without discount rate. They characterize socially optimal solutions and Nash equilibria in each case and, depending on the initial allocation, characterize the buyer and seller in the emission trading market. The main findings prove that the agents' equilibrium is not efficient when transaction costs are positive.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

NEO members are involved in the

- Inria-Nokia Bell Labs joint laboratory: the joint laboratory consists of five ADRs (Action de Recherche/Research Action) in its third phase (starting October 2017). NEO members participate in two ADRs: "Distributed Learning and Control for Network Analysis" (see §8.1.1) and "Rethinking the network: virtualizing network functions, from middleboxes to application" (see §8.1.2).
- Inria-QWANT joint laboratory "Smart search is privacy" (see §8.1.3);
- Inria-Orange Labs joint laboratory (see §8.1.4).

NEO has contracts with Accenture (see §8.1.5), Azursoft (see §8.1.6), MyDataModels (see §8.1.7), Huawei (see §8.1.8), and Payback Network (see §8.1.9).

8.1.1. ADR Nokia on the topic "Distributed Learning and Control for Network Analysis" (October 2017 – September 2021)

Participants: Eitan Altman, Konstantin Avrachenkov, Mandar Datar, Maximilien Dreveton.

- Contractor: Nokia Bell Labs (http://www.bell-labs.com)
- Collaborator: Gérard Burnside

Over the last few years, research in computer science has shifted focus to machine learning methods for the analysis of increasingly large amounts of user data. As the research community has sought to optimize the methods for sparse data and high-dimensional data, more recently new problems have emerged, particularly from a networking perspective that had remained in the periphery.

The technical program of this ADR consists of three parts: Distributed machine learning, Multiobjective optimisation as a lexicographic problem, and Use cases / Applications. We address the challenges related to the first part by developing distributed optimization tools that reduce communication overhead, improve the rate of convergence and are scalable. Graph-theoretic tools including spectral analysis, graph partitioning and clustering will be developed. Further, stochastic approximation methods and D-iterations or their combinations will be applied in designing fast online unsupervised, supervised and semi-supervised learning methods.

8.1.2. ADR Nokia on the topic "Rethinking the network: virtualizing network functions, from middleboxes to application" (October 2017 – September 2021)

Participants: Sara Alouf, Giovanni Neglia.

- Contractor: Nokia Bell Labs (http://www.bell-labs.com)
- Collaborators: Fabio Pianese, Massimo Gallo

A growing number of network infrastructures are being presently considered for a software-based replacement: these range from fixed and wireless access functions to carrier-grade middle boxes and server functionalities. On the one hand, performance requirements of such applications call for an increased level of software optimization and hardware acceleration. On the other hand, customization and modularity at all layers of the protocol stack are required to support such a wide range of functions. In this scope the ADR focuses on two specific research axes: (1) the design, implementation and evaluation of a modular NFV architecture, and (2) the modelling and management of applications as virtualized network functions. Our interest is in low-latency machine learning prediction services and in particular how the quality of the predictions can be traded off with latency.

8.1.3. Qwant contract on “Asynchronous on-line computation of centrality measures” (15 December 2017 – 14 May 2020)

Participants: Nicolas Allegra, Konstantin Avrachenkov, Patrick Brown.

- Contractor: Qwant
- Collaborators: Sylvain Peyronnet, Thomas Aynaud

We shall study asynchronously distributed methods for network centrality computation. The asynchronous distributed methods are very useful because they allow efficient and flexible use of computational resources on the one hand (e.g., using a cluster or a cloud) and on the other hand they allow quick local update of centrality measures without the need to recompute them from scratch.

8.1.4. Orange CIFRE on the topic “Self-organizing features in the virtual 5G radio access network” (November 2017 – October 2020)

Participants: Eitan Altman, Marie Masson.

- Contractor: Orange Labs (https://www.orange.com/en/Infographics/Orange-and-Research/Orange-and-Research)
- Collaborator: Zwi Altman

The considerable extent of the complexity of 5G networks and their operation is in contrast with the increasing demands in terms of simplicity and efficiency. This antagonism highlights the critical importance of network management. Self-Organizing Networks (SON), which cover self-configuration, self-optimization and self-repair, play a central role for 5G Radio Access Network (RAN).

This CIFRE thesis aims at innovating in the field of managing 5G RAN, with a special focus on the features of the SON-5G. Three objectives are identified: a) develop self-organizing features (SON in 5G-RAN), b) develop cognitive managing mechanisms for the SON-5G features developed, and c) demonstrate how do the self-organizing mechanisms fit in the virtual RAN.

8.1.5. Accenture contract on the topic “Distributed Machine Learning for IoT applications” (Dec 2019 – May 2020)

Participant: Giovanni Neglia.

- Contractor: Accenture Labs (https://www.accenture.com/fr-fr/accenture-lab-sophia-antipolis)
- Collaborators: Laetitia Kameni, Richard Vidal

IoT applications will become one of the main sources to train data-greedy machine learning models. Until now, IoT applications were mostly about collecting data from the physical world and sending them to the Cloud. Google’s federated learning already enables mobile phones, or other devices with limited computing capabilities, to collaboratively learn a machine learning model while keeping all training data locally, decoupling the ability to do machine learning from the need to store the data in the cloud. While Google envisions only users’ devices, it is possible that part of the computation is executed at other intermediate elements in the network. This new paradigm is sometimes referred to as Edge Computing or Fog Computing. Model training as well as serving (provide machine learning predictions) are going to be distributed between IoT devices, cloud services, and other intermediate computing elements like servers close to base stations as envisaged by the Multi-Access Edge Computing framework. The goal of this project is to propose distributed learning schemes for the IoT scenario, taking into account in particular its communication constraints. This 6-month contract prepares a CIFRE.

8.1.6. AzurSoft contract on the topic "Proof of concept on automatic detection of false alarms" (May 2019 – April 2020)

Participants: Konstantin Avrachenkov, Andrei Bobu.

- Contractor: AzurSoft (https://www.azursoft.com/)
- Collaborators: Marc Vaillant, Beatrice Escuyer

Intrusion detection or telesurveillance systems generates signals from sensors that allow to raise alarm and start a checking procedure for a potential intrusion or anomaly. Typically, one telesurveillance system surveys many sites and is challenged by a stream of false alarms. In this project, we aim to reduce the rate of false alarms by using various supervised and semi-supervised learning methods.

8.1.7. MyDataModels contract on the topic "Semi supervised variational autoencoders for versatile data" (June 2019 – May 2022)

Participants: Konstantin Avrachenkov, Mikhail Kamalov.

- Contractor: MyDataModels (https://www.mydatamodels.com/)
- Collaborators: Denis Bastiment, Carlo Fanara

Variational autoencoders are highly flexible machine learning techniques for learning latent dimension representation. This model is applicable for denoising data as well as for classification purposes. In this thesis we plan to add semi-supervision component to the variational autoencoder techniques. We plan to develop methods which are universally applicable to versatile data such as categorical data, images, texts, etc. Initially starting from static data we aim to extend the methods to time-varying data such as audio, video, time-series, etc. The proposed algorithms can be integrated into the internal engine of MyDataModels company and tested on use cases of MyDataModels.

8.1.8. Huawei CIFRE on the topic "Scalable Online Algorithms for SDN controllers" (June 2016 – May 2019)

Participants: Zaid Allybokus, Konstantin Avrachenkov.

- Contractor: Huawei Technologies (http://www.huawei.com/en/about-huawei/research-development)
- Collaborators: Jérémie Leguay

Software-Defined Networking (SDN) technologies have radically transformed network architectures. They provide programmable data planes that can be configured from a remote controller platform.

The objective of this CIFRE thesis was to provide fundamental answers on how powerful SDN controller platforms could solve large online flow problems to optimize networks in real-time and in a distributed or semi-distributed fashion. We use methods from both optimization and dynamic programming.

8.1.9. Consulting contract with Payback Network (November 2019 - January 2020)

Participant: Giovanni Neglia.

- Contractor: Payback Network
- Collaborators: Tanguy Racinet, Anne Legencre

Consulting with the startup Payback Network on differential privacy techniques.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. MYDATA (Sept. 2018 - Nov. 2020)

Participant: Giovanni Neglia.

This is a research project in cooperation with two other labs (LJAD and GREDEG) from Univ Côte d'Azur to study how to achieve privacy through obfuscation. The project is funded by IDEX UCA$^{\text{JEDI}}$ Academy 1 on "Networks, Information and Digital society". It involves the participation of Vidhya Kannan.

9.2. National Initiatives

9.2.1. PIA ANSWER

Participants: Konstantin Avrachenkov, Abhishek Bose, Kishor Yashavant Patil.

Project Acronym: ANSWER

Project Title: Advanced aNd Secured Web Experience and seaRch

Coordinator: QWANT

Duration: 15 November 2017 – 31 December 2020

Others Partners: Inria Project-Teams WIMMICS, INDES, COFFEE

Abstract: ANSWER is a joint project between QWANT and Inria, funded by the French Government's initiative PIA "Programme d'Investissement d'Avenir".

The aim of the ANSWER project is to develop the new version of the search engine http://www.qwant.com by introducing radical innovations in terms of search criteria as well as indexed content and security. This initiative is a part of the Big Data Big Digital Challenges field, since a Web search engine deals with large volumes of heterogeneous and dynamic data.

Of the five characteristics of big data, the ANSWER project will focus more particularly on the aspects of Velocity in terms of near real-time processing of results, and Variety for the integration of new indicators (emotions, sociality, etc.) and meta-data. The Volume, Value and Veracity aspects will necessarily be addressed jointly with these first ones and will also be the subject of locks, especially on the topics of crawling and indexing.

This registration of the search engine in the Big Data domain will only be reinforced by developments in the Web such as the Web of data, and generally by the current trend to integrate the Web of increasingly diverse, rich and complex resources.

9.2.2. ANR MAESTRO5G

Participant: Eitan Altman.

Project Acronym: MAESTRO5G

Project Title: MAnagEment of Slices in The Radio access Of 5G networks

Coordinator: Orange Labs

Duration: February 2019 – January 2022

Others Partners: Nokia Bell Labs, Univ Avignon, Inria Project-Team AGORA, Sorbonne Univ, Telecom SudParis, CentraleSupélec.

Abstract: The project develops enablers for implementing and managing slices in the 5G radio access network, not only for the purpose of serving heterogeneous services, but also for dynamic sharing of infrastructure between operators. MAESTRO-5G develops a framework for resource allocation between slices and a business layer for multi-tenant slicing. It provides an orchestration framework based on Software Define Networking that manages resources and virtual functions for slices. A hardware demonstrator brings the slicing concept to reality and showcases the project's innovations.

9.3. European Initiatives

9.3.1. Collaborations in European Programs, Except FP7 & H2020

Participant: Konstantin Avrachenkov.

Program: EU COST

Project acronym: COSTNET

Project title: European Cooperation for Statistics of Network Data Science

Duration: May 2016 - April 2020

Coordinator: Ernst Wit (NL), Gesine Reinert (UK)

Other partners: see http://www.cost.eu/COST_Actions/ca/CA15109

Abstract: A major challenge in many modern economic, epidemiological, ecological and biological questions is to understand the randomness in the network structure of the entities they study: for example, the SARS epidemic showed how preventing epidemics relies on a keen understanding of random interactions in social networks, whereas progress in curing complex diseases is aided by a robust data-driven network approach to biology.

Although analysis of data on networks goes back to at least the 1930s, the importance of statistical network modelling for many areas of substantial science has only been recognized in the past decade. The USA is at the forefront of institutionalizing this field of science through various interdisciplinary projects and networks. Also in Europe there are excellent statistical network scientists, but until now cross-disciplinary collaboration has been slow.

This Action aims to facilitate interaction and collaboration between diverse groups of statistical network modellers, establishing a large and vibrant interconnected and inclusive community of network scientists. The aim of this interdisciplinary Action is two-fold. On the scientific level, the aim is to critically assess commonalities and opportunities for cross-fertilization of statistical network models in various applications, with a particular attention to scalability in the face of Big Data. On a meta-level, the aim is to create a broad community which includes researchers across the whole of Europe and at every stage in their scientific career and to facilitate contact with stakeholders.

9.4. International Initiatives

9.4.1. Inria Associate Teams Not Involved in an Inria International Labs

9.4.1.1. MALENA

Title: Machine Learning for Network Analytics

International Partner (Institution - Laboratory - Researcher):

Indian Institute of Technology Bombay (India) - Electrical Communication Engineering - Vivek Borkar

Start year: 2017

See also: http://www-sop.inria.fr/members/Konstantin.Avratchenkov/MALENA.html

In the past couple of decades network science has seen an explosive growth, enough to be identified as a discipline of its own, overlapping with engineering, physics, biology, economics and social sciences. Much effort has gone into modelling, performance measures, classification of emergent features and phenomena, etc, particularly in natural and social sciences. The algorithmic side, all important to engineers, has been recognised as a thrust area (e.g., two recent Nevanlinna Prize (J. Kleinberg 2006 and D. Spielman 2010) went to prominent researchers in the area of network analytics). Still, in our opinion the area is yet to mature and has a lot of uncharted territory. This is because networks provide a highly varied landscape, each flavour demanding different considerations (e.g., sparse vs dense graphs, Erdos-Renyi vs planted partition graphs, standard graphs vs hypergraphs, etc). Even adopting existing methodologies to these novel situations is often a nontrivial exercise, not to mention many problems that cry out for entirely new algorithmic paradigms. It is in this context that we propose this project of developing algorithmic tools, drawing not only upon established as well as novel methodologies in machine learning and big data analytics, but going well beyond, e.g., into statistical physics tools.

9.4.1.2. THANES

Title: THeory and Application of NEtwork Science

International Partner (Institution - Laboratory - Researcher):

Universidade Federal do Rio de Janeiro (Brazil) - Computer Science Department - Daniel Ratton Figueiredo

Start year: 2017

See also: https://team.inria.fr/thanes/

This team is the follow-up of a joint Inria-UFRJ team (funded by FAPERJ in Rio de Janeiro, Brazil) with the same name and almost the same permanent researchers involved. During the first three years THANES has studied how services in Online Social Networks (OSNs) can be efficiently designed and managed. The joint research activity continued along the line of network science with a focus on network growth models, community detection, information spreading, and recommendation systems for online social networks. A new research axis on deep learning spawned during 2018.

9.4.2. Participation in Other International Programs

9.4.2.1. Indo-French Center of Applied Mathematics (IFCAM)

NEO is involved in the IFCAM with the MALENA project. See 9.4.1.1.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

9.5.1.1. Professors/Researchers

Mindaugas Bloznelis, Date: 2-7 Oct, Institution: Vilnius Univ (Lithuania)

Damiano Carra, Date: 17-26 Jun, Institution: Univ of Verona (Italy)

Mahmoud El Chamie, Date: 16-20 Dec, Institution: United Technologies Research Center, East Hartford (USA)

Lasse Leskela, Date: 8-19 April, Institution: Aalto Univ (Finland)

Nelly Litvak, Date: 20 May-2 Jun, Institution: Univ of Twente (Netherlands)

Vincenzo Mancuso, Date: 16-18 Jul , Institution: IMDEA Networks Institute (Spain)

Angelia Nedich, Date: 8-10 Dec, Institution: Arizona State Univ (USA)

Sreenath Ramanath, Date: 2-7 Jul, Institution: Lekha Wireless (India)

Daniel Sadoc Menasche, Date: 24-28 Jun, Institution: UFRJ (Brazil)

Neeraja Sahasrabudhe, Date: 9 May - 4 Jun and 16-20 Dec, Institution: IIT Bombay (India)

Matteo Sereno, Date: 15-17 July, Institution: Univ of Turin (Italy)

Georgy Shevlyakov, Date: 3-17 Nov, Institution: Peter the Great St. Petersburg Polytechnic Univ (Russia)

Gugan Thoppe, Date: 25 Nov - 6 Dec, Institution: IISc Bangalore (India)

Don Towsley, Date: 1-4 Apr, Institution: UMass Amherst (USA)

Kavitha Voleti Veeraruna, Date: 27 May - 8 Jun, Institution: IIT Bombay (India)

9.5.1.2. Postdoc/PhD Students

Tejas Bodas, Date: 12-22 Apr and 11-22 Jun, Postdoc at IIS Bangalore (India)

Mikhail Grigorev, Date: 2-31 Jan, PhD student at MFTI Moscow (Russia)

Eduardo Hargreaves, Date: 24-28 Jun, PhD student at UFRJ (Brazil)

Maksim Mironov, Date: 2-31 Jan and 24 Aug - 7 Sep, PhD student at MFTI Moscow (Russia)

Maksim Ryzhov, Date: 4 Apr - 3 May, PhD student at MFTI Moscow (Russia)

Anirudh Sabnis, Date: 1 Jul - 6 Oct, PhD student at UMass Amherst (USA)

9.5.2. Internships

Note: UCA is the Univ Côte d'Azur.

Younes Ben Mazziane, Date: 19 Nov-13 Dec, Institution: PFE Master Ubinet, UCA, Supervisors: S. Alouf and G. Neglia

Vidhya Kannan, Date: from Dec, Institution: UCA, Supervisor : G. Neglia

Carlos Eduardo Marciano, Date: 13 Sep-9 Dec, Institution: Master student at UFRJ, Brazil, Supervisor: G. Neglia

Kaiyun Pan, Date: 19 Nov-13 Dec, Institution: PFE Master Ubinet, UCA, Supervisor: G. Neglia

Quentin Petitjean, Date: 11 Jun-26 Jul, Institution: ENS Cachan, Supervisors: S. Alouf and A. Jean-Marie

Vilc Queupe Rufino, Date: 17-19 Jun, Institution: Master student at UFRJ, Brazil, Supervisor: D. Sadoc Menasche (UFRJ)

Varvara Samoili, Date: 11 Jan-10 Jul, Institution: Bodossaki Foundation, Supervisor: G. Neglia

Nicola Sebastianelli, Date: 1 Mar-31 Aug, Institution: Master Ubinet, UCA, Supervisor: G. Neglia

Adeel Siddiqui, Date: until Jan 2019, Institution: UCA, Supervisor : G. Neglia

Siemo Zhang, Date: 1 Sep-30 Nov, Institution: Master student at Univ of Twente, Netherlands, Supervisor: K. Avrachenkov

9.6. Visits to International Teams

9.6.1. Research Stays Abroad

Eitan Altman

- Date: 29 January - 4 February, 28 March - 6 April, 20 June - 10 July, 18 October - 4 December, Institution: Technion and Univ Tel-Aviv (Israel)

Konstantin Avrachenkov

- Date: 17-22 February, Institution: Friedrich-Alexander Univ (Germany)
- Date: 4-15 March, Institution: Petrozavodsk State Univ (Russia)
- Date: 26-28 October, Institution: IISc Bangalore (India)
- Date: 30 October - 2 November, Institution: IIT Bombay (India)
- Date: 24-26 November, Institution: Univ Twente (The Netherlands)

Maximilien Dreveton

- Date: 24 May - 9 June, Institution: Aalto Univ (Finland)

Alain Jean-Marie

Date: 17 October - 4 November, Institution: GERAD (Montréal, Canada)

Giovanni Neglia

- Date: 20-22 February, Institution: Univ Florence and Univ Pisa (Italy)
- Date: 23-26 September, Institution: Northeastern Univ and Boston Univ (Massachusetts, United States)

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events: Organisation

10.1.1.1. General Chair, Scientific Chair

- Eitan Altman was the general chair of the 12th EAI International Conference on Performance Evaluation Methodologies and Tools (VALUETOOLS 2019), Palma de Mallorca, Spain, 13-15 March 2019;
- Konstantin Avrachenkov co-organized the 16th Workshop on Algorithms and Models for the Web Graph (WAW 2019), University of Queensland, Brisbane, Australia, 6-7 July 2019;
- Eitan Altman is chairman of the Steering committee of the workshop NetGCoop - Networking Games, Control and Optimisation;
- Eitan Altman is member of the steering committee of the conferences WiOpt and Valuetools.

10.1.1.2. Member of the Organizing Committees

- Giovanni Neglia was publicity co-chair of the 20th International Symposium on Mobile Ad Hoc Networking and Computing (ACM MobiHoc 2019), Catania, Italy, 2-5 July 2019.

10.1.2. Scientific Events: Selection

10.1.2.1. Chair of Conference Program Committees

- Konstantin Avrachenkov was the co-chair of the 16th Workshop on Algorithms and Models for the Web Graph (WAW 2019), University of Queensland, Brisbane, Australia, 6-7 July 2019.
- Konstantin Avrachenkov was the co-chair of the 9th EAI International Conference on Game Theory for Networks (GameNets 2019), Paris, France, April 25-26, 2019.

10.1.2.2. Member of the Conference Program Committees

- ACM Sigmetrics / IFIP Performance 2019 (Phoenix, Arizona, USA) (S. Alouf, K. Avrachenkov);
- ACM Sigmetrics 2020 (Boston, Massachusetts, USA) (S. Alouf);
- IEEE Intl. Conf. on Computer Communications (INFOCOM 2020, Beijing, China) (G. Neglia);
- 39th IEEE Intl. Conf. on Distributed Computing Systems (ICDCS 2019, Dallas, Texas, USA) (K. Avrachenkov);
- 27th IEEE Intl. Conf. on Network Protocols (ICNP 2019, Chicago, Illinois, USA) (K. Avrachenkov);
- 25th Intl. Conf. on Analytical & Stochastic Modelling Techniques & Applications (ASMTA 2019, Moscow, Russia) (K. Avrachenkov);
- 10th Conf. on Decision and Game Theory for Security (GameSec 2019, Stockholm, Sweden) (K. Avrachenkov);
- 8th Intl. Conf. on Complex Networks and their Applications (Lisbon, Portugal) (K. Avrachenkov);
- 26th Intl. Conf. on Telecommunications (ICT 2019, Hanoi, Vietnam) (K. Avrachenkov);
- SIAM Conf. on Control and Its Applications (CT19, Chengdu, China) (K. Avrachenkov);
- SIAM Intl. Conf. on Data Mining (SDM19, Calgary, Canada) (K. Avrachenkov);
- 20th Conf. of the Société Française de Recherche Opérationnelle et d'Aide à la Décision (ROADEF 2019, Le Havre, France) (A. Jean-Marie);
- 7th Symposium on Control, Automation, Industrial Informatics and Smart Grid (ICAIS'19, Trivandrum, Kerala, India) (K. Avrachenkov);
- 16th Intl. Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt 2019, Avignon, France) (K. Avrachenkov);
- 16th European Performance Engineering Workshop (EPEW2019, Milan, Italy) (A. Jean-Marie);
- IEEE INFOCOM Workshop on the Communications and Networking Aspects of Online Social Networks (CAOS'19, Paris, France), (G. Neglia);
- 21st Workshop on MAthematical performance Modeling and Analysis (MAMA 2019, Phoenix, USA) (A. Jean-Marie).

10.1.2.3. Reviewer

- 27th IEEE International Conference on Software Analysis, Evolution and Reengineering (SANER 2020, London, Canada) (A. Jean-Marie);
- Forum on Specification & Design Languages (FDL 2019, Southampton, UK) (S. Alouf).

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- *ACM Transactions on Modeling and Performance Evaluation of Computing Systems (ACM ToMPECS)* (K. Avrachenkov);
- *AIMS: Journal of Dynamic Games* (E. Altman);
- *Elsevier Computer Communications (COMCOM)* (G. Neglia);
- *Elsevier International Journal of Performance Evaluation (PEVA)* (K. Avrachenkov);
- *IEEE Transactions on Mobile Computing* (G. Neglia);
- Editor at large in *IEEE/ACM Transaction of Networking* (E. Altman);
- *Probability in the Engineering and Informational Sciences* (K. Avrachenkov);
- *Springer: Dynamic Games and Applications* (E. Altman);
- *Stochastic Models* (K. Avrachenkov);
- *Wiley Transactions on Emerging Telecommunications Technologies (ETT)* (S. Alouf).

10.1.3.2. Reviewer - Reviewing Activities

- *Dynamic Games And Applications* (A. Jean-Marie);
- *Elsevier Computer Networks* (G. Neglia);
- *Elsevier International Journal of Performance Evaluation* (PEVA) (S. Alouf);
- *EURO Journal on Computational Optimization* (A. Jean-Marie);
- *IEEE Internet of Things Journal* (C. Xu);
- *IEEE Networking Letters* (G. Neglia);
- *IEEE/ACM Transactions on Mobile Computing (TMC)* (G. Neglia);
- *IEEE/ACM Transactions on Networking (ToN)* (G. Neglia);
- *Journal of Economic Dynamics and Control* (A. Jean-Marie);
- *Theoretical Computer Science (TCS)* (A. Jean-Marie).

10.1.4. Tutorials, Invited Talks

- E. Altman gave a tutorial on “Network Games” at the Workshop on Network, population and congestion games (NPCG19) 17 April, Paris, France.
- G. Neglia gave an invited talk on “Machine Learning Training: Research Challenges and Opportunities for Distributed Computing” at the International Workshop on Distributed Cloud Computing (DCC), 18 October, Budapest, Hungary.
- C. Xu gave an invited talk on "Dynamic back up workers in distributed machine learning" at Sun Yat-sen University, September 3, Guangzhou, China.

10.1.5. Leadership within the Scientific Community

S. Alouf

- has been elected for two years at the Board of Directors of ACM SIGMETRICS.
- is a member of the Equality and Diversity committee of ACM SIGMETRICS.
- is a member of the Conference Advisory committee of ACM SIGMETRICS.

E. Altman

- is a fellow member of IEEE (Class of 2010).

– is a fellow member of EAI (Class of 2019)
– is an elected member of IFIP WG 7.3 on “Computer System Modeling”.
– is a member of WG 6.3 of IFIP on Performance of Communication Systems.

K. Avrachenkov

– is a member of the scientific committee for Labex UCN@Sophia;
– is a member of Conseil Scientifique & Pédagogique EUR DS4H Université Côte d’Azur;

A. Jean-Marie

– is a member of the Steering Committee of the GDR RO, a national research initiative on Operations Research sponsored by the CNRS;
– is an elected member of IFIP WG 7.3 on “Computer System Modeling”.

G. Neglia is member of the scientific animation committee for the IDEX UCA$^{\mathrm{JEDI}}$ research program “Social Interactions and Complex Dynamics” since 2017.

10.1.6. Scientific Expertise

Giovanni Neglia is a consultant for the startup Payback Network in the period November 2019 - January 2020. The consultancy is on differential privacy techniques.

10.1.7. Research Administration

S. Alouf

– is member of CLF, the training committee of Inria Sophia Antipolis Méditerranée, since November 2014;
– is vice-head of project-team NEO since January 2017.

K. Avrachenkov

– is responsible for the supervision and validation of the project-teams’ yearly activity reports since 2010;
– is a member of NICE, the Invited Researchers Committee of Inria Sophia Antipolis Méditerranée, since 2010.
– is a member of scientific and pedagogical committee for the graduate school DS4H of UCA.

A. Jean-Marie

– is the scientific coordinator of Inria activities in Montpellier (since 2008); as part of this duty, he represents Inria at: the Scientific Council of the Doctoral School “Sciences and Agrosciences” of the Univ of Avignon; at the Regional Conference of Research Organisms (CODOR);
– is member of the managing sub-committee of the Project-Team Committee of the Inria Sophia Antipolis – Méditerranée research center since December 2017;
– is Head of project-team NEO since January 2017.

G. Neglia

– is the scientific delegate for European partnerships for Inria Sophia Antipolis – Méditerranée since 2014;
– is member of the Inria COST GTRI (International Relations Working Group of Inria’s Scientific and Technological Orientation Council since 2016.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Note: UNS is the Univ Nice Sophia-Antipolis, UCA is the Univ Côte d’Azur.

Licence : M. Dreveton, “Tools for biology – Statistics”, 24H, L1 Life Sciences, UNS, France;

Master : S. Alouf, “Performance Evaluation of Networks”, 27H, M2 Ubinet, UCA, France;

Master : K. Avrachenkov, “Statistical Analysis of Graphs”, 6H, M2 Data Science, UCA, France;

Master : M. Dreveton, “Statistical Analysis of Graphs”, 26H, M2 Data Science, UCA, France;

Master : G. Neglia, “Distributed Optimization and Games”, 31.5H, M2 Ubinet, UNS, France;

Master : G. Neglia, “Performance Evaluation of Networks”, 4.5H, M2 Ubinet, UCA, France;

Master : G. Neglia, responsible for the “Winter School on Hands-on Machine Learning”, 22.5H, M1 Computer Science, UNS, France.

Doctorat: A. Jean-Marie, “Queueing Systems”, 6H, Summer School ResCom 2019, Anglet, France.

10.2.2. Supervision

PhD: Zaid Allybokus, “Scalable Online Algorithms for SDN Controllers”, UCA, 11 June 2019, advisors: Konstantin Avrachenkov, Jeremie Leguay and Lorenzo Maggi (Huawei).

PhD: Dimitra Politaki, “Greening data center”, UCA, 16 July 2019, advisors: Sara Alouf and Fabien Hermenier (Nutanix).

PhD in progress: Mandar Datar, “Singular perturbation approach for machine learning in multiobjective optimisation”, Univ Avignon, 1 May 2018, advisor: Eitan Altman.

PhD in progress: Maximilien Dreveton, “Statistical Physics Methods for Distributed Machine Learning”, UCA, 1 Oct. 2018, advisor: Konstantin Avrachenkov.

PhD in progress: Guilherme Iecker Ricardo, “Caching for wireless networks”, UCA, 1 Sept. 2018, advisors: Giovanni Neglia and Pietro Elia (EURECOM).

PhD in progress: Mikhail Kamalov, “Semi-supervised variational autoencoders versatile data”, UCA, 1 June 2019, advisor: Konstantin Avrachenkov.

PhD in progress: Marie Masson, “Fonctionnalités auto-organisantes dans le réseau d’accès radio 5G virtuels”, UCA, 1 Dec. 2017, advisors: Eitan Altman and Zwi Altman (Orange).

PhD in progress: Tareq Si Salem, “Federated Learning”, UCA, 1 October 2019, advisor: Giovanni Neglia.

PhD interrupted: Abhishek Bose, “Adaptive crawling with machine learning techniques”, 1 June 2018 – 30 Sep. 2029.

10.2.3. Juries

NEO members participated in the Ph.D. committees of (in alphabetical order):

- Zaid Allybokus, “Scalable Online Algorithms for SDN Controllers”, UCA, 11 June (K. Avrachenkov as advisor);
- Lea Bayati, “Data Centers Energy Optimization”, Univ Paris-Est Créteil, 20 September (A. Jean-Marie as reviewer);
- Céline Comte, “Resource management in computer clusters: algorithm design and performance analysis”, Telecom ParisTech, 24 September (A. Jean-Marie as jury president);
- Muhammad Jawad Khokhar, “Modeling Quality of Experience of Internet Video Streaming by Controlled Experimentation and Machine Learning”, UCA, 15 October (G. Neglia as jury member)
- Xiaoyi Mai, “Methods of random matrices for large dimensional statistical learning”, CentraleSupelec, 16 October (K. Avrachenkov as jury member);
- Antonio Massaro, “Optimisation, games and learning strategies in telecommunication systems subject to structural constraints”, University of Trento, 7 May (K. Avrachenkov as reviewer);
- Dimitra Politaki, “Greening data center”, UCA, 16 July (S. Alouf as advisor);
- Yonathan Portilla, Univ Avignon, “Study of Social Networks: modelling and analysis”, 20 May (E. Altman as co-advisor);
- Arthur Vallet, “Modélisation markovienne de lasers multimodes à semiconducteurs”, Université de Montpellier, 15 October (A. Jean-Marie as jury member).

10.3. Popularization

10.3.1. Interventions

- Sara Alouf presented the Researcher profession at the *Forum des Métiers*, Collège Emile Roux, Le Cannet, on 15 March 2019, to a total of 62 students in 6 groups, aging 12-14 years.

11. Bibliography

Major publications by the team in recent years

[1] K. AVRACHENKOV, V. S. BORKAR.*Whittle Index Policy for Crawling Ephemeral Content*, in "IEEE Transactions on Control of Network Systems", March 2018, vol. 5, n^{o} 1, p. 446-455 [*DOI :* 10.1109/TCNS.2016.2619066], https://hal.inria.fr/hal-01937994

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Publications of the year

Doctoral Dissertations and Habilitation Theses

[9] Z. ALLYBOKUS.*Real-Time Scalable Algorithms for Alpha-Fair Resource Allocation in Software Defined Networks*, Universié Côte d'Azur, 2019

[10] D. POLITAKI.*On Modeling Green Data Center Clusters*, Universié Côte d'Azur, 2019

Articles in International Peer-Reviewed Journal

[11] E. ALTMAN, D. MENASCHÉ, A. REIFFERS-MASSON, M. DATAR, S. DHAMAL, C. TOUATI, R. EL-AZOUZI.*Blockchain competition between miners: a game theoretic perspective*, in "Frontiers in Blockchain", 2019, forthcoming [*DOI :* 10.3389/FBLOC.2019.00026], https://hal.inria.fr/hal-02411738

[12] K. AVRACHENKOV, V. S. BORKAR.*Metastability in Stochastic Replicator Dynamics*, in "Dynamic Games and Applications", June 2019, vol. 9, n^o 2, p. 366-390 [*DOI :* 10.1007/S13235-018-0265-7], https://hal.inria.fr/hal-02398561

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Project-Team STAMP

Safety Techniques based on Formalized Mathematical Proofs

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Proofs and Verification

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Project-Team STAMP

Creation of the Project-Team: 2019 November 01

Keywords:

Computer Science and Digital Science:

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A2.4.3. - Proofs
A4.5. - Formal methods for security
A5.10.3. - Planning
A7.2. - Logic in Computer Science
A7.2.3. - Interactive Theorem Proving
A7.2.4. - Mechanized Formalization of Mathematics
A8.3. - Geometry, Topology
A8.4. - Computer Algebra
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Other Research Topics and Application Domains:

B6.1. - Software industry
B9.5.1. - Computer science
B9.5.2. - Mathematics

1. Team, Visitors, External Collaborators

Research Scientists

Yves Bertot [Team leader, Inria, Senior Researcher, HDR]
Cyril Cohen [Inria, Researcher]
Benjamin Grégoire [Inria, Researcher]
José Grimm [Inria, Researcher, until September 2019 (deceased)]
Laurence Rideau [Inria, Researcher]
Enrico Tassi [Inria, Researcher]
Laurent Théry [Inria, Researcher]

External Collaborators

Gilles Barthe [Max Planck Institute, Bochum, Germany, HDR]
Loïc Pottier [Ministère de l'Education Nationale, HDR]

PhD Students

Cécile Baritel-Ruet [Inria, PhD Student]
Sophie Bernard [Univ de Nice - Sophia Antipolis, PhD Student, until Sep 2019]
Mohamad El Laz [Inria, PhD Student]
Damien Rouhling [Ministère de l'Enseignement Supérieur et de la Recherche, PhD Student, until Sep 2019]

Post-Doctoral Fellow

Pierre Boutry [Inria, Post-Doctoral Fellow, from Sep 2019]

Visiting Scientists

Reynald Affeldt [AIST, Japan, from Oct 2019]
Manuel Barbosa [University of Porto, from Jun 2019 until Jul 2019]
Christian Doczkal [Univ. Côte d'Azur, from Oct 2019]
Kazuhiko Sakaguchi [University of Tsukuba, Japan]

Administrative Assistant
Nathalie Bellesso [Inria, Administrative Assistant]

2. Overall Objectives

2.1. Overall Objectives

Computers and programs running on these computers are powerful tools for many domains of human activities. In some of these domains, program errors can have enormous consequences. It will become crucial for all stakeholders that the best techniques are used when designing these programs.

We advocate using higher-order logic proof assistants as tools to obtain better quality programs and designs. These tools make it possible to build designs where all decisive arguments are explicit, ambiguity is alleviated, and logical steps can be verified precisely. In practice, we are intensive users of the Coq system and we participate actively to the development of this tool, in collaboration with other teams at Inria, and we also take an active part in advocating its usage by academics and industrial users around the world.

Many domains of modern computer science and engineering make a heavy use of mathematics. If we wish to use proof assistants to avoid errors in designs, we need to develop corpora of formally verified mathematics that are adapted to these domains. Developing libraries of formally verified mathematics is the main motivation for our research. In these libraries, we wish to capture not only the knowledge that is usualy recorded in definitions and theorems, but also the practical knowledge that is recorded in mathematical practice, idoms, and work habits. Thus, we are interested in logical facts, algorithms, and notation habits. Also, the very process of developing an ambitious library is a matter of organisation, with design decisions that need to be evaluated and improved. Refactoring of libraries is also an important topic. Among all higher-order logic based proof assistants, we contend that those based on Type theory are the best suited for this work on libraries, thanks to to they strong capabilities for abstraction and modular re-use.

The interface between mathematics, computer science and engineering is large. To focus our activities, we will concentrate our activity on applications of proof assistants to two main domains: cryptography and robotics. We also develop specific tools for proofs in cryptography, mainly around a proof tool named EasyCrypt.

3. Research Program

3.1. Theoretical background

The proof assistants that we consider provide both a programming language, where users can describe algorithms performing tasks in their domain of interest, and a logical language to reason about the programs, thus making it possible to ensure that the algorithms do solve the problems for which they were designed. trustability is gained because algorithms and logical statements provide multiple views of the same topic, thus making it possible to detect errors coming from mismatch between expected and established properties. The verification process is itself a logical process, where the computer can bring rigor in aligning expectations and guarantees.

The foundations of proof assistants rest on the very foundations of mathematics. As a consequence, all aspects of reasoning must be made completely explicit in the process of formally verifying an algorithm. All aspects of the formal verification of an algorithm are expressed in a discourse whose consistency is verified by the computer, so that unclear or intuitive arguments need to be replaced by precise logical inferences.

One of the foundational features on which we rely extensively is *Type Theory*. In this approach a very simple programming language is equiped with a powerful discipline to check the consistency of usage: types represent sets of data with similar behavior, functions represent algorithms mapping types to other types, and the consistency can be verified by a simple computer program, a *type-checker*. Although they can be verified by a simple program, types can express arbitrary complex objects or properties, so that the verification work lives in an interesting realm, where verifying proofs is decidable, but finding the proofs is undecidable.

This process for producing new algorithms and theorems is a novelty in the development of mathematical knowledge or algorithms, and new working methods must be devised for it to become a productive approach to high quality software development. Questions that arise are numerous. How do we avoid requiring human assistance to work on mundane aspects of proofs? How do we take advantage of all the progress made in automatic theorem proving? How do we organize the maintenance of ambitious corpora of formally verified knowledge in the long term?

To acquire hands-on expertise, we concentrate our activity on three aspects. The first one is foundational: we develop and maintain a library of mathematical facts that covers many aspects of algebra. In the past, we applied this library to proofs in group theory, but it is increasingly used for many different areas of mathematics and by other teams around the world, from combinatorics to elliptic cryptography, for instance. The second aspect is applicative: we develop a specific tool for proofs in cryptography, where we need to reason on the probability that opponents manage to access information we wish to protect. For this activity, we develop a specific proof system, relying on a wider set of automatic tools, with the objective of finding the tools that are well adapted to this domain and to attract users that are initially specialists in cryptography but not in formal verification. The third domain is robotics, as we believe that the current trend towards more an more autonomous robots and vehicles will raise questions of safety and trustability where formal verification can bring significant added value.

4. Application Domains

4.1. Mathematical Components

The Mathematical Components is the main by-product of an effort started almost two decades ago to provide a formally verified proof for a major theorem in group theory. Because this major theorem had a proof published in books of several hundreds of pages, with elements coming from character theory, other coming from algebra, and some coming from real analysis, it was an exercice in building a large library, with results in many domains, and in establishing clear guidelines for further increase and data search.

This library has proved to be a useful repository of mathematical facts for a wide area of applications, so that it has a growing community of users in many contries (Denmark, France, Germany, Japan, Singapore, Spain, Sweden, UK, USA, at the time of writing these lines in 2019) and for a wide variety of topics (transcendental number theory, elliptic curve cryptography, articulated robot kinematics, recently block chain foundations).

Interesting questions on this library range around the importance of decidability and proof irrelevance, the way to structure knowledge to automatically inherit theorems from one topic to another, the way to generate infrastructure to make this automation efficient and predictable. In particular, we want to concentrate on adding a new mathematical topic to this library: real analysis and then complex analysis (Mathematical Components Analysis).

On the front of automation, we are convinced that a higher level language is required to describe similarities between theories, to generate theorems that are immediate consequences of structures, etc, and for this reason, we invest in the development of a new language on top of the proof assistant (ELPI).

4.2. Proofs in cryptography

When we work on cryptography, we are interested in the formal verification of proofs showing that some cryptographic primitives provide good guarantees against unwanted access to information. Over the years we have developed a technique for this kind of reasoning that relies on a programing logic (close to Hoare logic) with probabilistic apsects and the capability to establish relations between several implementations of a problem. The resulting programming logic is called *probabilistic relational Hoare logic*. In more recent work, we have also started to study questions of *side-channel* attacks, where we wish to guarantee that opponents cannot gain access to protected knowledge, even if they observe specific features of execution, like execution time (to which the answer lies in *constant-time* execution) or partial access to memory bits (to which the answer lies in *masking*).

For this domain of application, we choose to work with a specific proof tool (EasyCrypt), which combines powerful first-order reasoning and uses of automatic tools, with a specific support for probabilistic relational Hoare Logic. The development of this EasyCrypt proof tool is one of the objectives of our team.

When it comes to formal proofs of resistance to side-channel attack, we contend that it is necessary to verify formally that the compiler used in the production of actually running code respects the resistance properties that were established in formally verified proofs. One of our objectives is to describe such a compiler (Jasmin) and show its strength on a variety of applications.

4.3. Proofs for robotics

Robots are man-made artifacts where numerous design decisions can be argued based on logical or mathematical principles. For this reason, we wish to use this domain of application as a focus for our investigations. The questions for which we are close to providing answers involve precision issues in numeric computation, obstacle avoidance and motion planning (including questions of graph theory), articulated limb cinematics and dynamics, and balance and active control.

From the mathematical perspective, these topics require that we improve our library to cover real algebraic geometry, computational geometry, real analysis, graph theory, and refinement relations between abstract algorithms and executable programs.

In the long run, we hope to exhibit robots where pieces of software and part of the design has been subject to formal verification.

5. New Software and Platforms

5.1. Coq

The Coq Proof Assistant

KEYWORDS: Proof - Certification - Formalisation

SCIENTIFIC DESCRIPTION: Coq is an interactive proof assistant based on the Calculus of (Co-)Inductive Constructions, extended with universe polymorphism. This type theory features inductive and co-inductive families, an impredicative sort and a hierarchy of predicative universes, making it a very expressive logic. The calculus allows to formalize both general mathematics and computer programs, ranging from theories of finite structures to abstract algebra and categories to programming language metatheory and compiler verification. Coq is organised as a (relatively small) kernel including efficient conversion tests on which are built a set of higher-level layers: a powerful proof engine and unification algorithm, various tactics/decision procedures, a transactional document model and, at the very top an IDE.

FUNCTIONAL DESCRIPTION: Coq provides both a dependently-typed functional programming language and a logical formalism, which, altogether, support the formalisation of mathematical theories and the specification and certification of properties of programs. Coq also provides a large and extensible set of automatic or semi-automatic proof methods. Coq's programs are extractible to OCaml, Haskell, Scheme, ...

RELEASE FUNCTIONAL DESCRIPTION: Coq version 8.10 contains two major new features: support for a native fixed-precision integer type and a new sort SProp of strict propositions. It is also the result of refinements and stabilization of previous features, deprecations or removals of deprecated features, cleanups of the internals of the system and API, and many documentation improvements. This release includes many user-visible changes, including deprecations that are documented in the next subsection, and new features that are documented in the reference manual.

Version 8.10 is the fifth release of Coq developed on a time-based development cycle. Its development spanned 6 months from the release of Coq 8.9. Vincent Laporte is the release manager and maintainer of this release. This release is the result of 2500 commits and 650 PRs merged, closing 150+ issues.

See the Zenodo citation for more information on this release: https://zenodo.org/record/3476303#.Xe54f5NKjOQ

NEWS OF THE YEAR: Coq 8.10.0 contains:

- some quality-of-life bug fixes,

- a critical bug fix related to template polymorphism,

- native 63-bit machine integers,

- a new sort of definitionally proof-irrelevant propositions: SProp,

- private universes for opaque polymorphic constants,

- string notations and numeral notations,

- a new simplex-based proof engine for the tactics lia, nia, lra and nra,

- new introduction patterns for SSReflect,

- a tactic to rewrite under binders: under,

- easy input of non-ASCII symbols in CoqIDE, which now uses GTK3.

All details can be found in the user manual.

- Participants: Yves Bertot, Frédéric Besson, Maxime Denes, Emilio Jesús Gallego Arias, Gaëtan Gilbert, Jason Gross, Hugo Herbelin, Assia Mahboubi, Érik Martin-Dorel, Guillaume Melquiond, Pierre-Marie Pédrot, Michael Soegtrop, Matthieu Sozeau, Enrico Tassi, Laurent Théry, Théo Zimmermann, Theo Winterhalter, Vincent Laporte, Arthur Charguéraud, Cyril Cohen, Christian Doczkal and Chantal Keller
- Partners: CNRS - Université Paris-Sud - ENS Lyon - Université Paris-Diderot
- Contact: Matthieu Sozeau
- URL: http://coq.inria.fr/

5.2. Math-Components

Mathematical Components library

KEYWORD: Proof assistant

FUNCTIONAL DESCRIPTION: The Mathematical Components library is a set of Coq libraries that cover the prerequiste for the mechanization of the proof of the Odd Order Theorem.

RELEASE FUNCTIONAL DESCRIPTION: This releases is compatible with Coq 8.9 and Coq 8.10 it adds many theorems for finite function, prime numbers, sequences, finite types, bigo operations, natural numbers, cycles in graphs.

- Participants: Alexey Solovyev, Andrea Asperti, Assia Mahboubi, Cyril Cohen, Enrico Tassi, François Garillot, Georges Gonthier, Ioana Pasca, Jeremy Avigad, Laurence Rideau, Laurent Théry, Russell O'Connor, Sidi Ould Biha, Stéphane Le Roux and Yves Bertot
- Contact: Assia Mahboubi
- URL: http://math-comp.github.io/math-comp/

5.3. Semantics

KEYWORDS: Semantic - Programming language - Coq

FUNCTIONAL DESCRIPTION: A didactical Coq development to introduce various semantics styles. Shows how to derive an interpreter, a verifier, or a program analyser from formal descriptions, and how to prove their consistency.

This is a library for the Coq system, where the description of a toy programming language is presented. The value of this library is that it can be re-used in classrooms to teach programming language semantics or the Coq system. The topics covered include introductory notions to domain theory, pre and post-conditions, abstract interpretation, and the proofs of consistency between all these point of views on the same programming language. Standalone tools for the object programming language can be derived from this development.

- Participants: Christine Paulin and Yves Bertot
- Contact: Yves Bertot
- URL: http://www-sop.inria.fr/members/Yves.Bertot/proofs/semantics_survey.tgz

5.4. Easycrypt

KEYWORDS: Proof assistant - Cryptography

FUNCTIONAL DESCRIPTION: EasyCrypt is a toolset for reasoning about relational properties of probabilistic computations with adversarial code. Its main application is the construction and verification of game-based cryptographic proofs. EasyCrypt can also be used for reasoning about differential privacy.

- Participants: Benjamin Grégoire, Gilles Barthe and Pierre-Yves Strub
- Contact: Gilles Barthe
- URL: https://www.easycrypt.info/trac/

5.5. ELPI

Embeddable Lambda Prolog Interpreter

KEYWORDS: Constraint Programming - Programming language - Higher-order logic

SCIENTIFIC DESCRIPTION: The programming language has the following features

- Native support for variable binding and substitution, via an Higher Order Abstract Syntax (HOAS) embedding of the object language. The programmer needs not to care about De Bruijn indexes.

- Native support for hypothetical context. When moving under a binder one can attach to the bound variable extra information that is collected when the variable gets out of scope. For example when writing a type-checker the programmer needs not to care about managing the typing context.

- Native support for higher order unification variables, again via HOAS. Unification variables of the meta-language (lambdaProlog) can be reused to represent the unification variables of the object language. The programmer does not need to care about the unification-variable assignment map and cannot assign to a unification variable a term containing variables out of scope, or build a circular assignment.

- Native support for syntactic constraints and their meta-level handling rules. The generative semantics of Prolog can be disabled by turning a goal into a syntactic constraint (suspended goal). A syntactic constraint is resumed as soon as relevant variables gets assigned. Syntactic constraints can be manipulated by constraint handling rules (CHR).

- Native support for backtracking. To ease implementation of search.

- The constraint store is extensible. The host application can declare non-syntactic constraints and use custom constraint solvers to check their consistency.

- Clauses are graftable. The user is free to extend an existing program by inserting/removing clauses, both at runtime (using implication) and at "compilation" time by accumulating files.

Most of these feature come with lambdaProlog. Constraints and propagation rules are novel in ELPI.

FUNCTIONAL DESCRIPTION: ELPI implements a variant of lambdaProlog enriched with Constraint Handling Rules, a programming language well suited to manipulate syntax trees with binders and unification variables.

ELPI is a research project aimed at providing a programming platform for the so called elaborator component of an interactive theorem prover.

ELPI is designed to be embedded into larger applications written in OCaml as an extension language. It comes with an API to drive the interpreter and with an FFI for defining built-in predicates and data types, as well as quotations and similar goodies that come in handy to adapt the language to the host application.

RELEASE FUNCTIONAL DESCRIPTION: improvement to the parser (parsing negative numbers) improvement to the foreign function interface (accepting ternary comparison, instead of equality) adds ternary comparisons to the standard library provides a builtin comparison cmp_term provides a builtin to check whether a term is ground

NEWS OF THE YEAR: There were 7 releases in 2019. Work done mostly in these areas:

- consolidation (documentation, bug fixes, test suits)

- API and FFI (making it easier to export host applications to ELPI)

- standard library

- Participant: Claudio Sacerdoti Coen
- Contact: Enrico Tassi
- Publications: ELPI: fast, Embeddable, λProlog Interpreter - Implementing Type Theory in Higher Order Constraint Logic Programming - Deriving proved equality tests in Coq-elpi: Stronger induction principles for containers in Coq
- URL: https://github.com/lpcic/elpi/

5.6. Coq-elpi

KEYWORDS: Metaprogramming - Extension

SCIENTIFIC DESCRIPTION: Coq-elpi provides a Coq plugin that embeds ELPI. It also provides a way to embed Coq's terms into lambdaProlog using the Higher-Order Abstract Syntax approach (HOAS) and a way to read terms back. In addition to that it exports to ELPI a set of Coq's primitives, e.g. printing a message, accessing the environment of theorems and data types, defining a new constant and so on. For convenience it also provides a quotation and anti-quotation for Coq's syntax in lambdaProlog. E.g. {{nat}} is expanded to the type name of natural numbers, or {{A -> B}} to the representation of a product by unfolding the -> notation. Finally it provides a way to define new vernacular commands and new tactics.

FUNCTIONAL DESCRIPTION: Coq plugin embedding ELPI

RELEASE FUNCTIONAL DESCRIPTION: Minor relase for extra API for global reference data types

NEWS OF THE YEAR: Releases 1.0, 1.1, and 1.2 were made in 2019, they constitute the first public release with tutorials and examples.

Work done in 2019 is mostly in these areas:

- expose a complete set of API to script Coq's vernacular language

- take advantage or recent ELPI API and FFI to convert back and forth terms containing existential variables (Evars)

- Contact: Enrico Tassi
- Publications: Deriving proved equality tests in Coq-elpi: Stronger induction principles for containers in Coq - Elpi: an extension language for Coq (Metaprogramming Coq in the Elpi λProlog dialect)

5.7. AutoGnP

KEYWORDS: Formal methods - Security - Cryptography

FUNCTIONAL DESCRIPTION: autoGnP is an automated tool for analyzing the security of padding-based public-key encryption schemes (i.e. schemes built from trapdoor permutations and hash functions). This years we extended the tool to be able to deal with schemes based on cyclic groups and bilinear maps.

- Participants: Benjamin Grégoire, Gilles Barthe and Pierre-Yves Strub
- Contact: Gilles Barthe
- URL: https://github.com/ZooCrypt/AutoGnP

5.8. MaskComp

KEYWORD: Masking

FUNCTIONAL DESCRIPTION: MaskComp is a compiler generating masked implémentation protected against side channel attack based on differential power analysis. It take a unmasked program in a syntaxe close to C and generate a new C protected program. We did not claim that the generate C program will be secure after compilation (C compiler can break protection), but it provide a good support for generating masked implementation.

- Contact: Benjamin Grégoire
- URL: https://sites.google.com/site/maskingcompiler/home

5.9. Jasmin

Jasmin compiler and analyser

KEYWORDS: Cryptography - Static analysis - Compilers

FUNCTIONAL DESCRIPTION: Analysing the execution time of a cryptographic code can be a way to discover the secret protected by this code. To avoid this pitfall, Jasmin proposes a high-level language and an analyzer for this language that makes it possible to predict when the execution of this code will happen in constant time and thus does not unveil the secret (for instance, the cryptographic key). Once the Jasmin code is valid with respect to the analyzer, the compiler produces assembly code that still preserves this property of constant time.

- Contact: Benjamin Grégoire

5.10. MaskVerif

KEYWORDS: Masking - Hardware and Software Platform

FUNCTIONAL DESCRIPTION: MaskVerif is a tool to verify the security of implementations protected against side channel attacks, in particular differential power analysis. It allows to check different security notions in the probing model: - Probing security - Non Interference - Strong Non Interference. The tool is able to analyse software implementations and hardware implementations (written in Verilog). It can prove the different security notions in presence of glitch or transition.

- Contact: Benjamin Grégoire
- URL: https://sites.google.com/view/maskverif/home

5.11. CoqEAL

The Coq Effective Algebra Library

KEYWORD: Proof assistant

FUNCTIONAL DESCRIPTION: This library contains formal developments in algebra and optimized algorithms on mathcomp data structures and a framework to ease change of data representation during a proof.

RELEASE FUNCTIONAL DESCRIPTION: First release

- Contact: Cyril Cohen

5.12. math-comp-analysis

Mathematical Components Analysis

KEYWORD: Proof assistant

FUNCTIONAL DESCRIPTION: This library adds definitions and theorems for real numbers and their mathematical structures

RELEASE FUNCTIONAL DESCRIPTION: Compatible with mathcomp 1.8.0, 1.9.0, and 1.10.0

NEWS OF THE YEAR: In 2019, there were 3 releases.

- Partners: Ecole Polytechnique - AIST Tsukuba
- Contact: Cyril Cohen
- Publication: Formalization Techniques for Asymptotic Reasoning in Classical Analysis
- URL: https://github.com/math-comp/analysis

5.13. math-comp-finmap

Finite maps and ordered types library

KEYWORD: Proof assistant

FUNCTIONAL DESCRIPTION: Support for reasoning about finite maps and ordered types

RELEASE FUNCTIONAL DESCRIPTION: This release is solely an update of order.v and set.v in order to integrate the changes in math-comp/math-comp#270

- Contact: Cyril Cohen

5.14. math-comp-real-closed

Real Closed Fields

KEYWORD: Proof assistant

FUNCTIONAL DESCRIPTION: Theorems for real closed fields

RELEASE FUNCTIONAL DESCRIPTION: First release

- Contact: Cyril Cohen
- URL: https://github.com/math-comp/real-closed

6. New Results

6.1. Hol-Light and Elpi

Participants: Enrico Tassi, Marco Maggesi [University of Florence, Italy].

We implemented an elaborator for HOL-Light in Elpi. In particular the new elaborator supports coercions and overloaded notations for algebraic structures.

6.2. Generating equality tests for inductive types

Participant: Enrico Tassi.

We show how to derive in a modular fashion equality tests for a wide variety of inductive type definitions. This makes an instrumental use of parametricity. This work has been published in an international conference [10]. This is also an interesting case study for the Elpi language [2].

6.3. Re-designing the state machine of Coq

Participants: Enrico Tassi, Maxime Dénès.

We redesigned the state machine of Coq to improve its support for LSP-based user interfaces [0]. In particular, we decoupled the representation of the document as seen by the User-Interface and the structured document as used by the STM to decide what to compute and how (in which order).

6.4. Formal proofs on session types

Participants: Enrico Tassi, Cinzia Di Giusto [University of Nice], Marco Giunti [New University of Lisbon], Kirstin Peters [University of Darmstadt], Antonio Ravara [New University of Lisbon].

We formalized in Coq and Isabelle a linear, monadic Pi calculus, its labelled transition system, and type system. We proved the properties of subject reduction and absence of linearity violation. These are based on De Bruijn levels and Nominals with the objective of comparing the approaches and provide automation for recurrent goals. This is done in Project PROSE (Provers for Sessions).

6.5. Formal proofs of an axiomatization of graphs with tree-width two

Participants: Christian Doczkal, Damien Pous [CNRS, ENS de lyon].

We finished the formalization of a completeness proof for an axiomatization of graphs of treewidth at most two in Coq+MathComp. This work was submitted for publication in a conference [11]. We are also revising the article presenting our proof of the Minor-Exclusion property for Treewidth-Two graphs [15] for publication in a journal. Most of the formal proofs are available from the following web-site https://perso.ens-lyon.fr/damien.pous/covece/graphs/.

6.6. Formal study of double-word arithmetic algorithms

Participants: Laurence Rideau, Jean-Michel Muller [CNRS, ENS de Lyon].

We finished the formalization of double-word arithmetic algorithms, described in the article *Tight and rigourous error bounds for basic building blocks of double-word arithmetic* [16].

Thanks to the formalization, errors were found in the proofs, but the stated results (correction of algorithms and error limits) were proven correct. On the other hand, for the purposes of this formalization, we had to develop a more general version of the proof of the Fast2Sum algorithm, which should soon be integrated into the Flocq library.

An article describing this work of formalisation is being written.

6.7. Approximations using Chebyshev polynomials

Participants: Laurent Théry, Florian Steinberg [Inria Saclay, Toccata project-team].

Florian Steinberg and Laurent Théry have been working on polynomial approximations using Chebyshev polynomials. This works has been presented at the ANR FastRelax final meeting (Lyon, June 2019) and is available as a library at https://github.com/FlorianSteinberg/Cheby.

6.8. Formalizing computational analysis

Participants: Laurent Théry, Florian Steinberg [Inria Saclay, Toccata project-team], Holger Thies [Kyushu University, Fukuoka].

Florian Steinberg, Holger Thies, and Laurent Théry have been working on formalizing computational analysis. This work is described in a paper to be submitted for publication [13]. A shorter version was published in a conference [9].

[0] LSP stands for Language Server Protocol

6.9. Formal study of probabilistic programs

Participants: Cécile Baritel-Ruet, Benjamin Grégoire, José Bacelar Almeida [INESC TEC], Manuel Barbosa [INESC TEC], Gilles Barthe [IMDEA], Sonia Belaïd [CryptoExpert], Matthew Campagna [AWS], Gaëtan Cassiers [UCL], Sunjay Cauligi [UC San Diego], Ernie Cohen [AWS], François Dupressoir [University of Surrey], Pierre-Alain Fouque [Université Rennes 1], Charlie Jacomme [LSV], Steve Kremer [Inria Nancy Grand-Est, PESTO project Team], Adrien Koutsos [LSV], Vincent Laporte [Inria], Tiago Oliveira [INESC TEC], Vitor Pereira [INESC TEC], Bernardo Portela [INESC TEC], Alley Stoughton [Boston University], François-Xavier Standaert [UCL], Deian Stefan [UC San Diego], Pierre-Yves Strub [Ecole Polytechnique], Serdar Tasiran [AWS].

We provide two differents tools:

- EasyCrypt (see http://www.easycrypt.info/) is a toolset for reasoning about relational properties of probabilistic computations with adversarial code. Its main application is the construction and verification of game-based cryptographic proofs.
- Jasmin (see https://github.com/jasmin-lang/jasmin) is certified compiler to generate high-speed and high-assurance cryptographic code.

6.10. Security of a key management service

Participants: Benjamin Grégoire, José Bacelar Almeida [INESC TEC], Manuel Barbosa [INESC TEC], Gilles Barthe [IMDEA], Matthew Campagna [AWS], Vitor Pereira [INESC TEC], Bernardo Portela [INESC TEC], Pierre-Yves Strub [Ecole Polytechnique], Serdar Tasiran [AWS].

We have developed a machine-checked proof of security for the domain management protocol of Amazon Web Services' KMS (Key Management Service) a critical security service used throughout AWS and by AWS customers. Domain management is at the core of AWS KMS; it governs the toplevel keys that anchor the security of encryption services at AWS. We show that the protocol securely implements an ideal distributed encryption mechanism under standard cryptographic assumptions. The proof is machine-checked in the EasyCrypt proof assistant and is the largest EasyCrypt development to date. This work corresponds to a contract with AWS and has been published in a major computer security conference [3].

6.11. High-assurance and high-speed SHA-3

Participants: Cécile Baritel-Ruet, Benjamin Grégoire, José Bacelar Almeida [INESC TEC], Manuel Barbosa [INESC TEC], Gilles Barthe [IMDEA], François Dupressoir [University of Surrey], Vincent Laporte [Inria], Tiago Oliveira [INESC TEC], Alley Stoughton [Boston University], Pierre-Yves Strub [Ecole Polytechnique].

We have developed a high-assurance and high-speed implementation of the SHA-3 hash function. Our implementation is written in the Jasmin programming language, and is formally verified for functional correctness, provable security and timing attack resistance in the EasyCrypt proof assistant. Our implementation is the first to achieve simultaneously the four desirable properties (efficiency, correctness, provable security, and side-channel protection) for a non-trivial cryptographic primitive. Concretely, our mechanized proofs show that:

1. The SHA-3 hash function is indifferentiable from a random oracle, and thus is resistant against collision, first and second preimage attacks;
2. The SHA-3 hash function is correctly implemented by a vectorized x86 implementation.

Furthermore, the implementation is provably protected against timing attacks in an idealized model of timing leaks. The proofs include new EasyCrypt libraries of independent interest for programmable random oracles and modular indifferentiability proofs. This work has been published at an international conference [4].

6.12. A domain-specific language for timing sensitive computation

Participants: Benjamin Grégoire, Sunjay Cauligi [UC San Diego], Gilles Barthe [IMDEA], Deian Stefan [UC San Diego].

Real-world cryptographic code is often written in a subset of C intended to execute in constant-time, thereby avoiding timing side channel vulnerabilities. This C subset eschews structured programming as we know it: if-statements, looping constructs, and procedural abstractions can leak timing information when handling sensitive data. The resulting obfuscation has led to subtle bugs, even in widely-used high profile libraries like OpenSSL. To address the challenge of writing constant-time cryptographic code, we have participate to the development of FaCT, a crypto DSL that provides high-level but safe language constructs. The FaCT compiler uses a secrecy type system to automatically transform potentially timing-sensitive high-level code into low-level, constant-time LLVM bitcode. While the language and the type system has been developed by our collaborator, we have formalized the constant-time transformation. We have performed an empirical evaluation that uses FaCT to implement core crypto routines from several open-source projects including OpenSSL, libsodium, and curve25519-donna. Our evaluation shows that FaCT's design makes it possible to write readable, high-level cryptographic code, with efficient, constant-time behavior. This work has been published at an international conference [7].

6.13. Proving equivalence between probabilistic programs

Participants: Benjamin Grégoire, Gilles Barthe [IMDEA], Steve Kremer [Inria Nancy Grand-Est, PESTO project Team], Pierre-Yves Strub [Ecole Polytechnique].

We have developed principled methods for proving equivalence between probabilistic programs that operate over finite fields and related algebraic structures. We have focused on three essential properties: program equivalence, information flow, and uniformity. We give characterizations of these properties based on deducibility and other notions from symbolic cryptography. We use (sometimes improve) tools from symbolic cryptography to obtain decision procedures or sound proof methods for program equivalence, information flow, and uniformity. A partial implementation of our approach is integrated in EasyCrypt and in MaskVerif. This work has been published at an international conference [6].

6.14. MaskVerif: automated verification of higher-order masking in presence of physical defaults

Participants: Benjamin Grégoire, Gilles Barthe [IMDEA], Sonia Belaïd [CryptoExpert], Gaëtan Cassiers [UCL], Pierre-Alain Fouque [Université Rennes 1], François-Xavier Standaert [UCL].

Power and electromagnetic based side-channel attacks are serious threats against the security of cryptographic embedded devices. In order to mitigate these attacks, implementations use countermeasures, among which masking is currently the most investigated and deployed choice. Unfortunately, commonly studied forms of masking rely on underlying assumptions that are difficult to satisfy in practice. This is due to physical defaults, such as glitches or transitions, which can recombine the masked data in a way that concretely reduces an implementation's security. We have developed and implemented an automated approach for verifying security of masked implementations in presence of physical defaults (glitches or transitions). Our approach helps to recover the main strengths of masking: rigorous foundations, composability guarantees, automated verification under more realistic assumptions. This work contributes to demonstrate the benefits of language-based approaches (specifically probabilistic information flow) for masking. This work was published at an international conference [5].

6.15. Frame type theory

Participants: Cyril Cohen, Assia Mahboubi [Inria Rennes Bretagne Atlantique, Gallinette project-team], Xavier Montillet [University of Nantes].

Writing modular programs in proof assistants is notoriously difficult. A significant literature and implementation effort is devoted to the topic, with approaches ranging from adding new constructions to the underlying logic, to adding features to the proof assistant. However, all current options (including records, sections and modules) are unsatisfactory in one way or another. In this work in progress we aim at reconciling several options using frames. The central idea is to consider records where some fields do not have a value yet. We will call these generalized records frames, and will say that a field is a definition (resp. abstraction) if it has (resp. does not have) a value. Frames can also be thought of as a reification of the contexts of CiC, as presented in the Coq manual.

6.16. Automated refinements on algorithms in Lean

Participants: Cyril Cohen, Tobias Grosser [ETH Zurich], Utz Haus [CRAY EMEA Research Lab], Chris Hughes [Imperial college].

We have experimented with Applying manual and automated program refinements techniques to a simple algorithm, in Lean, with Tobias Grosser, Utz Haus and Chris Hughes, in Zürich. Experiments on this topic are available at the following address https://github.com/ChrisHughes24/LP.

This work also includes investigations on parametricity in Lean as visible at the following address https://github.com/CohenCyril/mathlib/tree/param.

6.17. Parametricity in Template Coq

Participants: Cyril Cohen, Damien Rouhling, Assia Mahboubi [Inria Rennes Bretagne Atlantique, Gallinette project team], Nicolas Tabareau [Inria Rennes Bretagne Atlantique, Gallinette project team].

We study the implementation of parametricity in Template Coq and improve on the work proposed the article *Equivalence for free!* [17]. This work is available at https://github.com/CoqHott/parametricity-a-la-carte.

6.18. A hierarchy builder

Participants: Kazuhiko Sakaguchi, Cyril Cohen.

We are studying how to generate mathematical structures from their axioms using the high-level language provided by the Coq-Elpi experiment. Ongoing experiments are visible at the following address https://github.com/math-comp/hierarchy-builder.

6.19. Adding measure theory to mathematical components analysis

Participants: Cyril Cohen, Damien Rouhling, Laurence Rideau, Reynald Affeldt [AIST, Japan], Georges Gonthier [Inria Saclay Ile de France, Specfun project team], Marie Kerjean [Inria Rennes Bretagne Atlantique, Gallinette project team], Assia Mahboubi [Inria Rennes Bretagne Atlantique, Gallinette project team], Pierre-Yves Strub [Ecole Polytechnique].

We started extending mathematical components analysis [14] with measure theory and Lebesgue-Stieljes integral. We are taking inspiration from work done on Coquelicot and in the MILC project (DIM-RFSI).

6.20. A formal description of exact real arithmetic

Participants: Yves Bertot, Nicolas Magaud [University of Strasbourg].

We revisited an old package available in the contributions to the Coq system, where algorithms to perform real number computations were described. This package was using primitives described using axioms. We showed that these axioms were faulty and proposed solutions to salvage the package and make it more safely usable in the future.

6.21. Formal study of a triangulation algorithm

Participant: Yves Bertot.

We wish to describe a triangulation algorithm in a way that respects both a high level of abstraction and a precise account of pointer manipulations. Using refinements approaches as in CoqEAL, we hope that this can lead to efficient implementation that are derived from the formal description.

6.22. Formal study of Voronoi diagrams and Fortune's algorithm

Participants: Ahmed Khulaif A Alharbi, Yves Bertot.

Voronoi diagrams are an example of data that can be used to solve problems in robot motion planning. In this experiment, we provided a formal description of Fortune's algorithm to compute such diagrams, together with a framework to animate this algorithm. Formal proofs of correctness will be the next step.

6.23. Formal study of a cell-decomposition algorithm

Participants: Julien Lamiroy, Yves Bertot.

To solve robot motion planning problems, a simple approach is to decompose the available space into obstacle-free cells and to more from one cell to another only by boundaries that are also obstacle free. We developed a formal description of an algorithm producing this kind of decomposition, with the aim of providing formal proofs of correctness in the long run.

6.24. A guide to use Coq for security evaluations

Participants: Maxime Dénès, Yves Bertot, Vincent Laporte, Arnaud Fontaine [ANSSI], Thomas Letan [ANSSI].

Common Criteria are an international standard for computer security certification. Evaluations are rated with Evaluation Assurance Levels, from 1 to 7. Eal6 and EAL7 require developers to conduct a formal analysis of their product with respect to certain security properties.

In France, the Certification Body (the entity emitting Common Criteria certificates) is part of the ANSSI (*l'Agence Nationale de la Sécurité des Systèmes d'Information*, also referred to as the French Cybersecurity Agency), and is one of the few emitters of EAL6 and EAL7 certificates.

Coq has already been used to support Common Criteria formal analysis. The ANSSI and Inria have been collaborating on an authoritative document to introduce guidelines and rules for formal analyses supported by Coq, in order to make these developments easier to read and evaluate.

6.25. Formalization of the Poincaré disk model in Isabelle

Participants: Pierre Boutry, Danijela Simić [University of Belgrade], Filip Marić [University of Belgrade].

The Poincaré disk model is a model that can be shown to satisfy all axioms of Tarski's system of geometry at the exception of the parallel postulate. We developed a formal proof of this fact in the Isabelle system and submitted an article for publication. Reviewers suggested that we add a proof that the postulate of the existence of limiting parallels does hold. This completes neatly the work on this topic, as it allows us to exhibit that the Poincaré disk model is not only a counter-model for the parallel postulate but also a model of hyperbolic geometry. An improved version of the article will be submitted soon.

6.26. Integration of the GeoCoq library to Logipedia

Participants: Pierre Boutry, Gaspard Ferey [Inria Saclay Ile de France, Deducteam project team].

We have proofs of independence of the parallel postulate for several models of hyperbolic geometry (among which the Poincaré disk model). An objective is to provide formal proofs that these models are actually isomorphic. An issue for this objective is the question of re-usability, because the formal proofs that we have so far exist in the realms of different theorem provers. The Logipedia effort is an attempt to make proofs from different proofs systems work together, by using a tool called Dedukti as a go-between. A particular point is to be able to translate proofs already done in Coq, namely the GeoCoq library, into proofs verifiable by Dedukti. This requires handling tactics based on internal computation (reflective tactics), that we used intensively in our Coq proof. However, handling reflective tactics is currently not well supported by Dedukti. This is our current point of attention.

6.27. Performance improvements for a reflective tactic in the GeoCoq library

Participants: Pierre Boutry, Benjamin Grégoire, Enrico Tassi.

The GeoCoq library relies on a reflective tactic. It is an interesting topic to understand how to make such a tactic more efficient. A first pass on the algorithm makes that we manage to gain 15% of performance for the whole library and several orders of magnitude on specific subgoals. Another area of the tactic can also be improved by relying on Coq-Elpi.

6.28. Mutual interpretability of cartesian planes with Tarski's system of geometry

Participants: Pierre Boutry, Cyril Cohen.

A previous result by Pierre Boutry is that cartesian planes over pythagorean ordered fields are mutually interpretable with Tarski's system of geometry without the continuity axiom. This result can be extended by linking cartesian planes over real closed fields and the full Tarski system of geometry, understanding the continuity axiom as an implementation of Dedekind cuts. On the one hand, this requires a new proof that is not already found in the literature, on the other hand, this will result in a verified quantifier elimination procedure for Tarski's system of geometry, thus extending previous work by Cyril Cohen.

6.29. Simplification of a constructive version of Tarski's system of geometry

Participant: Pierre Boutry.

Our long term project is to show the independence of all thirteen axioms in a variant of Tarski's system of geometry. In the current situation, ten axioms have been checked to be independent using counter-models. Specific questions arise around the continuity axiom and decidability of equality between points. This is related to investigations concerning mutual interpretability with cartesian planes and an alternative system proposed by Michael Beeson.

6.30. Formal proofs of Tarjan's strongly connected components algorithm

Participants: Cyril Cohen, Laurent Théry, Ran Chen [Institute of Software, Chinese Academy of Science, Beijing], Jean-Jacques Lévy [Inria Paris, $\pi.r^2$ project-team], Stephan Merz [Inria Nancy Grand Est, Veridis project-team].

Comparing provers on a formalization of the same problem is always a valuable exercise. In this work, we present the formal proof of correctness of a non-trivial algorithm from graph theory that was carried out in three proof assistants: Why3, Coq, and Isabelle. This was published in an international conference [8].

7. Partnerships and Cooperations

7.1. National Initiatives

7.1.1. ANR

- FastRelax, "Fast and Reliable Approximations", started on October 1st, 2014, for 60 months (ending in September 2019), with a grant of 75 kEuros for Marelle. Other partners are Inria Grenoble (ARIC project-team), LAAS-CNRS (Toulouse), Inria Saclay (Toccata and Specfun project-teams), and LIP6-CNRS (Paris). The corresponding researcher for this contract is Laurence Rideau.
- TECAP "Analyse de protocoles, Unir les outils existants", starting on October 1st, 2017, for 60 months, with a grant of 89 kEuros. Other partners are Inria teams PESTO (Inria Nancy grand-est), Ecole Polytechnique, ENS Cachan, IRISA Rennes, and CNRS. The corresponding researcher for this contract is Benjamin Grégoire.
- SafeTLS "La sécurisation de l'Internet du futur avec TLS 1.3" started on October 1st, 2016, for 60 months, with a grant of 147kEuros. Other partners are Université de Rennes 1, and secrétariat Général de la Défense et de la Sécurité Nationale. The corresponding researcher for this contract is Benjamin Grégoire.
- BRUTUS "Chiffrements authentifiés et résistants aux attaques par canaux auxiliaires", started on October 1st, 2014, for 60 months, with a grant of 41 kEuros for STAMP. Other partners are Université de Rennes 1, CNRS, secrétariat Général de la défense et de la sécurité nationale, and Université des Sciences et Technologies de Lille 1. The corresponding researcher for this contract is Benjamin Grégoire.
- Scrypt "Compilation sécurisée de primitives cryptographiques" started on February 1st, 2019, for 48 months, with a grant of 100 kEuros. Other partners are Inria team Celtique (Inria Rennes Bretagne Atlantique), Ecole polytechnique, and AMOSSYS SAS. The corresponding researcher for this contract is Benjamin Grégoire.

7.1.2. FUI

The acronym *FUI* stands for “fonds unique interministériel” and is aimed at research and development projects in pre-industrial phase. The STAMP team is part of one such project.

- VERISICC (formal verification for masking techniques for security against side-channel attacks). This contract concerns 5 partners: CRYPTOEXPERTS a company from the Paris region (Île de France), ANSSI (Agence Nationale de Sécurité des Systèmes d'Information), Oberthur Technologies, University of Luxembourg, and STAMP. A sixth company (Ninjalabs) acts as a sub-contractant. The financial grant for STAMP is 391 kEuros, including 111kEuros that are reserved for the sub-contractant. This project started in October 2018 for a duration of 4 years. The corresponding researcher for this contract is Benjamin Grégoire.

7.2. European Initiatives

7.2.1. Collaborations in European Programs, Except FP7 & H2020

Program: COST

Project acronym: EUTypes

Project title: The European research network on types for programming and verification (EUTypes)

Coordinator: Prof. Herman Geuvers, Radboud University, The Netherlands

Abstract:This COST Action will give a strong impetus to research on type theory and its many applications in computer science, by promoting (1) the synergy between theoretical computer scientists, logicians and mathematicians to develop new foundations for type theory, for example as based on the recent development of "homotopy type theory", (2) the joint development of type theoretic tools as proof assistants and integrated programming environments, (3) the study of dependent types for programming and its deployment in software development, (4) the study of dependent types for verification and its deployment in software analysis and verification. The action will also tie together these different areas and promote cross-fertilisation.

7.2.2. Collaborations with Major European Organizations

Partner 1: MPI Bochum, Gilles Barthe, Germany

Formally verified cryptography

7.3. International Initiatives

7.3.1. Informal International Partners

We have strong collaborations with AIST in Japan. Reynald Affeldt, a researcher from AIST has been visiting our team since October 1st 2019. The topic of choice is formalization of a variety of topics using the Mathematical Components library, aiming mostly at formalizing robotics.

7.4. International Research Visitors

7.4.1. Visits of International Scientists

We received the visit of Marc Gourjon (Technische Universität Hamburg) in April and from Manuel Barbosa (University of Porto) in June and July.

We received the visit of Reynald Affeldt (AIST, Japan) starting on October 1st.

We received the visit of Kazuhiko Sakaguchi (University of Tsukuba), from January 1st to October 31st.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events: Organisation

8.1.1.1. Member of the Organizing Committees

Yves Bertot and Maxime Dénès organized the Coq User and Developer workshop in Sophia Antipolis, June 3–7, 2019.

8.1.2. Scientific Events: Selection

8.1.2.1. Member of the Conference Program Committees

Enrico Tassi was a member of the PC for PADL and LFMTP. Benjamin Grégoire was a member of the PC for latincrypt and PriSC. Cyril Cohen was a member of the PC for CICM. Yves Bertot was a member of the PC for ITP.

8.1.2.2. Reviewer

Benjamin Grégoire: Conference on Computer and Communication Security (CCS), Certified Programs and Proofs (CPP), Interactive Theorem Proving (ITP). Cyril Cohen: LICS.

8.1.3. Journal

8.1.3.1. Reviewer - Reviewing Activities

Laurent Théry: Journal of Automated Reasoning, Science of Computer Programming, Formal Aspects of Computing. Cyril Cohen: MSCS (Journal on Mathematical Structures in Computer Science), Journal of Automated Reasoning, Theoretical Computer Science, Information Processing Letters.

8.1.4. Invited Talks

Enrico Tassi gave talks at the Coq developer Working Group on the migration of the package index from opam v1 to opam v2 and at the Coq workshop on the improvements to SSReflect in Coq 8.10 (with E. Martin-Dorel from the University of Toulouse). He also gave a talk in the seminar of the Inria Parsifal project-team on synthesizing proved equality tests.

Benjamin Grégoire gave an invited talk at PriSC (Principles of Secure Compilation) in January 2019.

Cyril Cohen gave a talk at the *Lean Together* meeting in 2019, on using unification hints.

8.1.5. Scientific Expertise

Yves Bertot is a member of the steering committee for the Inria-Nomadic Labs collaboration.

Yves Bertot is a member of the steering committee for the ITP series of conferences.

Yves Bertot was a member of the hiring committee for an associate professor at ENSIIE (Ecole Nationale Supérieure d'Informatique pour l'Industrie et l'Entreprise) in Evry, France.

8.1.6. Research Administration

Benjamin Grégoire is a member of the CUMI committee facilitating communication between IT services, administrative services, and researchers at Inria.

Yves Bertot was coordinator for the evaluation of the theme "Proof and verification" in March 2019. This work involved polling 13 heads of Inria project teams for names of international experts, selecting an appropriate panel, and attributing a small group of experts to each project-team.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Master : Yves Bertot, "Proofs and reliable programming using Coq", 21hours ETD, Sept-Nov 2019, Université Nice Côte d'Azur, France.

Doctorat : Benjamin Grégoire, "EasyCrypt and Jasmin", 14 ETD, summer school on Formal Techniques, Menlo College, California, USA, 18–25 May 2019.

Doctorat : Benjamin Grégoire, "Formal verification of masked implementations" Summer school on security of software/Hardware interfaces, 3 ETD, 8–12 July 2019, Inria, France.

Doctorat : Yves Bertot "Coq introductory course", EUTypes summer school, 6 ETD, Ohrid, Aug. 30–Sep. 4, 2019, North Macedonia.

8.2.2. Supervision

PhD: Damien Rouhling, *Formalization Tools for Classical Analysis – A Case Study in Control Theory*, Université Côte d'Azur, September 2019, supervised by Yves Bertot and Cyril Cohen [1].

Yves Bertot and Laurence Rideau supervise the doctoral thesis of Sophie Bernard.

Yves Bertot and Benjamin Grégoire supervise the doctoral thesis of Cécile Baritel-Ruet.

Benjamin Grégoire and Tamara Rezk (Indes) supervise the doctoral thesis of Mohamad El Laz.

8.2.3. Juries

Yves Bertot was a member of the Jury for the Habilitation to direct research of Guillaume Melquiond.

Laurent Théry was a member of the thesis committee for David Braun (University of Strasbourg).

Laurent Théry was an external reviewer for a PhD at ANU (Australia, anonymity rules apply).

Enrico Tassi was a member of the Jury for the PhD defense of Ulysse Gérard (Inria Saclay).

Yves Bertot was a member of the Jury with report duties for the thesis of Florian Faissole (University of Paris-Saclay).

Yves Bertot was a member of the Jury with report duties for the thesis of Armaël Guéneau (University of Paris Diderot).

Yves Bertot was a member of the Jury for the thesis of Gaëtan Gilbert (Institut Mines Télécom Atlantique, Nantes).

8.3. Popularization

8.3.1. Internal action

- Yves Bertot gave a talk on Coq in the *Café-In* series of seminars for all publics of Inria personnel.
- Yves Bertot gave a general presentation on Coq in the *Doctoral seminar* of Inria Sophia Antipolis Méditerranée.

9. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

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International Conferences with Proceedings

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Project-Team Stars

Spatio-Temporal Activity Recognition Systems

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Vision, perception and multimedia interpretation

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Project-Team Stars

Creation of the Team: 2012 January 01, updated into Project-Team: 2013 January 01

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1. Team, Visitors, External Collaborators

Research Scientists

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Monique Thonnat [Inria, Senior Researcher, HDR]
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Srijan Das [University Côte d'Azur]
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Abhijit Das [Inria, until Apr 2019]
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David Anghelone [Thales, from Sep 2019]
Seungryul Baek [PhD, Imperial College London, from Jun 2019 until Aug 2019]
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Audrey Sayaque [Univ Côte d'Azur, from Oct 2019 until Nov 2019]

2. Overall Objectives

2.1. Presentation

The **STARS (Spatio-Temporal Activity Recognition Systems)** team focuses on the design of cognitive vision systems for Activity Recognition. More precisely, we are interested in the real-time semantic interpretation of dynamic scenes observed by video cameras and other sensors. We study long-term spatio-temporal activities performed by agents such as human beings, animals or vehicles in the physical world. The major issue in semantic interpretation of dynamic scenes is to bridge the gap between the subjective interpretation of data and the objective measures provided by sensors. To address this problem Stars develops new techniques in the field of computer vision, machine learning and cognitive systems for physical object detection, activity understanding, activity learning, vision system design and evaluation. We focus on two principal application domains: visual surveillance and healthcare monitoring.

2.1.1. Research Themes

Stars is focused on the design of cognitive systems for Activity Recognition. We aim at endowing cognitive systems with perceptual capabilities to reason about an observed environment, to provide a variety of services to people living in this environment while preserving their privacy. In today world, a huge amount of new sensors and new hardware devices are currently available, addressing potentially new needs of the modern society. However the lack of automated processes (with no human interaction) able to extract a meaningful and accurate information (i.e. a correct understanding of the situation) has often generated frustrations among the society and especially among older people. Therefore, Stars objective is to propose novel autonomous systems for the **real-time semantic interpretation of dynamic scenes** observed by sensors. We study long-term spatio-temporal activities performed by several interacting agents such as human beings, animals and vehicles in the physical world. Such systems also raise fundamental software engineering problems to specify them as well as to adapt them at run time.

We propose new techniques at the frontier between computer vision, knowledge engineering, machine learning and software engineering. The major challenge in semantic interpretation of dynamic scenes is to bridge the gap between the task dependent interpretation of data and the flood of measures provided by sensors. The problems we address range from physical object detection, activity understanding, activity learning to vision system design and evaluation. The two principal classes of human activities we focus on, are assistance to older adults and video analytic.

A typical example of a complex activity is shown in Figure 1 and Figure 2 for a homecare application. In this example, the duration of the monitoring of an older person apartment could last several months. The activities involve interactions between the observed person and several pieces of equipment. The application goal is to recognize the everyday activities at home through formal activity models (as shown in Figure 3) and data captured by a network of sensors embedded in the apartment. Here typical services include an objective assessment of the frailty level of the observed person to be able to provide a more personalized care and to monitor the effectiveness of a prescribed therapy. The assessment of the frailty level is performed by an Activity Recognition System which transmits a textual report (containing only meta-data) to the general practitioner who follows the older person. Thanks to the recognized activities, the quality of life of the observed people can thus be improved and their personal information can be preserved.

The ultimate goal is for cognitive systems to perceive and understand their environment to be able to provide appropriate services to a potential user. An important step is to propose a computational representation of people activities to adapt these services to them. Up to now, the most effective sensors have been video cameras due to the rich information they can provide on the observed environment. These sensors are currently perceived as intrusive ones. A key issue is to capture the pertinent raw data for adapting the services to the people while preserving their privacy. We plan to study different solutions including of course the local processing of the data without transmission of images and the utilization of new compact sensors developed for interaction (also called RGB-Depth sensors, an example being the Kinect) or networks of small non visual sensors.

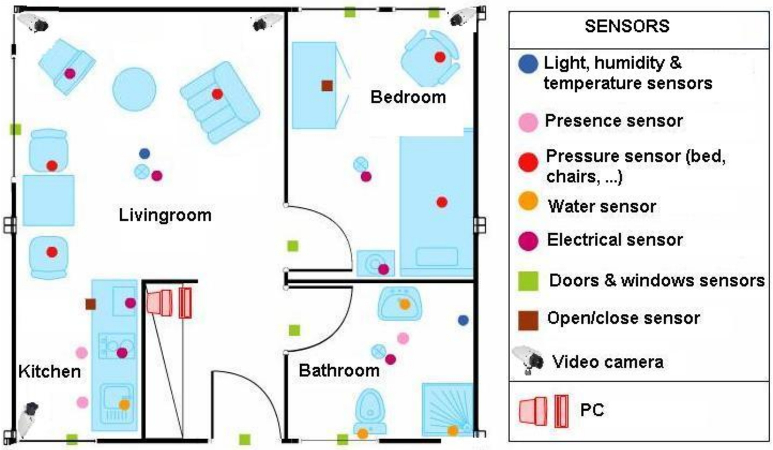

Figure 1. Homecare monitoring: the set of sensors embedded in an apartment

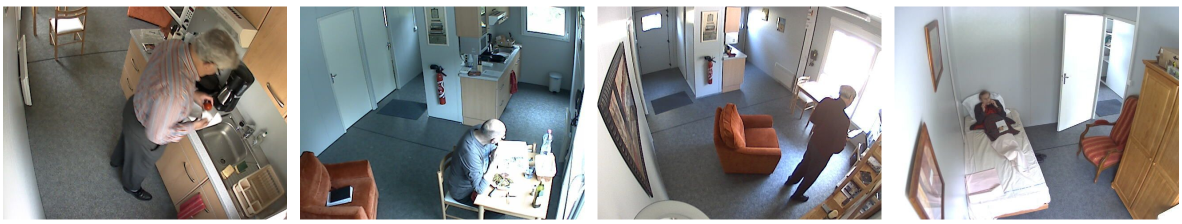

Figure 2. Homecare monitoring: the different views of the apartment captured by 4 video cameras

Activity (*PrepareMeal*,	
PhysicalObjects(	(p : Person), (z : Zone), (eq : Equipment))
Components(	(s_inside : InsideKitchen(p, z))
	(s_close : CloseToCountertop(p, eq))
	(s_stand : PersonStandingInKitchen(p, z)))
Constraints(	(z->Name = Kitchen)
	(eq->Name = Countertop)
	(s_close->Duration >= 100)
	(s_stand->Duration >= 100))
Annotation(	AText("prepare meal")
	AType("not urgent")))

Figure 3. Homecare monitoring: example of an activity model describing a scenario related to the preparation of a meal with a high-level language

2.1.2. International and Industrial Cooperation

Our work has been applied in the context of more than 10 European projects such as COFRIEND, ADVISOR, SERKET, CARETAKER, VANAHEIM, SUPPORT, DEM@CARE, VICOMO, EIT Health. We had or have industrial collaborations in several domains: *transportation* (CCI Airport Toulouse Blagnac, SNCF, Inrets, Alstom, Ratp, Toyota, GTT (Italy), Turin GTT (Italy)), *banking* (Crédit Agricole Bank Corporation, Eurotelis and Ciel), *security* (Thales R&T FR, Thales Security Syst, EADS, Sagem, Bertin, Alcatel, Keeneo), *multi-media* (Thales Communications), *civil engineering* (Centre Scientifique et Technique du Bâtiment (CSTB)), *computer industry* (BULL), *software industry* (AKKA), *hardware industry* (ST-Microelectronics) and *health industry* (Philips, Link Care Services, Vistek).

We have international cooperations with research centers such as Reading University (UK), ENSI Tunis (Tunisia), Idiap (Switzerland), Multitel (Belgium), National Cheng Kung University, National Taiwan University (Taiwan), MICA (Vietnam), IPAL, I2R (Singapore), University of Southern California, University of South Florida, University of Maryland (USA).

2.1.2.1. Industrial Contracts

- *Toyota:* (Action Recognition System):
  This project run from the 1st of August 2013 up to 2023. It aimed at detecting critical situations in the daily life of older adults living home alone. The system is intended to work with a Partner Robot (to send real-time information to the robot for assisted living) to better interact with older adults. The funding was 106 Keuros for the 1st period and more for the following years.
- *Gemalto:* This contract is a CIFRE PhD grant and runs from September 2018 until September 2021 within the French national initiative SafeCity. The main goal is to analyze faces and events in the invisible spectrum (i.e., low energy infrared waves, as well as ultraviolet waves). In this context models will be developed to efficiently extract identity, as well as event - information. This models will be employed in a school environment, with a goal of pseudo-anonymized identification, as well as event-detection. Expected challenges have to do with limited colorimetry and lower contrasts.
- *Kontron:* This contract is a CIFRE PhD grant and runs from April 2018 until April 2021 to embed CNN based people tracker within a video-camera.
- *ESI:* This contract is a CIFRE PhD grant and runs from September 2018 until March 2022 to develop a novel Re-Identification algorithm which can be easily set-up with low interaction.

3. Research Program

3.1. Introduction

Stars follows three main research directions: perception for activity recognition, action recognition and semantic activity recognition. **These three research directions are organized following the workflow of activity recognition systems**: First, *the perception* and *the action recognition* directions provide new techniques to extract powerful features, whereas *the semantic activity recognition* research direction provides new paradigms to match these features with concrete video analytic and healthcare applications.

Transversely, we consider a *new research axis in machine learning*, combining a priori knowledge and learning techniques, to set up the various models of an activity recognition system. A major objective is to automate model building or model enrichment at the perception level and at the understanding level.

3.2. Perception for Activity Recognition

Participants: François Brémond, Antitza Dantcheva, Sabine Moisan, Monique Thonnat.

Activity Recognition, Scene Understanding, Machine Learning, Computer Vision, Cognitive Vision Systems, Software Engineering

3.2.1. Introduction

Our main goal in perception is to develop vision algorithms able to address the large variety of conditions characterizing real world scenes in terms of sensor conditions, hardware requirements, lighting conditions, physical objects, and application objectives. We have also several issues related to perception which combine machine learning and perception techniques: learning people appearance, parameters for system control and shape statistics.

3.2.2. Appearance Models and People Tracking

An important issue is to detect in real-time physical objects from perceptual features and predefined 3D models. It requires finding a good balance between efficient methods and precise spatio-temporal models. Many improvements and analysis need to be performed in order to tackle the large range of people detection scenarios.

Appearance models. In particular, we study the temporal variation of the features characterizing the appearance of a human. This task could be achieved by clustering potential candidates depending on their position and their reliability. This task can provide any people tracking algorithms with reliable features allowing for instance to (1) better track people or their body parts during occlusion, or to (2) model people appearance for re-identification purposes in mono and multi-camera networks, which is still an open issue. The underlying challenge of the person re-identification problem arises from significant differences in illumination, pose and camera parameters. The re-identification approaches have two aspects: (1) establishing correspondences between body parts and (2) generating signatures that are invariant to different color responses. As we have already several descriptors which are color invariant, we now focus more on aligning two people detection and on finding their corresponding body parts. Having detected body parts, the approach can handle pose variations. Further, different body parts might have different influence on finding the correct match among a whole gallery dataset. Thus, the re-identification approaches have to search for matching strategies. As the results of the re-identification are always given as the ranking list, re-identification focuses on learning to rank. "Learning to rank" is a type of machine learning problem, in which the goal is to automatically construct a ranking model from a training data.

Therefore, we work on information fusion to handle perceptual features coming from various sensors (several cameras covering a large scale area or heterogeneous sensors capturing more or less precise and rich information). New 3D RGB-D sensors are also investigated, to help in getting an accurate segmentation for specific scene conditions.

Long term tracking. For activity recognition we need robust and coherent object tracking over long periods of time (often several hours in video surveillance and several days in healthcare). To guarantee the long term coherence of tracked objects, spatio-temporal reasoning is required. Modeling and managing the uncertainty of these processes is also an open issue. In Stars we propose to add a reasoning layer to a classical Bayesian framework modeling the uncertainty of the tracked objects. This reasoning layer can take into account the a priori knowledge of the scene for outlier elimination and long-term coherency checking.

Controlling system parameters. Another research direction is to manage a library of video processing programs. We are building a perception library by selecting robust algorithms for feature extraction, by insuring they work efficiently with real time constraints and by formalizing their conditions of use within a program supervision model. In the case of video cameras, at least two problems are still open: robust image segmentation and meaningful feature extraction. For these issues, we are developing new learning techniques.

3.3. Action Recognition

Participants: François Brémond, Antitza Dantcheva, Monique Thonnat.

Machine Learning, Computer Vision, Cognitive Vision Systems

3.3.1. Introduction

Due to the recent development of high processing units, such as GPU, this is now possible to extract meaningful features directly from videos (e.g. video volume) to recognize reliably short actions. Action Recognition benefits also greatly from the huge progress made recently in Machine Learning (e.g. Deep Learning), especially for the study of human behavior. For instance, Action Recognition enables to measure objectively the behavior of humans by extracting powerful features characterizing their everyday activities, their emotion, eating habits and lifestyle, by learning models from a large number of data from a variety of sensors, to improve and optimize for example, the quality of life of people suffering from behavior disorders. However, Smart Homes and Partner Robots have been well advertised but remain laboratory prototypes, due to the poor capability of automated systems to perceive and reason about their environment. A hard problem is for an automated system to cope 24/7 with the variety and complexity of the real world. Another challenge is to extract people fine gestures and subtle facial expressions to better analyze behavior disorders, such as anxiety or apathy. Taking advantage of what is currently studied for self-driving cars or smart retails, there is a large avenue to design ambitious approaches for the healthcare domain. In particular, the advance made with Deep Learning algorithms has already enabled to recognize complex activities, such as cooking interactions with instruments, and from this analysis to differentiate healthy people from the ones suffering from dementia.

To address these issues, we propose to tackle several challenges:

3.3.2. Action recognition in the wild

The current Deep Learning techniques are mostly developed to work on few clipped videos, which have been recorded with students performing a limited set of predefined actions in front of a camera with high resolution. However, real life scenarios include actions performed in a spontaneous manner by older people (including people interactions with their environment or with other people), from different viewpoints, with varying framerate, partially occluded by furniture at different locations within an apartment depicted through long untrimmed videos. Therefore, a new dedicated dataset should be collected in a real-world setting to become a public benchmark video dataset and to design novel algorithms for ADL activity recognition. A special attention should be taken to anonymize the videos.

3.3.3. Attention mechanisms for action recognition

Activities of Daily Living (ADL) and video-surveillance activities are different from internet activities (e.g. Sports, Movies, YouTube), as they may have very similar context (e.g. same background kitchen) with high intra-variation (different people performing the same action in different manners), but in the same time low inter-variation, similar ways to perform two different actions (e.g. eating and drinking a glass of water). Consequently, fine-grained actions are badly recognized. So, we will design novel attention mechanisms for action recognition, for the algorithm being able to focus on a discriminative part of the person conducting the action. For instance, we will study attention algorithms, which could focus on the most appropriate body parts (e.g. full body, right hand). In particular, we plan to design a soft mechanism, learning the attention weights directly on the feature map of a 3DconvNet, a powerful convolutional network, which takes as input a batch of videos.

3.3.4. Action detection for untrimmed videos

Many approaches have been proposed to solve the problem of action recognition in short clipped 2D videos, which achieved impressive results with hand-crafted and deep features. However, these approaches cannot address real life situations, where cameras provide online and continuous video streams in applications such as robotics, video surveillance, and smart-homes. Here comes the importance of action detection to help recognizing and localizing each action happening in long videos. Action detection can be defined as the ability to localize starting and ending of each human action happening in the video, in addition to recognizing each action label. There have been few action detection algorithms designed for untrimmed videos, which are based on either sliding window, temporal pooling or frame-based labeling. However, their performance is too low to address real-word datasets. A first task consists in benchmarking the already published approaches to study their limitations on novel untrimmed video datasets, recorded following real-world settings. A second task could be to propose a new mechanism to improve either 1) the temporal pooling directly from the 3DconvNet architecture using for instance Temporal Convolution Networks (TCNs) or 2) frame-based labeling with a clustering technique (e.g. using Fisher Vectors) to discover the sub-activities of interest.

3.3.5. View invariant action recognition

The performance of current approaches strongly relies on the used camera angle: enforcing that the camera angle used in testing is the same (or extremely close to) as the camera angle used in training, is necessary for the approach performs well. On the contrary, the performance drops when a different camera view-point is used. Therefore, we aim at improving the performance of action recognition algorithms by relying on 3D human pose information. For the extraction of the 3D pose information, several open-source algorithms can be used, such as openpose or videopose3D (from CMU or Facebook research, https://github.com/CMU-Perceptual-Computing-Lab/openpose. Also, other algorithms extracting 3d meshes can be used. To generate extra views, Generative Adversial Network (GAN) can be used together with the 3D human pose information to complete the training dataset from the missing view.

3.3.6. Uncertainty and action recognition

Another challenge is to combine the short-term actions recognized by powerful Deep Learning techniques with long-term activities defined by constraint-based descriptions and linked to user interest. To realize this objective, we have to compute the uncertainty (i.e. likelihood or confidence), with which the short-term actions are inferred. This research direction is linked to the next one, to Semantic Activity Recognition.

3.4. Semantic Activity Recognition

Participants: François Brémond, Sabine Moisan, Monique Thonnat.

Activity Recognition, Scene Understanding, Computer Vision

3.4.1. Introduction

Semantic activity recognition is a complex process where information is abstracted through four levels: signal (e.g. pixel, sound), perceptual features, physical objects and activities. The signal and the feature levels are characterized by strong noise, ambiguous, corrupted and missing data. The whole process of scene understanding consists in analyzing this information to bring forth pertinent insight of the scene and its dynamics while handling the low level noise. Moreover, to obtain a semantic abstraction, building activity models is a crucial point. A still open issue consists in determining whether these models should be given a priori or learned. Another challenge consists in organizing this knowledge in order to capitalize experience, share it with others and update it along with experimentation. To face this challenge, tools in knowledge engineering such as machine learning or ontology are needed.

Thus we work along the following research axes: high level understanding (to recognize the activities of physical objects based on high level activity models), learning (how to learn the models needed for activity recognition) and activity recognition and discrete event systems.

3.4.2. High Level Understanding

A challenging research axis is to recognize subjective activities of physical objects (i.e. human beings, animals, vehicles) based on a priori models and objective perceptual measures (e.g. robust and coherent object tracks).

To reach this goal, we have defined original activity recognition algorithms and activity models. Activity recognition algorithms include the computation of spatio-temporal relationships between physical objects. All the possible relationships may correspond to activities of interest and all have to be explored in an efficient way. The variety of these activities, generally called video events, is huge and depends on their spatial and temporal granularity, on the number of physical objects involved in the events, and on the event complexity (number of components constituting the event).

Concerning the modeling of activities, we are working towards two directions: the uncertainty management for representing probability distributions and knowledge acquisition facilities based on ontological engineering techniques. For the first direction, we are investigating classical statistical techniques and logical approaches. For the second direction, we built a language for video event modeling and a visual concept ontology (including color, texture and spatial concepts) to be extended with temporal concepts (motion, trajectories, events ...) and other perceptual concepts (physiological sensor concepts ...).

3.4.3. Learning for Activity Recognition

Given the difficulty of building an activity recognition system with a priori knowledge for a new application, we study how machine learning techniques can automate building or completing models at the perception level and at the understanding level.

At the understanding level, we are learning primitive event detectors. This can be done for example by learning visual concept detectors using SVMs (Support Vector Machines) with perceptual feature samples. An open question is how far can we go in weakly supervised learning for each type of perceptual concept (i.e. leveraging the human annotation task). A second direction is to learn typical composite event models for frequent activities using trajectory clustering or data mining techniques. We name composite event a particular combination of several primitive events.

3.4.4. Activity Recognition and Discrete Event Systems

The previous research axes are unavoidable to cope with the semantic interpretations. However they tend to let aside the pure event driven aspects of scenario recognition. These aspects have been studied for a long time at a theoretical level and led to methods and tools that may bring extra value to activity recognition, the most important being the possibility of formal analysis, verification and validation.

We have thus started to specify a formal model to define, analyze, simulate, and prove scenarios. This model deals with both absolute time (to be realistic and efficient in the analysis phase) and logical time (to benefit from well-known mathematical models providing re-usability, easy extension, and verification). Our purpose is to offer a generic tool to express and recognize activities associated with a concrete language to specify activities in the form of a set of scenarios with temporal constraints. The theoretical foundations and the tools being shared with Software Engineering aspects.

The results of the research performed in perception and semantic activity recognition (first and second research directions) produce new techniques for scene understanding and contribute to specify the needs for new software architectures (third research direction).

4. Highlights of the Year

4.1. Highlights of the Year

4.1.1. People detection

People detection is a very challenging topic, where many top-level research groups are competing and have already proposed impressive approaches (e.g. Faster-RCNN, SSD, YOLO). Yet, we were able to design a novel algorithm able to better balance the speed and accuracy trade-off on the most challenging pedestrian detection benchmarks (e.g. Caltech and Citypersons).

4.1.2. Person Re-Identification

Person Re-Identification is a very challenging task, where current Computer Vision algorithms manage to obtain better results than humans. By proposing a simple and elegant technique, based on Spatial-Channel Partitions, we have obtained the best performance compared to the State-of-the-art approaches on the most popular benchmark datasets (e.g. Market-1501, CUHK03 and MARS).

4.1.3. Action recognition

This year, we have proposed several action recognition approaches able to outperform the State-of-the-art algorithms and get nearly maximal performance on most of ADL benchmark video datasets (e.g. Northwestern-UCLA Multiview Action 3D, NTUTU-RGB and DAHLIA). We have also released a novel ADL benchmark video dataset, which is more challenging, as it has been collected within real-world settings.

4.1.4. Awards

Antitza Dantcheva and Abhijit Das recceived a Best Poster Award at the 14th IEEE International Conference on Automatic Face and Gesture Recognition (FG 2019) in Lille, France (the flagship face analysis conference) for the paper: "Robust remote heart rate estimation from face utilizing spatial-temporal attention" [28].

5. New Software and Platforms

5.1. SUP

Scene Understanding Platform

KEYWORDS: Activity recognition - 3D - Dynamic scene

FUNCTIONAL DESCRIPTION: SUP is a software platform for perceiving, analyzing and interpreting a 3D dynamic scene observed through a network of sensors. It encompasses algorithms allowing for the modeling of interesting activities for users to enable their recognition in real-world applications requiring high-throughput.

- Participants: Etienne Corvée, François Brémond, Hung Nguyen and Vasanth Bathrinarayanan
- Partners: CEA - CHU Nice - USC Californie - Université de Hamburg - I2R
- Contact: François Brémond
- URL: https://team.inria.fr/stars/software

5.2. VISEVAL

FUNCTIONAL DESCRIPTION: ViSEval is a software dedicated to the evaluation and visualization of video processing algorithm outputs. The evaluation of video processing algorithm results is an important step in video analysis research. In video processing, we identify 4 different tasks to evaluate: detection, classification and tracking of physical objects of interest and event recognition.

- Participants: Bernard Boulay and François Brémond
- Contact: François Brémond
- URL: http://www-sop.inria.fr/teams/pulsar/EvaluationTool/ViSEvAl_Description.html

6. New Results

6.1. Introduction

This year Stars has proposed new results related to its three main research axes: (i) perception for activity recognition, (ii) action recognition and (iii) semantic activity recognition.

6.1.1. Perception for Activity Recognition

Participants: François Brémond, Juan Diego Gonzales Zuniga, Abhijit Das, Antitza Dantcheva, Ujjwal Ujjwal, Srijan Das, David Anghelone, Monique Thonnat.

The new results for perception for activity recognition are:

- Handling the Speed-Accuracy Trade-off in Deep Learning based Pedestrian Detection (see 6.2)
- Deep Learning applied on Embedded Systems for People Tracking (see 6.3)
- Partition and Reunion: A Two-Branch Neural Network for Vehicle Re- identification (see 6.4)
- Improving Face Sketch Recognition via Adversarial Sketch-Photo Transformation (see 6.5)
- Impact and Detection of Facial Beautification in Face Recognition: An Overview (see 6.6)
- Computer Vision and Deep Learning applied to Facial analysis in the invisible spectra (see 6.7)

6.1.2. Action Recognition

Participants: François Brémond, Juan Diego Gonzales Zuniga, Abhijit Das, Antitza Dantcheva, Ujjwal Ujjwal, Srijan Das, Monique Thonnat.

The new results for action recognition are:

- ImaGINator: Conditional Spatio-Temporal GAN for Video Generation (see 6.8)
- Characterizing the State of Apathy with Facial Expression and Motion Analysis (see 6.9)
- Dual-threshold Based Local Patch Construction Method for Manifold Approximation And Its Application to Facial Expression Analysis (see 6.10)
- A Weakly Supervised Learning Technique for Classifying Facial Expressions (see 6.11)
- Robust Remote Heart Rate Estimation from Face Utilizing Spatial- temporal Attention (see 6.12)
- Quantified Analysis for Epileptic Seizure Videos (see 6.13)
- Toyota Smarthome: Real-World Activities of Daily Living (see 6.15)
- Looking deeper into Time for Activities of Daily Living Recognition (see 6.15.1)
- Self-Attention Temporal Convolutional Network for Long-Term Daily Living Activity Detection (see 6.16)

6.1.3. Semantic Activity Recognition

Participants: François Brémond, Elisabetta de Maria, Antitza Dantcheva, Srijan Das, Abhijit Das, Daniel Gaffé, Thibaud L'Yvonnet, Sabine Moisan, Jean-Paul Rigault, Annie Ressouche, Ines Sarray, Yaohui Wang, S L Happy, Alexandra König, Philippe Robert, Monique Thonnat.

For this research axis, the contributions are:

- DeepSpa Project (see 6.17)
- Store Connect and Solitaria (see 6.18)
- Synchronous Approach to Activity Recognition (see 6.19)
- Probabilistic Activity Modeling (see 6.20)

6.2. Handling the Speed-Accuracy Trade-off in Deep Learning based Pedestrian Detection

Participants: François Brémond, Ujjwal Ujjwal.

Pedestrian detection is a specific instance of the more general problem of object detection. Pedestrian detection plays a fundamental role in many modern applications involving but not limited to *autonomous vehicles* and *surveillance systems*. These applications as many others are safety-critical. This implies that the cost of not correctly detecting a pedestrian is very high. At the same time applications such as the ones mentioned before, are expected to be real-time. This implies that a pedestrian be detected with minimum time delay. The subject of our recent work has been to design a pedestrian detector which is capable of detecting pedestrians with a high accuracy and high speed – two traits which are known to be difficult to achieve simultaneously.

Most of the pedestrian detectors in computer vision are derived from general-category object detectors. We reflect upon its implication in terms of speed and accuracy below.

6.2.1. Speed-Accuracy Trade-off

Speed and accuracy of object detectors are mutually trade-off factors. Emphasis on higher accuracy usually entails intensive computations which sacrifice the detection speed. On the other hand, emphasis on higher detection speed usually leads to simpler computations which sacrifice the detection accuracy.

We have recently been able to balance this trade-off by identifying that the means of computations on anchors are a major source of the speed-accuracy trade-off. Anchors are hypothetical bounding boxes and are reminiscent of sliding windows used in earlier works on object detection. There are two distinct means of processing anchors – *feature pooling* and *feature probing*. We have recently demonstrated that feature pooling is a costlier strategy than feature probing in terms of computational cost. However, in contrast, feature pooling is a more precise means to process anchors.

We leverage this difference in our approach by utilizing feature pooling throughout in our system. However, in order to gain in terms of run-time performance, we reduce the number of anchors to be processed. This reduction does allow us to process a small number of relevant anchors with high precision.

The block diagram of our proposed approach is shown in figure 4.

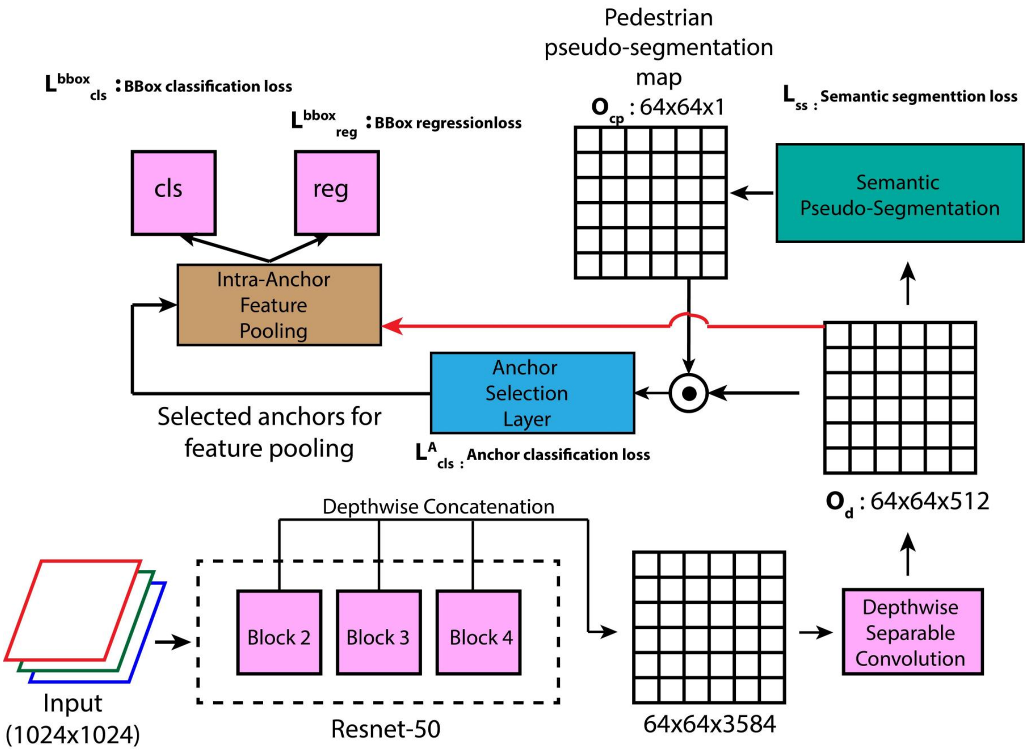

Figure 4. The block diagram of our proposed approach

We fuse the feature maps of multiple layers in order to improve the feature diversity. An increased feature diversity assists in learning from a range of hierarchical features generated by a convolutional neural network, often abbreviated as CNN. A depth-wise separable convolutional layer then further processes the fused feature map in order to reduce the number of feature dimensions. One of the prime novelties in our work is the use of pseudo-semantic segmentation. Pseudo-semantic segmentation allows one to obtain a rough estimate of the localization of pedestrians in the form of a heatmap. This step is important, as it provides us with a basis to select a small set of anchors instead of processing all the tiling anchors on the feature map. An anchor classification layer uses anchor-specific kernel sizes to classify a given anchor as positive or negative. A positive or negative anchor is characterized by the overlap between the anchor and the ground truth bounding box during training. This overlap is measured in terms of the well known intersection-over-union (IoU) metric in computer vision. The positive anchors are then pooled from, followed by classification and regression to obtain the final detection.

6.2.2. Results

Method	Stages	LAMR		Speed
		caltech-reasonable (test) (w/o CP pre-training) (CP pre-trained)	citypersons (val) (trained only on CP)	
Faster-RCNN	2	12.10	15.4	7
SSD	1	17.78 (16.36)	19.69	48
YOLOv2	1	21.62 (20.83)	NA	60
RPN-BF	2	9.6 (NA)	NA	7
MS-CNN	2	10.0 (NA)	NA	8
SDS-RCNN	2	7.6 (NA)	NA	5
ALF-Net	1	4.5 (NA)	12.0	20
Rep-Loss	2	5.0 (4.0)	13.2	-
Ours	1.5	**4.76 (3.99)**	**8.12**	**32**

Figure 5. Performance comparison of the proposed method with other methods for caltech-reasonable test set and citypersons validation set. The speed figures are in frames per second.

Figure 5 summarizes the performance of the proposed approach vis-à-vis other approaches. The proposed approach provides significant improvements over other approaches in terms of both speed and accuracy. From figure 5 it is clear that we benefit from initial training on the citypersons data set. Moreover, we obtain the state-of-art performance on the citypersons data set, improving the existing best performing techniques by nearly 4 LAMR points.

6.3. Deep Learning applied on Embedded Systems for People Tracking

Participants: Juan Diego Gonzales Zuniga, Ujjwal Ujjwal, François Brémond, Serge Tissot [Kontron].

Our work objective is two-fold: a) Perform tracking of multiple people in videos, which is an instance of Multiple Object Tracking (MOT) problem, and b) optimize this tracking on embedded and open source hardware platforms such as OpenVINO and ROCm.

People tracking is a challenging and relevant problem since it needs multiple additional modules to perform the data association between nodes. In addition, state-of-the-art solutions require intensive memory allocation and power consumption which are not available on embedded hardware. Most architectures either require great amounts of memory or large computing time to achieve a state-of-the-art performance, these results are mostly achieved with dedicated hardware at data centers.

6.3.1. Online Joint Detection and Tracking

In people tracking, we are questioning the main paradigm that is tracking-by-detection which heavily relies on the performance of the underlying detection method. This requires access to a highly accurate and robust people detector. On the other hand, few frameworks attempt detect and track people jointly. Our intent is to perform people tracking *online* and *jointly with detection*.

We are trying to determinate a manner in which a single model can both perform detection and tracking simultaneously. Along these lines, we experimented with a variation of I3D on the Posetrack data set that takes an input of 8 frames in order to create heatmaps along multiple frames as seen in Figure 6. Giving that the data of Posetrack or MOT cannot train a network as I3D, we are doing the pretraining with the synthetic JTA-Dataset.

This work is inspired by the less common methods of traking-by-tracks and tracking-by-tracklets. Both [40] and [41] generate multi-frame bounding box tuplet proposals and extract detection scores and features with a CNN and LSTM, respectively. Recent researches improve object detection by applying optical flow to propagate scores between frames.

Another method we implemented is by using the detections of previous frames as proposal for the data association, it only uses the IOU between two objects as a distance metric. This approach is simple and efficient assuming the objects do not move drastically. An improved method increases the performance by using a siamese network to conserve identity across frames and predictions for death and birth of tracks.

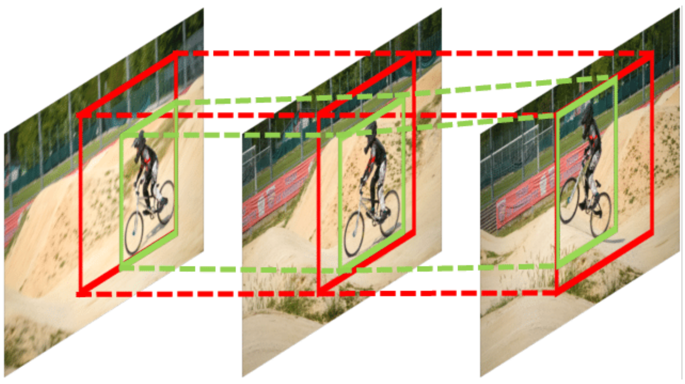

Figure 6. People tracking by tubelets

6.3.2. OpenVINO and ROCm

Regarding embedded hardware, we focus on enlarging both implementation and experimentation of two specific frameworks; OpenVINO and ROCm.

OpenVINO allows us to transfer deep learning models into Myriad and KeemBay chips, taking advantage of their capacity to compute multiple operations without the need of much power consumption. We have thoroughly tested their power consumption under different scenarios as well as implemented many qualitative algorithms with these two platforms, Figure 7 shows the Watt consumption and frame rate of the most popular backbone networks, making it viable to use on embedded applications with a reasonable 25FPS.

For ROCm, we have used the approach of [38] to optimize the compiler execution for a variety of CNN features and filters using a substitute GPU with similar computation capability as Nvidia but still remaining a low branch consumption around 15 Watts.

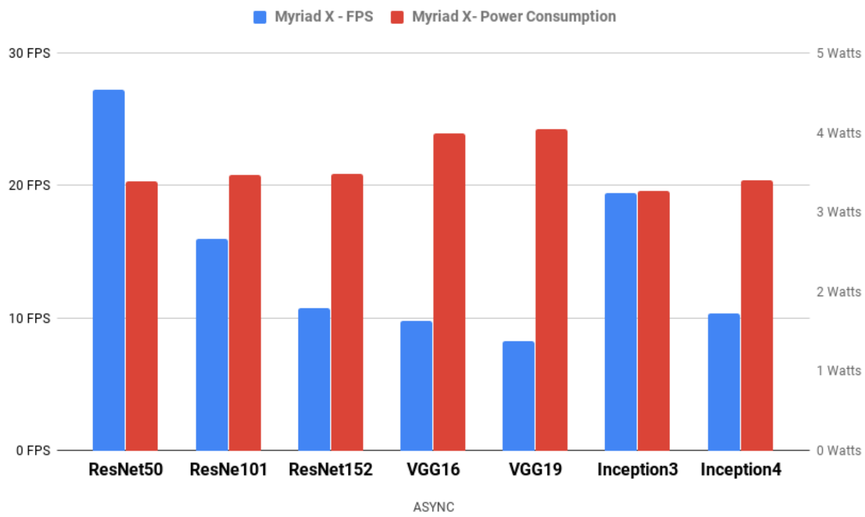

Figure 7. Power Consumption vs Frame rate

6.4. Partition and Reunion: A Two-Branch Neural Network for Vehicle Re-identification

Participants: Hao Chen, Benoit Lagadec, François Brémond.

The smart city vision raises the prospect that cities will become more intelligent in various fields, such as more sustainable environment and a better quality of life for residents. As a key component of smart cities, intelligent transportation system highlights the importance of vehicle re-identification (Re-ID). However, as compared to the rapid progress on person Re-ID, vehicle Re-ID advances at a relatively slow pace. Some previous state-of-the-art approaches strongly rely on extra annotation, like attributes (vehicle color and type) and key-points (wheels and lamps). Recent work on person Re-ID shows that extracting more local features can achieve a better performance without considering extra annotation. In this work, we propose an end-to-end trainable two-branch Partition and Reunion Network (PRN) for the challenging vehicle Re-ID task. Utilizing only identity labels, our proposed method outperforms existing state-of-the-art methods on four vehicle Re-ID benchmark datasets, including VeRi-776, VehicleID, VRIC and CityFlow-ReID by a large margin. The general architecture of our proposed method is represented in the Figure 8.

6.4.1. Learning Discriminative and Generalizable Representations by Spatial-Channel Partition for Person Re-Identification

In Person Re-Identification (Re-ID) task, combining local and global features is a common strategy to overcome missing key parts and misalignment on models based only on global features. Using this combination, neural networks yield impressive performance in Re-ID task. Previous part-based models mainly focus on spatial partition strategies. Recently, operations on channel information, such as Group Normalization and Channel Attention, have brought significant progress to various visual tasks. However, channel partition has not drawn much attention in Person Re-ID. We conduct a study to exploit the potential of channel partition in Re-ID task [32]. Based on this study, we propose an end-to-end Spatial and Channel partition Representation network (SCR) in order to better exploit both spatial and channel information. Experiments conducted on three mainstream image-based evaluation protocols including Market-1501, DukeMTMC-ReID and CUHK03 and

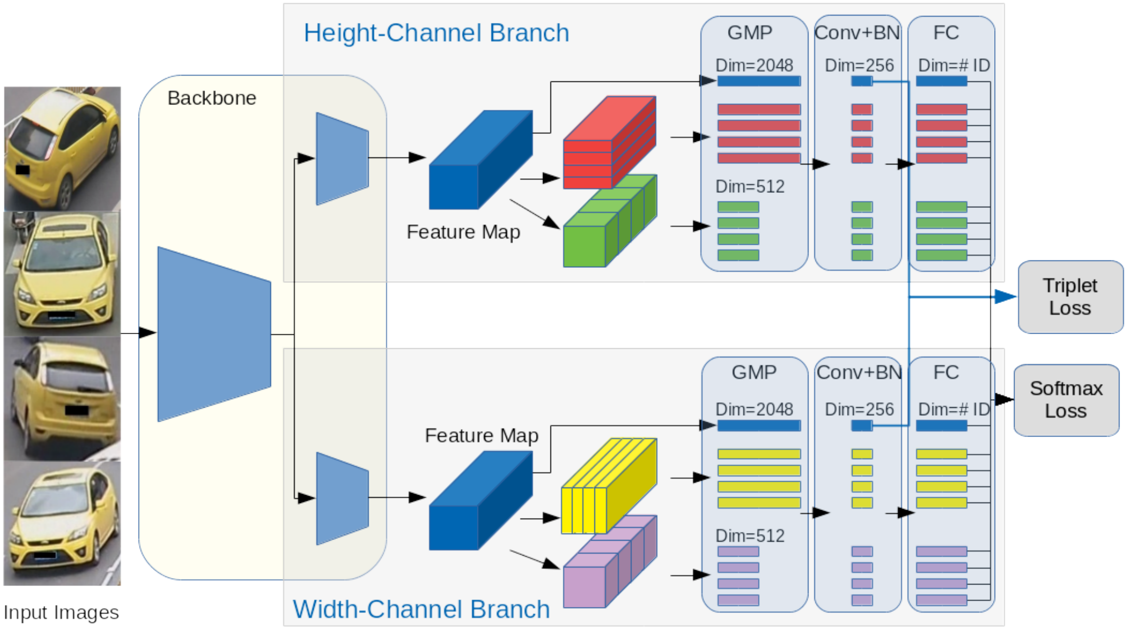

*Figure 8. General architecture of our proposed model. In this work, a ResNet-50 is used as our backbone network. Layers after conv4_1 in Resnet-50 are duplicated to split our network into 2 independent branches. GMP refers to Global Max Pooling. Conv refers to 1*1 convolutional layer, which aims to unify dimensions of global and local feature vectors. FC refers to fully connected layer. BN refers to Batch Normalization layer. In the test phase, all the feature vectors (Dim=256) after Batch Normalization layer are concatenated together as an appearance signature (Dim=256*18).*

one video-based evaluation protocol MARS validate the performance of our model, which outperforms previous state-of-the-art in both single and cross domain Re-ID tasks. The general architecture of our proposed method is represented in the Figure 9.

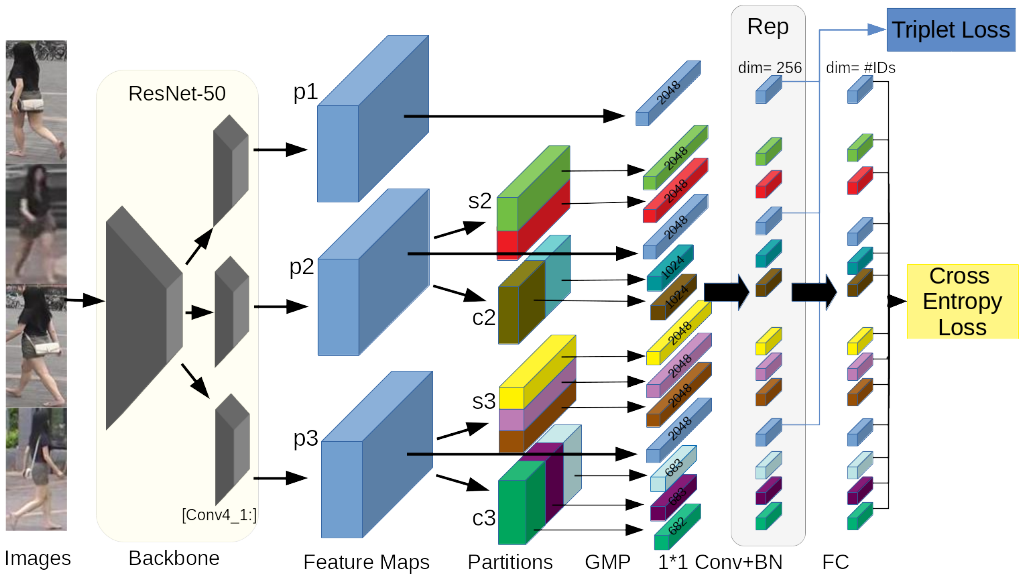

*Figure 9. Spatial and Channel Partition Representation network. For the backbone network, we duplicate layers after conv4_1 into 3 identical but independent branches that generate 3 feature maps "p1", "p2" and "p3". Then, multiple spatial-channel partitions are conducted on the feature maps. "s2" and "c2" refer to 2 spatial parts and 2 channel groups. "s3" and "c3" refer to 3 spatial parts and 3 channel groups. After global max pooling (GMP), dimensions of global (dim = 2048) and local (dim = 2048, 1024*2 and 683*2+682) features are unified by 1*1 convolution (1*1 Conv) and batch normalization (BN) to 256. Then, fully connected layers (FC) give identity predictions of input images. All the dimension unified feature vectors (dim = 256) are aggregated together as appearance representation (Rep) for testing.*

6.5. Improving Face Sketch Recognition via Adversarial Sketch-Photo Transformation

Participants: Antitza Dantcheva, Shikang Yu [Chinese Academy of Sciences], Hu Han [Chinese Academy of Sciences], Shiguang Shan [Chinese Academy of Sciences], Xilin Chen [Chinese Academy of Sciences].

participants

Face sketch-photo transformation has broad applications in forensics, law enforcement, and digital entertainment, particular for face recognition systems that are designed for photo-to-photo matching. While there are a number of methods for face photo-to-sketch transformation, studies on sketch-to-photo transformation remain limited. In this work, we proposed a novel conditional CycleGAN for face sketch-to-photo transformation. Specifically, we leveraged the advantages of CycleGAN and conditional GANs and designed a feature-level loss to assure the high quality of the generated face photos from sketches. The generated face photos were used, as a replacement of face sketches, and particularly for face identification against a gallery set of mugshot photos. Experimental results on the public-domain database CUFSF showed that the proposed approach was able to generate realistic photos from sketches, and the generated photos were instrumental in improving the sketch identification accuracy against a large gallery set. This work has been presented at the IEEE International Conference on Automatic Face and Gesture Recognition (FG 2019) [30].

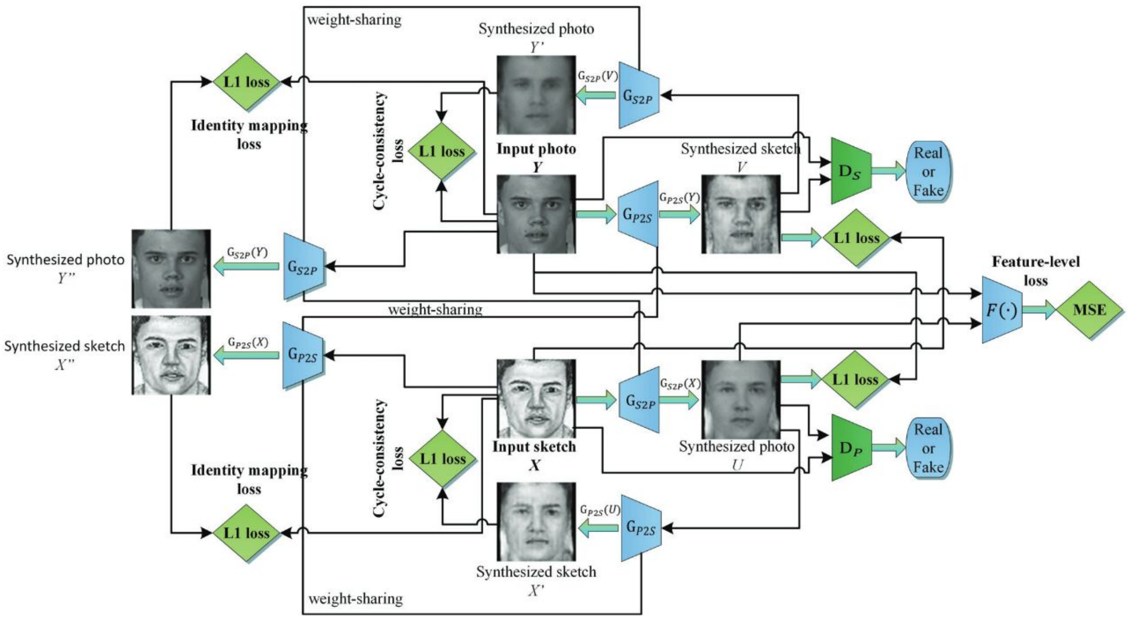

Figure 10. Overview of the proposed GAN for sketch-to-photo transformation using feature-level loss.

6.6. Impact and Detection of Facial Beautification in Face Recognition: An Overview

Participants: Antitza Dantcheva, Christian Rathgeb [Hochschule Darmstadt], Christoph Busch [Hochschule Darmstadt].

Facial beautification induced by plastic surgery, cosmetics or retouching has the ability to substantially alter the appearance of face images. Such types of beautification can negatively affect the accuracy of face recognition systems. In this work, a conceptual categorisation of beautification was presented, relevant scenarios with respect to face recognition were discussed, and related publications were revisited. Additionally, technical considerations and trade-offs of the surveyed methods were summarized along with open issues and challenges in the field. This survey is targeted to provide a comprehensive point of reference for biometric researchers and practitioners working in the field of face recognition, who aim at tackling challenges caused by facial beautification. This work was published in IEEE Access [18].

6.7. Computer Vision and Deep Learning applied to Facial analysis in the invisible spectra

Participants: David Anghelone, Antitza Dantcheva.

The goal of our work is to analyze faces, as well as recognize events in the invisible spectra. In the last few years, face analysis has been a highly active area and has attracted a lot of interest from the scientific community. Limitations encountered in the visible spectrum such as illumination-restriction have the ability to be overcome in the infrared spectrum. We explored the state-of-the-Art of facial analysis in the invisible spectrum including low energy infrared waves, as well as ultraviolet waves. In this context we have captured images in each spectra and intend to process the data. We aim at designing a model, which extracts biometric features. The key challenges are the processing of contours, shape, etc. This subject is within the framework of the national project *SafeCity*: Security of Smart Cities.

6.8. ImaGINator: Conditional Spatio-Temporal GAN for Video Generation

Participants: Yaohui Wang, Antitza Dantcheva, Piotr Bilinski [University of Warsaw], François Brémond.

keywords: GANs, Video Generation

Generating human videos based on single images entails the challenging simultaneous generation of realistic and visual appealing appearance and motion. In this context, we propose a novel conditional GAN architecture, namely ImaGINator [35] (see Figure 11), which given a single image, a condition (label of a facial expression or action) and noise, decomposes appearance and motion in both latent and high level feature spaces, generating realistic videos. This is achieved by (i) a novel spatio-temporal fusion scheme, which generates dynamic motion, while retaining appearance throughout the full video sequence by transmitting appearance (originating from the single image) through all layers of the network. In addition, we propose (ii) a novel transposed (1+2)D convolution, factorizing the transposed 3D convolutional filters into separate transposed temporal and spatial components, which yields significantly gains in video quality and speed. We extensively evaluate our approach on the facial expression datasets MUG and UvA-NEMO, as well as on the action datasets NATOPS and Weizmann. We show that our approach achieves significantly better quantitative and qualitative results than the state-of-the-art (see Table 1).

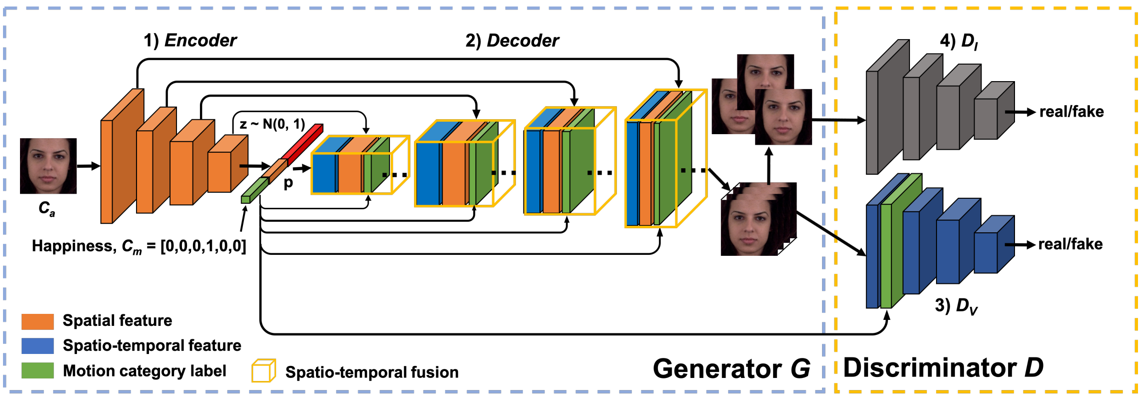

Figure 11. ***Overview of the proposed ImaGINator****. In the GeneratorG, the Encoder firstly encodes an input image c_a into a single vector p. Then, the Decoder produces a video based on a motion c_m and a random vector z. By using spatio-temporal fusion, low level spatial feature maps from the Encoder are directly concatenated into the Decoder. While D_I discriminates whether the generated images contain an authentic appearance, D_V additionally determines whether the generated videos contain an authentic motion.*

6.9. Characterizing the State of Apathy with Facial Expression and Motion Analysis

Participants: S L Happy, Antitza Dantcheva, Abhijit Das, François Brémond, Radia Zeghari [Cobtek], Philippe Robert [Cobtek].

Table 1. Evaluation of VGAN, MoCoGAN and proposed ImaGINator with respect to image quality (SSIM/PSNR) and video quality (FID).

	MUG		NATOPS	
	SSIM/PSNR	FID	SSIM/PSNR	FID
VGAN	0.28/14.54	74.72	0.72/20.09	167.71
MoCoGAN	0.58/18.16	45.46	0.74/21.82	49.46
ImaGINator	**0.75/22.63**	**29.02**	**0.88/27.39**	**26.86**
	Weizmann		**UvA-NEMO**	
	SSIM/PSNR	FID	SSIM/PSNR	FID
VGAN	0.29/15.78	127.31	0.21/13.43	30.01
MoCoGAN	0.42/17.58	116.08	0.45/16.58	29.81
ImaGINator	**0.73/19.67**	**99.80**	**0.66/20.04**	**16.16**

Reduced emotional response, lack of motivation, and limited social interaction comprise the major symptoms of apathy. Current methods for apathy diagnosis require the patient's presence in a clinic, and time consuming clinical interviews and questionnaires involving medical personnel, which are costly and logistically inconvenient for patients and clinical staff, hindering among other large scale diagnostics. In this work we introduced a novel machine learning framework to classify apathetic and non-apathetic patients based on analysis of facial dynamics, entailing both emotion and facial movement. Our approach catered to the challenging setting of current apathy assessment interviews, which include short video clips with wide face pose variations, very low-intensity expressions, and insignificant inter-class variations. We tested our algorithm on a dataset consisting of 90 video sequences acquired from 45 subjects and obtained an accuracy of 84% in apathy classification. Based on extensive experiments, we showed that the fusion of emotion and facial local motion produced the best feature set for apathy classification. In addition, we trained regression models to predict the clinical scores related to the mental state examination (MMSE) and the neuropsychiatric apathy inventory (NPI) using the motion and emotion features. Our results suggested that the performance can be further improved by appending the predicted clinical scores to the video-based feature representation. This work has been presented at the IEEE International Conference on Automatic Face and Gesture Recognition (FG 2019) [25].

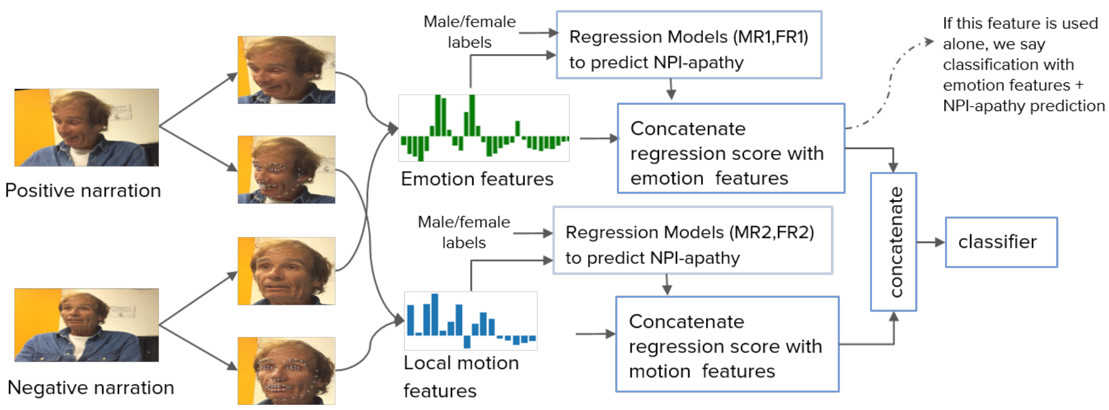

Figure 12. Overall framework for apathy detection from facial videos.

6.10. Dual-threshold Based Local Patch Construction Method for Manifold Approximation And Its Application to Facial Expression Analysis

Participants: S L Happy, Antitza Dantcheva, Aurobinda Routray [IIT Kharagpur].

In this paper, we propose a manifold based facial expression recognition framework which utilizes the intrinsic structure of the data distribution to accurately classify the expression categories. Specifically, we model the expressive faces as the points on linear subspaces embedded in a Grassmannian manifold, also called as expression manifold. We propose the dual-threshold based local patch (DTLP) extraction method for constructing the local subspaces, which in turn approximates the expression manifold. Further, we use the affinity of the face points from the subspaces for classifying them into different expression classes. Our method is evaluated on four publicly available databases with two well known feature extraction techniques. It is evident from the results that the proposed method efficiently models the expression manifold and improves the recognition accuracy in spite of the simplicity of the facial representatives. This work has been presented at the European Signal Processing Conference (EUSIPCO'19) [26].

6.11. A Weakly Supervised Learning Technique for Classifying Facial Expressions

Participants: S L Happy, Antitza Dantcheva, François Brémond.

The universal hypothesis suggests that the six basic emotions: anger, disgust, fear, happiness, sadness, and surprise, are being expressed by similar facial expressions by all humans. While existing datasets support the universal hypothesis and comprise of images and videos with discrete disjoint labels of profound emotions, real-life data contains jointly occurring emotions and expressions of different intensities. Models, which are trained using categorical one-hot vectors often over-fit and fail to recognize low or moderate expression intensities. Motivated by the above, as well as by the lack of sufficient annotated data, we propose a weakly supervised learning technique for expression classification, which leveraged the information of unannotated data. Crucial in our approach was that we first trained a convolutional neural network (CNN) with label smoothing in a supervised manner and proceeded to tune the CNN-weights with both labelled and unlabelled data simultaneously. Experiments on four datasets demonstrated large performance gains in cross-database performance, as well as showed that the proposed method achieved to learn different expression intensities, even when trained with categorical samples. This work was published in Pattern Recognition Letters [15].

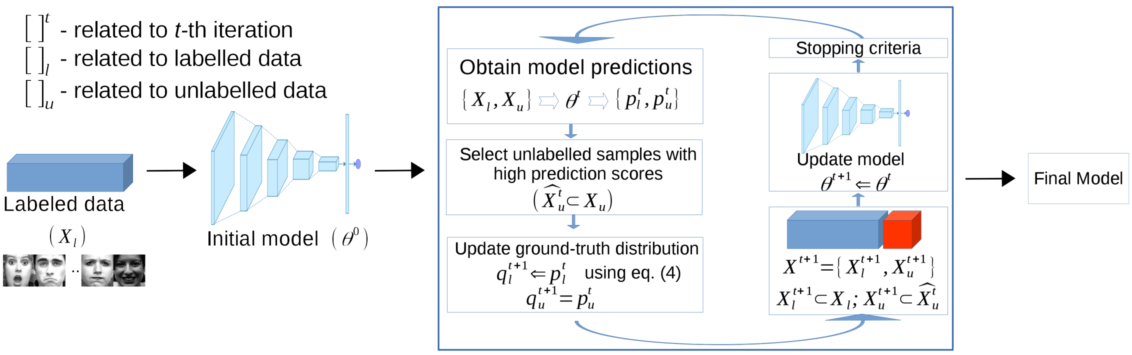

Figure 13. Workflow of the proposed method for weakly supervised learning of facial expressions.

6.12. Robust Remote Heart Rate Estimation from Face Utilizing Spatial-temporal Attention

Participants: Antitza Dantcheva, Abhijit Das, Xuesong Niu [Chinese Academy of Sciences], Xingyuan Zhao [Chinese Academy of Sciences], Hu Han [Chinese Academy of Sciences], Shiguang Shan [Chinese Academy of Sciences], Xilin Chen [Chinese Academy of Sciences].

We proposed an end-to-end approach for robust remote heart rate (HR) measurement gleaned from facial videos. Specifically the approach was based on remote photoplethysmography (rPPG), which constitutes a pulse triggered perceivable chromatic variation, sensed in RGB-face videos. Incidentally rPPGs can be affected in less-constrained settings. To unpin the shortcoming, the proposed algorithm utilized a spatio-temporal attention mechanism, which placed emphasis on the salient features included in rPPG-signals. In addition, we proposed an effective rPPG augmentation approach, generating multiple rPPG signals with varying HRs from a single face video. Experimental results on the public datasets VIPL-HR and MMSE-HR showed that the proposed method outperformed state-of-the-art algorithms in remote HR estimation. This work has been presented at the IEEE International Conference on Automatic Face and Gesture Recognition (FG 2019) [28].

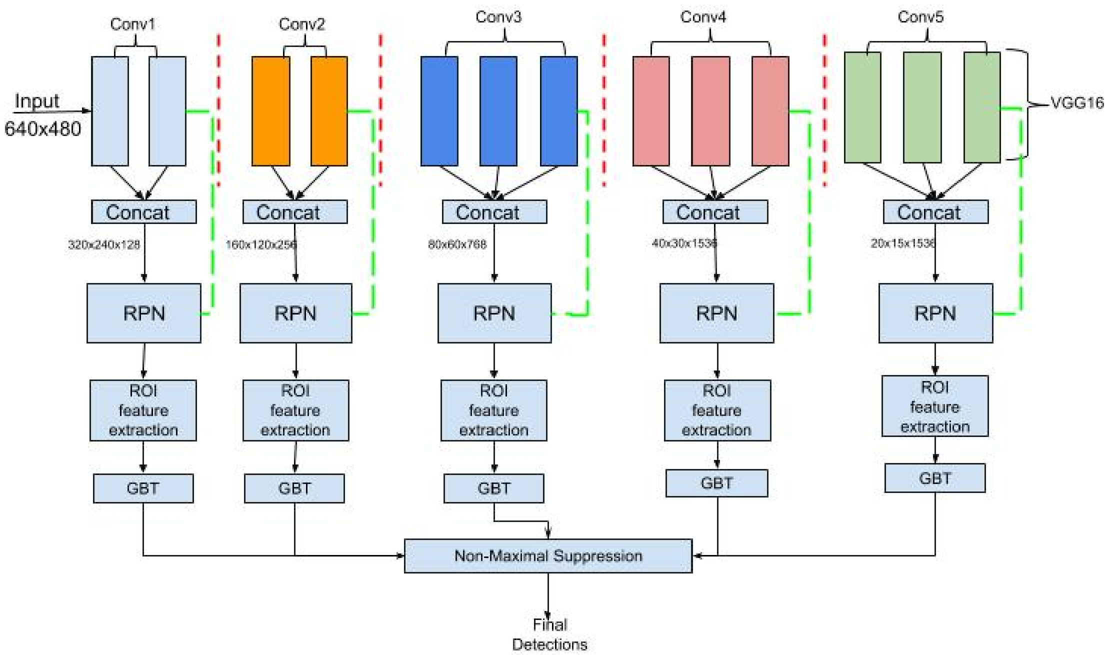

Figure 14. Overview of the proposed end-to-end trainable approach for rPPG based remote HR measurement via representation learning with spatial-temporal attention.

6.13. Quantified Analysis for Epileptic Seizure Videos

Participants: Jen-Cheng Hou, Monique Thonnat.

Epilepsy is a type of neurological disorder, affecting around 50 million people worldwide. Epilepsy's main symptoms are seizures, which are caused by abnormal neuronal activities in the brain. To determine appropriate treatments, neurologists assess manifestation of patients' behavior when seizures occur. Nevertheless, there are few objective criteria regarding the procedure, and diagnosis could be biased due to subjective evaluation.

Hence it is important to quantify patients' ictal behaviors for better assessment of the disorder. In collaboration with Dr. Fabrice Bartolomei and Dr. Aileen McGonigal from Timone Hospital, Marseille, we have access to video recordings from epilepsy monitoring unit for analysis, with consent from ethics committee (IRB) and the patients involved.

6.13.1. Seizure Video Classification and Background Video Collection

In an epilepsy monitoring unit, EEG and video recording are usually collected. For patients who need brain surgery to remove lobes that produce seizures, stereo-EEG (SEEG) recordings are particularly measured. SEEG is an intrusive measurement and provides information of the seizure type. We have 86 seizure videos from 20 patients along with the corresponding SEEG conclusion (i.e. pre-frontal epilepsy, occipital epilepsy, etc.). In this study, the goal is to classify seizure videos to their seizure types. Classification was conducted by fine-tuning a pre-trained video classification model, I3D, with 10-fold cross-validation. Due to the relatively small volume of data we have and the challenging nature of our videos, the performance was not satisfactory enough. Inspired by recent semi-supervised works in leveraging large unlabeled dataset for better adaptation to certain tasks, we are collecting large volume of background videos in the epilepsy monitoring unit, in which patients' behavior are normal, such as eating, sleeping, and talking. The volume of the background video can be up to 1000 hours, which could be taken as unlabeled dataset for semi-supervised learning in our case.

6.13.2. Quantifying Rhythmic Rocking Movement with Head Tracking

In this study, six seizures from three patients with pre-frontal epilepsy were analyzed. The duration of rocking was 15-40 seconds, with marked regularity throughout each seizure. Our objective is to document time-evolving frequencies of antero-posterior rocking body movements occurring during seizures. We adopted MobileNet [39] as our backbone model for detecting head of the patient, and hence obtain the trajectories of head movement (see Figure 15). After smoothing the trajectories and find the valid peaks corresponding to the antero-posterior movement, we compute the time-evolving movement frequency for each seizure video. Whereas the rocking frequency varied substantially between patients and seizures (0.3-1Hz), coefficient of variation of frequency was low ($\leq 12\%$). The study report is under review for a medical journal.

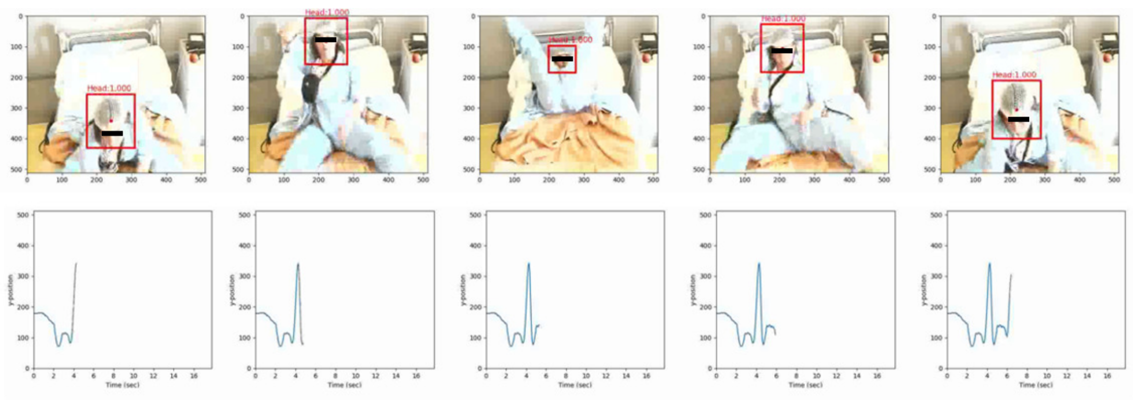

Figure 15. The first row demonstrates the image samples of the antero-posterior movement. The second row shows the position of the head through time in the vertical direction.

6.14. Skeleton Image Representation for 3D Action Recognition

Participants: Carlos Caetano, François Brémond.

Due to the availability of large-scale skeleton datasets, 3D human action recognition has recently called the attention of computer vision community. Many works have focused on encoding skeleton data as skeleton image representations based on spatial structure of the skeleton joints, in which the temporal dynamics of the sequence is encoded as variations in columns and the spatial structure of each frame is represented as rows of a matrix. To further improve such representations, we introduce a novel skeleton image representation to be used as input of Convolutional Neural Networks (CNNs), named SkeleMotion. The proposed approach encodes the temporal dynamics by explicitly computing the magnitude and orientation values of the skeleton joints. Different temporal scales are employed to compute motion values to aggregate more temporal dynamics to the representation making it able to capture long-range joint interactions involved in actions as well as filtering noisy motion values. Experimental results demonstrate the effectiveness of the proposed representation on 3D action recognition outperforming the state-of-the-art on NTU RGB+D 120 dataset. This work has been published in AVSS 2019 [31].

In another work, we have explore how to better represent motion information in a video. The temporal component of videos provides an important clue for activity recognition, as a number of activities can be reliably recognized based on the motion information. In view of that, this work proposes a novel temporal stream for two-stream convolutional networks based on images computed from the optical flow magnitude and orientation, named Magnitude-Orientation Stream (MOS), to learn the motion in a better and richer manner. Our method applies simple non-linear transformations on the vertical and horizontal components of the optical flow to generate input images for the temporal stream. Moreover, we also employ depth information to use as a weighting scheme on the magnitude information to compensate the distance of the subjects performing the activity to the camera. Experimental results, carried on two well-known datasets (UCF101 and NTU), demonstrate that using our proposed temporal stream as input to existing neural network architectures can improve their performance for activity recognition. Results demonstrate that our temporal stream provides complementary information able to improve the classical two-stream methods, indicating the suitability of our approach to be used as a temporal video representation. two-stream convolutional networks, spatiotemporal information, optical flow, depth information. This work has been published in the Journal of Visual Communication and Image Representation [14].

6.15. Toyota Smarthome: Real-World Activities of Daily Living

Participants: Srijan Das, Rui Dai, François Brémond.

The performance of deep neural networks is strongly influenced by the quantity and quality of annotated data. Most of the large activity recognition datasets consist of data sourced from the Web, which does not reflect challenges that exist in activities of daily living. In this work, we introduce a large real-world video dataset for activities of daily living: Toyota Smarthome. The dataset consists of 16K RGB+D clips of 31 activity classes, performed by seniors in a smarthome. Unlike previous datasets, videos were fully unscripted. As a result, the dataset poses several challenges: high intra-class variation, high class imbalance, simple and composite activities, and activities with similar motion and variable duration. Activities were annotated with both coarse and fine-grained labels. These characteristics differentiate Toyota Smarthome from other datasets for activity recognition as illustrated in 16.

As recent activity recognition approaches fail to address the challenges posed by Toyota Smarthome, we present a novel activity recognition method with attention mechanism. We propose a pose driven spatio-temporal attention mechanism through 3D ConvNets. We show that our novel method outperforms state-of-the-art methods on benchmark datasets, as well as on the Toyota Smarthome dataset. We release the dataset for research use at https://project.inria.fr/toyotasmarthome. This work is done in collaboration with Toyota Motors Europe and is published in ICCV 2019 [21].

6.15.1. Looking deeper into Time for Activities of Daily Living Recognition

Participants: Srijan Das, Monique Thonnat, François Brémond.

In this work, we introduce a new approach for Activities of Daily Living (ADL) recognition. In order to discriminate between activities with similar appearance and motion, we focus on their temporal structure.

Figure 16. Sample frames from Toyota Smarthome dataset: 1-7 label at the right top corner respectively correspond to camera view 1, 2, 3, 4, 5, 6 and 7 as marked in the plan of the apartment on the right. Image from camera view (1) Drink from can, (2) Drink from bottle, (3) Drink form glass and (4) Drink from cup are all fine grained activities with a coarse label drink. Image from camera view (5) Watch TV and (6) Insert tea bag show activities with large source-to-camera distance and occlusion. Images with camera view (7) Enter illustrate the RGB image and the provided 3D skeleton.

Actions with subtle and similar motion are hard to disambiguate since long-range temporal information is hard to encode. So, we propose an end-to-end Temporal Model to incorporate long-range temporal information without losing subtle details. The temporal structure is represented globally by different temporal granularities and locally by temporal segments as illustrated in fig. 17. We also propose a two-level pose driven attention mechanism to take into account the relative importance of the segments and granularities. We validate our approach on 2 public datasets: a 3D human activity dataset (NTU-RGB+D) and a human action recognition dataset with object interaction dataset (Northwestern-UCLA Multiview Action 3D). Our Temporal Model can also be incorporated with any existing 3D CNN (including attention based) as a backbone which reveals its robustness. This work has been accepted in WACV 2020 [20].

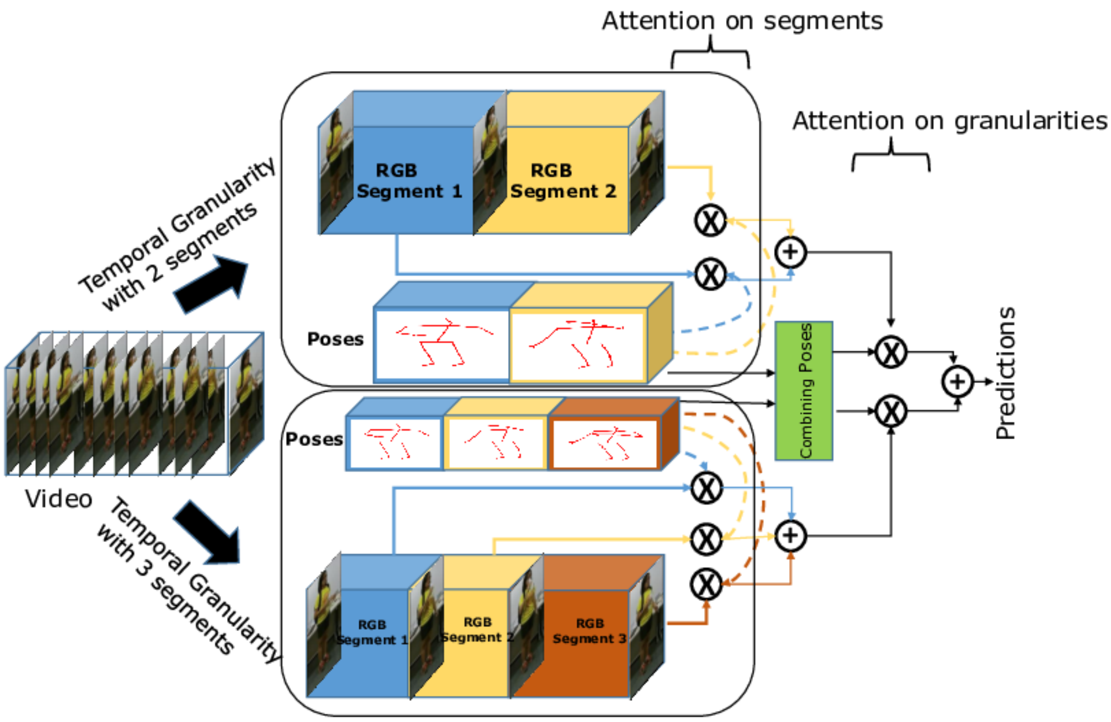

Figure 17. Framework of the proposed approach in a nutshell for two temporal granularities. The articulated poses soft-weight the temporal segments and the temporal granularities using a two-level attention mechanism.

6.16. Self-Attention Temporal Convolutional Network for Long-Term Daily Living Activity Detection

Participants: Rui Dai, François Brémond.

This year, we proposed a Self-Attention - Temporal Convolutional Network (SA-TCN), which is able to capture both complex activity patterns and their dependencies within long-term untrimmed videos [34]. This attention block can also embed with other TCN-nased models. We evaluate our proposed model on DAily Home LIfe Activity Dataset (DAHLIA) and Breakfast datasets. Our proposed method achieves state-of-the-art performance on both datasets.

6.16.1. Work Flow

Given an untrimmed video, we represent each non-overlapping snippet by a visual encoding over 64 frames. This visual encoding is the input to the encoder-TCN, which is the combination of the following operations: 1D temporal convolution, batch normalization, ReLu, and max pooling. Next, we send the output of the encoder-TCN into the self-attention block to capture long-range dependencies. After that, the decoder-TCN applies the 1D convolution and up sampling to recover a feature map of the same dimension as visual encoding. Finally, the output will be sent to a fully connected layer with softmax activation to get the prediction. Fig 18 and 19 provide the structure of our model.

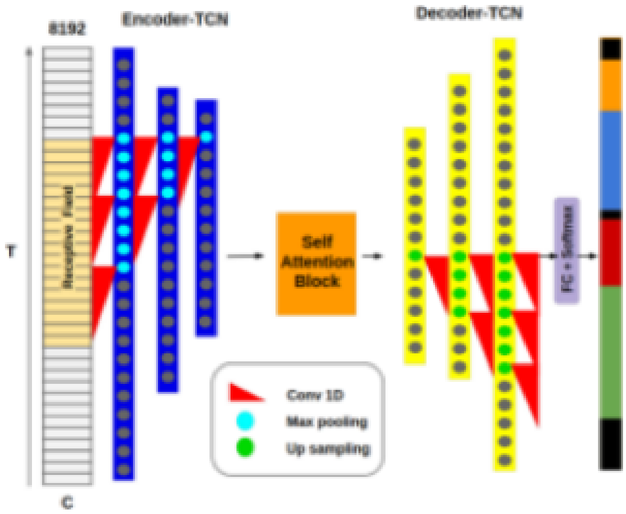

*Figure 18. **Overview**. The model contains mainly three parts: (1) visual encoding, (2) encoder-decoder structure, (3) attention block*

6.16.2. Result

We evaluated the proposed method on two daily-living activity datasets (DAHLIA, Breakfast) and achieved state-of-the-art performances. We compared with these following State-of the arts: DOHT, Negin *et al.*, GRU , ED-TCN, TCFPN.

Table 2. Activity detection results on DAHLIA dataset with the average of view 1, 2 and 3. * marked methods have not been tested on DAHLIA in their original paper.

Model	**FA1**	**F-score**	**IoU**	**mAP**
DOHT	0.803	0.777	0.650	-
GRU*	0.759	0.484	0.428	0.654
ED-TCN*	0.851	0.695	0.625	0.826
Negin *et al.*	0.847	0.797	0.723	-
TCFPN*	0.910	**0.799**	0.738	**0.879**
SA-TCN	**0.921**	0.788	**0.740**	0.862

6.17. DeepSpa Project

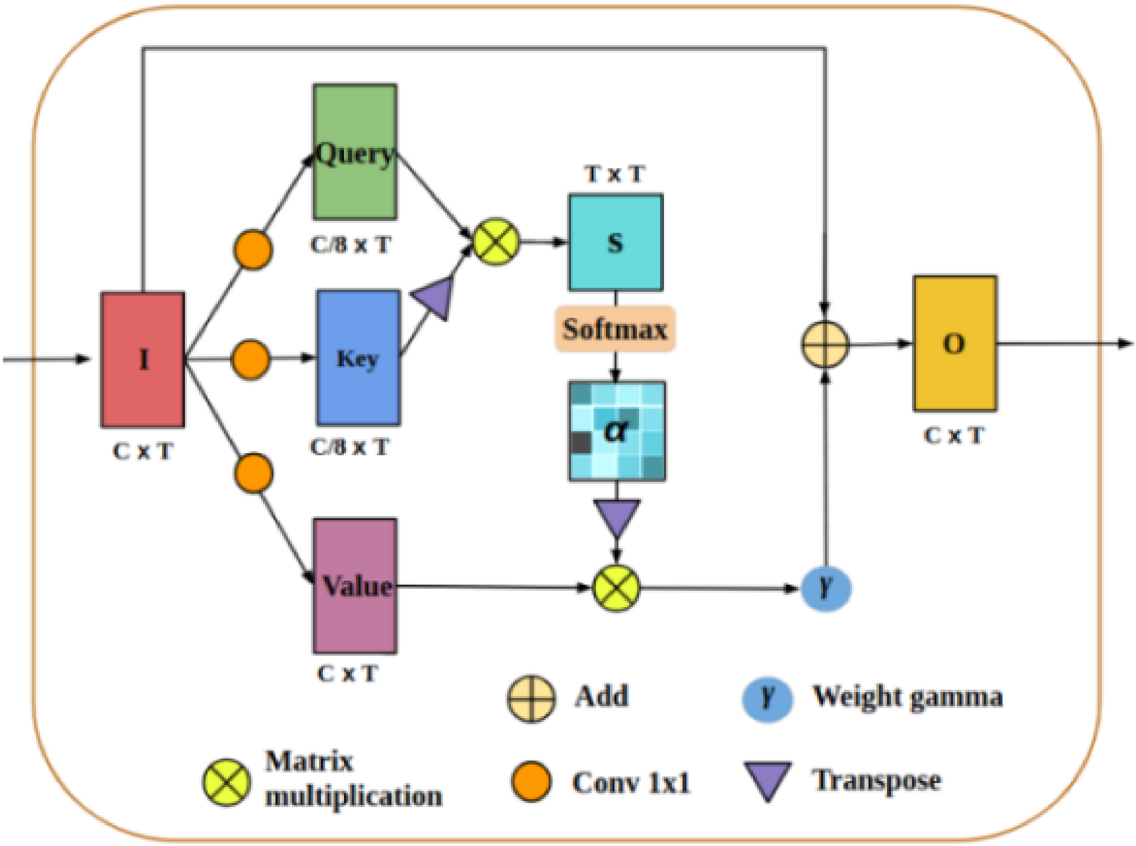

*Figure 19. **Attention block**. This figure presents the structure of attention block*

Table 3. Activity detection results on Breakfast dataset.

Model	**FA1**	**F-Score**	**IoU**	**mAP**
GRU	0.368	0.295	0.198	0.380
ED-TCN	0.461	0.462	0.348	0.478
TCFPN	**0.519**	0.453	0.362	0.466
SA-TCN	0.497	**0.494**	**0.385**	**0.480**

Table 4. Average precision of ED-TCN on DAHLIA.

Activities	**Background**	**House work**	**Working**	**Cooking**
AP	0.36	0.65	0.95	0.96
Activities	**Laying table**	**Eating**	**Clearing table**	**Wash dishes**
AP	0.90	0.97	0.80	0.97

Table 5. Combination of attention block with other TCN-based model: TCFPN. (Evaluated on DAHLIA dataset)

Model	**FA1**	**F-score**	**IoU**	**mAP**
TCFPN	0.910	**0.799**	0.738	0.879
SA-TCFPN	**0.917**	**0.799**	**0.748**	**0.894**

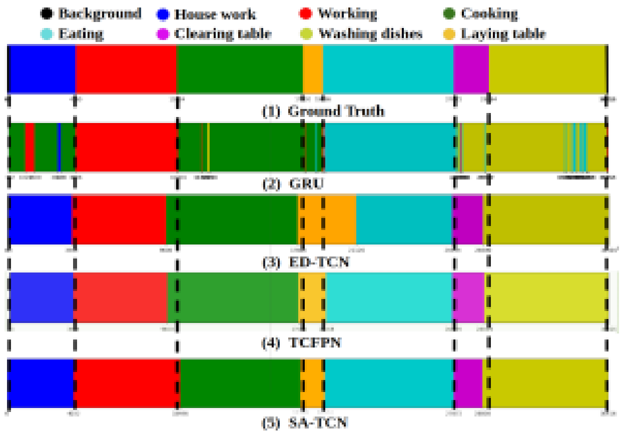

Figure 20. ***Detection visualization****. The detection visualization of video 'S01A2K1' in DAHLIA: (1) ground truth, (2) GRU, (3) ED-TCN, (4) TCFPN and (5) SA-TCN.*

Participants: Alexandra König, Rachid Guerchouche, Minh Tran-Duc, Antitza Dantcheva, S L Happy, Abhijit Das.

The DeepSpa (Deep Speech Analysis, January 2019 - June 2020) project aims to deliver telecommunication-based neurocognitive assessment tools for early screening, early diagnostic and follow-up of cognitive disorders, mainly in elderly. The target is also clinical trials addressing Alzheimer's and other neurodegenerative diseases. By combining AI in speech recognition and video analysis for facial expression recognition, the proposed tools allow remote cognitive and psychological testing, thereby saving time and money.

The partners of the project are:

- Inria: technical partner and project coordinator
- University of Maastricht: clinical partner
- Jansen & Jansen: pharma partner and business champion
- Association Innovation Alzheimer: subgranted clinical partner
- Ki-element: subgranted technical partner.

6.17.1. Project structure

The DeepSpA project is structured in two use-cases:

- Use-case 1: remote assessment through phone for early screening of cognitive disorders (University of Maastricht, Jansen & Jansen and Ki-element): using AI based speech recognition; assessments through phone are made possible. A clinical trial is currently running in Maastricht (by end 2019, 70 subjects will be included, and 50 others will be included in 2020), the goal is to study the feasibility of such phone assessment in comparison to face-to-face assessment.
- Use-case 2: remote assessment through video-conference system (telemedicine tool) (Inria, Jansen & Jansen and Association Innovation Alzheimer): Inria developed a telemedicine tool which allows complete remote assessment. AI based speech and facial expression recognition empower the cognitive assessment by providing extra features useful for clinicians.

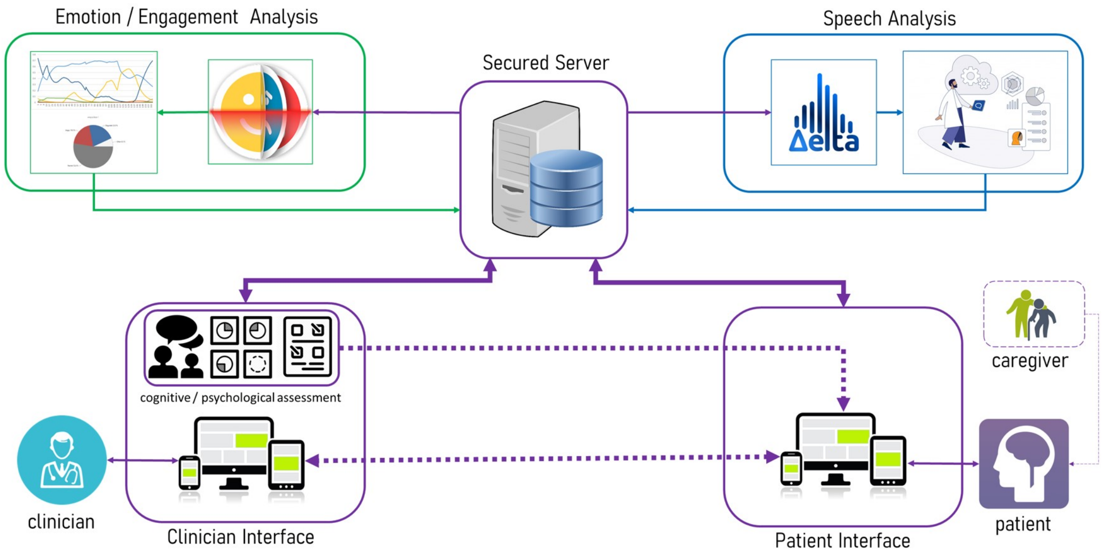

Figure 21. Global view of the telemedicine tool developed by Inria (STARS).

6.17.2. Telemedicine / Clinical Study with Digne-les-Bains

In order to evaluate the feasibility of remote assessment through the telemedicine tool, a collaboration with the city of Digne-les-Bains started in March 2019. The Hospital of Digne-les-Bains, la Maison de la Santé and the ADMR (association dealing with isolated people) are involved in a running clinical study, which aims at evaluating the feasibility of the remote assessment in two different setups:

- Clinical setup: a fixed place where the participant will undergo the telemedicine session: clinic, hospital, pharmacy, health centres ....
- Mobile Units: a mobile unit goes to the subjects home, the telemedicine session is done inside the mobile unit (e.g., van).

We already started including subjects in the clinical setup case. By end 2019, we expect to include about 15 subjects, 25 extra subjects will be included during 2020. Mobile units setup will be tested during 2020.

First results and observations already showed that the telemedicine tool allows full assessments. Clinicians and patients showed strong interest and appreciation of such tool.

6.17.3. Facial expressions recognition and engagement evaluation in the telemedicine tool

The STARS team is doing research on facial expressions analysis, which could be integrated as part of the vision module of the telemedicine tool [25].

Notable software related to this research is the provided API on the cloud, which allows sending video files and retrieving emotions, gaze direction, facial movements and head direction (implemented by S L Happy).

6.18. Store Connect and Solitaria

Participants: Sébastien Gilabert, Minh Khue Phan Tran, François Brémond.

Store-Connect was a consortium aiming at detecting and positioning people in a supermarket. Several technologies were explore such as computing and merging trajectories obtained from the mobile phone of

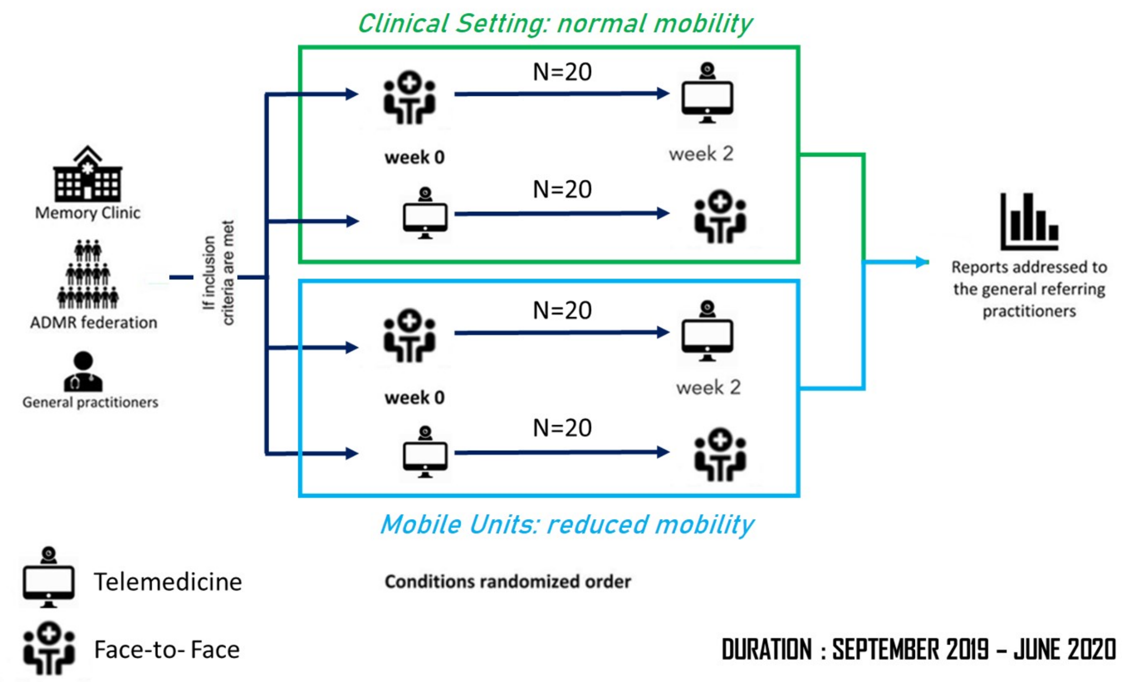

Figure 22. Global view of the clinical study with Digne-les-Bains.

customers and from video cameras. In a second step, the goal was to detect all the 'stop' events of the customers while shopping in the store.

6.18.1. SupICP

We have developed with the SED team, SupICP, a platform for integrating all plugins developed by STARS team. Our main contribution is the Ontology Language Plugin. With this plugin, we can use contextual and knowledge information inside scenarios designed for video event recognition. Currently, we are improving this plugin for combining the Ontology Language with Deep Learning technology towards “Action recognition based on Deep Learning and Ontology Language”.

We have also installed this software at the Institute Claude Pompidou, in order to conduct clinical trials, and to work with medical scientists.

6.18.2. Solitaria

The aim of this project is to combine data extracted from domestic sensors and from video cameras, and to implement this plugin into SupICP to monitor older people at home.

6.19. Synchronous Approach to Activity Recognition

Participants: Daniel Gaffé, Sabine Moisan, Annie Ressouche, Jean-Paul Rigault, Ines Sarray.

Activity Recognition aims at recognizing and understanding sequences of actions and movements of mobile objects (human beings, animals or artifacts), that follow the predefined model of an activity. We propose to describe activities as a series of actions, triggered and driven by environmental events.

This year we mainly refined the ADeL description language, the semantics of some of its instructions and their compilation into equation systems. We also improved the recognition engine and the synchronizer to better handle the synchronous/asynchronous transformation.

Work remains to be done to complete a full framework to generate generic recognition systems and automatic tools to interface with static and dynamic analysis tools, such as model checkers or performance monitors.

6.19.1. Activity Description Language

The ADeL language was designed to describe various activities, it provides two different (and equivalent) formats: graphical and textual. This year we started to describe use case examples in the medical domain: serious games and exercises for patients having cognitive problems, such as Alzheimer or autistic persons. This kind of games are used to test patients and to evaluate their behavior and interactions. These use cases lead us to improve the language and part of its semantics. An example of the graphical format describing a simple exercise activity is given in figure 23.

Work remains to be done to improve the usability of the language by our end-users.

6.19.2. Synchronizer

Using the synchronous paradigm makes time manipulation easy thanks to determinism and synchronous parallellism; moreover, tools exist to support formal verification. However, the sensor environment is asynchronous and it is thus necessary to transform asynchronous events given by sensors into synchronous logical instants. It is a difficult problem that does not have an exact and complete solution. We introduced a component called "synchronizer" between the environment sensors and the recognition engine. The synchronizer is responsible for filtering the sensor data, grouping them into logical instants, and sending these instants to the recognition engine.

We specified a generic algorithm, based on *awaited* events, i.e. the events which may trigger transitions to a next state. These events are provided by each automaton in each state. This algorithm is parametrized by heuristics to adapt to different situations. There are two main points of variation in the synchronizer where heuristics can be applied: when processing data coming from the sensors (to collect and combine raw data) and when building logical instants (to decide on the end of instants and to manage preemptions).

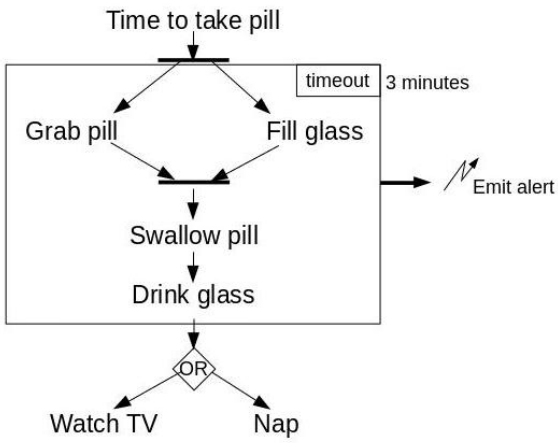

Figure 23. Example of a simple activity (patient should take a pill at a given time) including a parallel and a timeout instructions.

This year we finished to implement a first version of the synchronizer (for one single activity to recognize), we defined different heuristics, and we tested the synchronizer algorithm on some uses cases with these heuristics [11].

6.20. Probabilistic Activity Modeling

Participants: Elisabetta de Maria, Sabine Moisan, Jean-Paul Rigault, Thibaud L'Yvonnet.

Serious games constitute a domain in which real-time activity recognition is particularly relevant: the expected behavior is well identified and it is possible to rely on different sensors (biometric and external) while playing the game. We focus on games to help in diagnosis and treatment of patients.

We developed a formal approach to model such activities, taking into account possible variations in human behavior. All the scenarios of an activity are not equivalent: some are typical (thus frequent) while others seldom happen. We propose to quantify the likelihood of these variations by associating probabilities with the key actions of the activity description. We rely on a formal model based on probabilistic discrete-time Markov chains (DTMCs). We used the PRISM framework and its model checking facilities to express and check interesting temporal logic properties (PCTL).

As a use case, we considered a serious game to analyze the behavior of Alzheimer patients. We encoded this game as a DTMC in PRISM and we defined several meaningful PCTL properties that are then automatically tested thanks to the PRISM model checker. Two kinds of properties may be defined: those to verify the model and those oriented toward the medical domain. The latter may give indications to a practitioner regarding a patient's behavior. These properties include the use of PRISM “rewards” to quantify the performance of patients.

We expect that such a modeling approach could provide doctors with new indications for interpreting patients' performance and we identified three medically interesting outcomes for this approach. First, to evaluate a new patient before the first diagnosis of doctors, we can compare her game performance to a reference model representing a "healthy" behavior. Second, to monitor known patients, a customized model can be created according to their first results, and, over time, their health improvement or deterioration could be monitored. Finally, to pre-select a cohort of patients, we can use a reference model to determine, in a fast way, whether a new group of patients belongs to this specific category.

This year we first addressed the model definition and its suitability to check behavioral properties of interest [24]. Indeed, this is mandatory before envisioning any clinical study.

The next step will be to validate our approach as well as to test its scalability on three other serious games selected with the help of clinicians. We wrote a medical protocol to be submitted to CERNI proposing clinical experimentations with patients. This protocol will be a collaboration with the ICP institute, member of the CoBTEX laboratory. The new games will be modeled in PRISM and different configurations (for example for Mild, Moderate or Severe Alzheimer) will be set up with the participation of clinicians. Then, several groups of patients will play these games and their results will be recorded to calibrate our initial models.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts and Grants with Industry

Stars team has currently several experiences in technological transfer towards industrials, which have permitted to exploit research result:

7.1.1. Ekinnox

is a spin-off project of the Stars team which aims at improving the rehabilitation process for caregivers and patients. Thanks to a computer vision based system (camera combined with algorithms detecting human motion), Ekinnox provides a simple and efficient tool to quantify and visualize the performance of patients (e.g. gait parameters computation such as side-by-side video comparison, automatic sequencing of video or 3D display) during their rehabilitation process. This company was created at the beginning of 2017.

7.1.2. Toyota

is working with Stars on action recognition software to be integrated on their robot platform. This project aims at detecting critical situations in the daily life of older adults alone at home. This will require not only recognition of ADLs but also an evaluation of the way and timing in which they are being carried out. The system we want to develop is intended to help them and their relatives to feel more comfortable because they know that potential dangerous situations will be detected and reported to caregivers if necessary. The system is intended to work with a Partner Robot - HSR - (to send real-time information to the robot) to better interact with the older adult.

7.1.3. Vedecom

is interested in developing algorithms for people detection for self-driving cars. Among many challenges in pedestrian detection, the ones of interest are a) Scale- handling, b) Occlusion-handling and c) Cross-dataset generalization. Each of the aforementioned challenges is critical to enable modern applications like self-driving vehicles become safe enough for active deployment. To improve the performance of contemporary pedestrian detectors, one of our first major idea is to use multiple layers of a CNN simultaneously. Towards this, we proposed a new pedestrian detection system called Multiple-RPN. Another recent work is adding pseudo-segmentation information to pedestrian detection. The proposed features of our system perform close to the best performing detectors today.

7.1.4. Kontron

has a collaboration with Stars, which runs from April 2018 until April 2021 to embed CNN based people tracker within a video-camera. Their system uses Intel VPU modules, such as Myriad X (MA2485), based on OpenVino library.

7.1.5. The company ESI

(European System Integration) has a collaboration with Stars, which runs from September 2018 until March 2022 to develop a novel Re-Identification algorithm which can be easily set-up with low interaction for video-surveillance applications. ESI provides software solutions for remote monitoring stations, remote assistance, video surveillance, and call centers. It was created in 1999 and ESI is a leader in the French remote monitoring market. Nowadays, ensuring the safety of goods and people is a major problem. For this reason, surveillance technologies are attracting growing interest and their objectives are constantly evolving: it is now a question of automating surveillance systems and helping video surveillance operators in order to limit interventions and staff. One of the current difficulties is the human processing of video, as the multiplication of video streams makes it difficult to understand meaningful events. It is therefore necessary to give video surveillance operators suitable tools to assist them with tasks that can be automated. The integration of video analytics modules will allow surveillance technologies to gain in efficiency and precision. In recent times, deep learning techniques have been made possible by the advent of GPU processors, which offer significant processing possibilities. This leads to the development of automatic video processing.

7.1.6. Fantastic Sourcing

is a French SME specialized in micro-electronics, it develops e-health technologies. Fantastic Sourcing is collaborating with Stars through the UCA Solitaria project, by providing their Nodeus system. Nodeus is a IoT (Internet of Things) system for home support for the elderly, which consists of a set of small sensors (without video cameras) to collect precious data on the habits of isolated people. Solitaria project performs a multi-sensor activity analysis for monitoring and safety of older and isolated people. With the increase of the ageing population in Europe and in the rest of the world, keeping elderly people at home, in their usual environment, as long as possible, becomes a priority and a challenge of modern society. A system for monitoring activities and alerting in case of danger, in permanent connection with a device (an application on a phone, a surveillance system ...) to warn relatives (family, neighbours, friends ...) of isolated people still living in their natural environment could save lives and avoid incidents that cause or worsen the loss of autonomy. In this R&D project, we propose to study a solution allowing the use of a set of innovative heterogeneous sensors in order to: 1) detect emergencies (falls, crises, etc.) and call relatives (neighbours, family, etc.); 2) detect, over short or longer predefined periods, behavioural changes in the elderly through an intelligent analysis of data from sensors.

7.1.7. Nively

is a French SME specialized in e-health technologies, it develops position and activity monitoring of activities of daily living platforms based on video technology. Nively's mission is to use technological tools to put people back at the center of their interests, with their emotions, identity and behavior. Nively is collaborating with Stars through the UCA Solitaria project, by providing their MentorAge system. This software allows the monitoring of elderly people in nursing homes in order to detect all the abnormal events in the lives of residents (falls, runaways, strolls, etc.). Nively's technology is based on RGBD video sensors (Kinects type) and a software platform for event detection and data visualization. Nively is also in charge of Software distribution for the ANR Activis project. This project is based on an objective quantification of the atypical behaviors on which the diagnosis of autism is based, with medical (diagnostic assistance and evaluation of therapeutic programs) and computer scientific (by allowing a more objective description of atypical behaviors in autism) objectives. This quantification requires video analysis of the behavior of people with autism. In particular, we propose to explore the issues related to the analysis of ocular movement, gestures and posture to characterize the behavior of a child with autism. Thus, Nively will add autistic behavior analysis software to its product range.

More bilateral Grants with industries is available at: http://www-sop.inria.fr/members/Francois.Bremond/topicsText/researchProjec

8. Partnerships and Cooperations

8.1. Regional Initiatives

See CoBTek, Nice Hospital, FRIS

8.2. National Initiatives

See Vedecom

8.2.1. ANR

8.2.1.1. ENVISION

Program: ANR JCJC

Project acronym: ENVISION

Project title: Computer Vision for Automated Holistic Analysis of Humans

Duration: October 2017-September 2020.

Coordinator: Antitza Dantcheva (STARS)

Abstract: The main objective of ENVISION is to develop the computer vision and theoretical foundations of efficient biometric systems that analyze appearance and dynamics of both face and body, towards recognition of identity, gender, age, as well as mental and social states of humans in the presence of operational randomness and data uncertainty. Such dynamics - which will include facial expressions, visual focus of attention, hand and body movement, and others, constitute a new class of tools that have the potential to allow for successful holistic analysis of humans, beneficial in two key settings: (a) biometric identification in the presence of difficult operational settings that cause traditional traits to fail, (b) early detection of frailty symptoms for health care.

8.2.2. FUI

8.2.2.1. Visionum

Program: FUI

Project acronym: Visionum

Project title: Visonium.

Duration: January 2015- December 2018.

Coordinator: Groupe Genious

Other partners: Inria (Stars), StreetLab, Fondation Ophtalmologique Rothschild, Fondation Hospitalière Sainte-Marie.

Abstract: This French project from Industry Minister aims at designing a platform to re-educate at home people with visual impairment.

8.2.2.2. StoreConnect

Program: FUI

Project acronym: StoreConect.

Project title: StoreConnect.

Duration: September 2016 - June 2019.

Coordinator: Ubudu (Paris).

Other partners: Inria (Stars), STIME (groupe Les Mousquetaires Paris), Smile (Paris), Thevolys (Dijon).

Abstract: StoreConnect is a FUI project started in 2016 and ended in 2019. The goal is to improve the shopping experience for customers inside supermarkets by adding new sensors such as cameras, beacons and RFID. By gathering data from all the sensors and combining them, it is possible to improve the way to communicate between shops and customers in a personalized way. StoreConnect acts as a middleware platform between the sensors and the shops to process the data and extract interesting knowledge organized via ontologies.

8.2.2.3. ReMinAry

Program: FUI

Project acronym: ReMinAry.

Project title: ReMinAry.

Duration: September 2016 - June 2020.

Coordinator: GENIOUS Systèmes,

Other partners: Inria (Stars), MENSIA technologies, Institut du Cerveau et de la Moelle épinière, la Pitié-Salpêtrière hospital.

Abstract: This project is based on the use of motor imagery (MI), a cognitive process consisting of the mental representation of an action without concomitant movement production. This technique consists in imagining a movement without realizing it, which entails an activation of the brain circuits identical to those activated during the real movement. By starting rehabilitation before the end of immobilization, a patient operated on after a trauma will gain rehabilitation time and function after immobilization is over. The project therefore consists in designing therapeutic video games to encourage the patient to re-educate in a playful, autonomous and active way in a phase where the patient is usually passive. The objective will be to measure the usability and the efficiency of the re-educative approach, through clinical trials centered on two pathologies with immobilization: post-traumatic (surgery of the shoulder) and neurodegenerative (amyotrophic lateral sclerosis).

8.3. European Initiatives

8.3.1. Collaborations in European Programs, Except FP7 & H2020

See EIT Health.

8.4. International Initiatives

8.4.1. Inria International Labs

- $EASafEE$: Associated team (2018-2020) Safe and Easy Environment for Alzheimer disease and related disorders. Inria Stars, National Taipei University of Technology Taiwan and CoBTeK team. The objective of SafEE is to develop an automated home support system, using information and communication technologies (ICT), to support the loss of autonomy and to improve the quality of life of the elderly population.
- $FER4HM$: Inria International Lab (2017-2020) Facial Expression Recognition for Health Monitoring. Coordinator: François Brémond, Antitza Dantcheva. Other partners: Chinese Academy of Sciences (CAS) (China). FER4HM aims to investigate computer vision methods for facial expression recognition in patients with Alzheimer's disease. Most importantly though, the project seeks to be part of a paradigm shift in current health care, efficiently and cost-effectively finding objective measures to (a) assess different therapy treatments, as well to (b) enable automated human-computer interaction in remote scale health care-frameworks.

8.4.1.1. Other IIL projects

- RESPECT

  Program: ANR PRCI (French-German, ANR-DFG)

  Project acronym: RESPECT

  Project title: Reliable, secure and privacy preserving multi-biometric person authentication

  Duration: April 2019-March 2023.

  Coordinator: Antitza Dantcheva (STARS)

Abstract: In spite of the numerous advantages of biometric recognition systems over traditional authentication systems based on PINs or passwords, these systems are vulnerable to external attacks and can leak data. Presentations attacks (PAs) – impostors who manipulate biometric samples to masquerade as other people – pose serious threats to security. Privacy concerns involve the use of personal and sensitive biometric information, as classified by the GDPR, for purposes other than those intended. Multi-biometric systems, explored extensively as a means of improving recognition reliability, also offer potential to improve PA detection (PAD) generalisation. Multi-biometric systems offer natural protection against spoofing since an impostor is less likely to succeed in fooling multiple systems simultaneously. For the same reason, previously unseen PAs are less likely to fool multi-biometric systems protected by PAD. RESPECT, a Franco-German collaborative project, explores the potential of using multi-biometrics as a means to defend against diverse PAs and improve generalisation while still preserving privacy. Central to this idea is the use of (i) biometric characteristics that can be captured easily and reliably using ubiquitous smart devices and, (ii) biometric characteristics which facilitate computationally manageable privacy preserving, homomorphic encryption.

The research focuses on characteristics readily captured with consumer-grade microphones and video cameras, specifically face, iris and voice. Further advances beyond the current state of the art involve the consideration of dynamic characteristics, namely utterance verification and lip dynamics. The core research objective is to determine which combination of biometrics characteristics gives the best biometric authentication reliability and PAD generalisation while remaining compatible with computationally efficient privacy preserving BTP schemes.

- $VIdeoSeizureAnalysis$: Inserm-Inria PhD grant (October 2018- September 2021). Partners: Prof F Bartolomei Inserm UMR 1106 La Timone Hospital Marseille and M Thonnat DR Inria Stars Sophia Antipolis. The objective of the PhD thesis entitled Quantified video analysis of seizure semiology in epilepsy is to provide new automated and objective analysis and interpretation of recorded videos of patients during epilepsy seizures.

8.4.2. Inria Associate Teams Not Involved in an Inria International Labs

8.4.2.1. SafEE (Safe & Easy Environment)

Title: SafEE (Safe Easy Environment) investigates technologies for the evaluation, stimulation and intervention for Alzheimer patients. The SafEE project aims at improving the safety, autonomy and quality of life of older people at risk or suffering from Alzheimer.

International Partner (Institution - Laboratory - Researcher):

National Taipei University of Technology Taipei (Taiwan) - Dept. of Electrical Engineering - Chao-Cheng Wu

Start year: 2018

See also: https://project.inria.fr/safee2/

SafEE (Safe Easy Environment) investigates technologies for the evaluation, stimulation and intervention for Alzheimer patients. The SafEE project aims at improving the safety, autonomy and quality of life of older people at risk or suffering from Alzheimer's disease and related disorders. More specifically the SafEE project : 1) focuses on specific clinical targets in three domains: behavior, motricity and cognition 2) merges assessment and non pharmacological help/intervention and 3) proposes easy ICT device solutions for the end users. In this project, experimental studies will be conducted both in France (at Hospital and Nursery Home) and in Taiwan.

8.4.2.2. Declared Inria International Partners

See Taiwan, China

8.4.3. Participation in Other International Programs

8.4.3.1. International Initiatives

FER4HM

Title: Facial expression recognition with application in health monitoring

International Partner (Institution - Laboratory - Researcher):

Institute of Computing Technology (ICT) of the Chinese Academy of Sciences (CAS) - Prof. Hu HAN

Duration: 2017 - 2019

Start year: 2017

See also: https://project.inria.fr/fer4hm/

The proposed research aims to provide computer vision methods for facial expression recognition in patients with Alzheimer's disease. Most importantly though, the work seeks to be part of a paradigm shift in current healthcare, in efficiently and cost effectively finding objective measures to (a) assess different therapy treatments, as well as to (b) enable automated human-computer interaction in remote large-scale healthcare- frameworks. Recognizing expressions in severely demented Alzheimer's disease (AD) patients is essential, since such patients have lost a substantial amount of their cognitive capacity, and some even their verbal communication ability (e.g., aphasia). This leaves patients dependent on clinical staff to assess their verbal and non-verbal language, in order to communicate important messages, as of discomfort associated to potential complications of the AD. Such assessment classically requires the patients' presence in a clinic, and time consuming examination involving medical personnel. Thus, expression monitoring is costly and logistically inconvenient for patients and clinical staff, which hinders among others large-scale monitoring. Approaches need to cater to the challenging settings of current medical recordings, which include continuous pose variations, occlusions, camera-movements, camera-artifacts, as well as changing illumination. Additionally and importantly, the (elderly) patients exhibit generally less profound facial activities and expressions in a range of intensities and predominantly occurring in combinations (e.g., talking and smiling). Both, Inria-STARS and CAS-ICT have already initiated research activities related to the here proposed topic. While both sides have studied facial expression recognition, CAS-ICT has explored additionally the use of heart rate monitoring sensed from a webcam in this context.

8.5. International Research Visitors

8.5.1. Visits of International Scientists

- Wael Abd-Almageed from the Information Sciences Institute of the University of Southern California (USC) Viterbi School of Engineering visited in January 2019.
- Timur Luguev from the Intelligent Systems Group of Fraunhofer Institute for Integrated Circuits, Germany visited STARS in March 2019.
- Alan Aboudib from College de France visited STARS in July 2019.
- Julien Pettre from Inria Rennes (Team Rainbow) visited STARS in July 2019.
- Radu Horaud from Inria Grenoble (Team Perception) visited STARS in September 2019.
- Marcos Zuniga from Universidad Tecnica Federico Santa Maria, Chile visited STARS in 2019.
- Chao-Cheng Hu from the National Taipei University of Technology, Taiwan visited STARS in October 2019.

8.5.2. Internships

Several students from India, China, South Korea

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events: Organisation

9.1.1.1. General Chair, Scientific Chair

- Elisabetta De Maria was General chair of the international conference CsBio 2019 (10th International Conference on Computational Systems-Biology and Bioinformatics), Nice, France.

9.1.1.2. Member of the Organizing Committees

- Antitza Dantcheva, Abhijit Das and François Brémond organized the special session on human health monitoring based on computer vision at the 14th IEEE International Conference on Automatic Face and Gesture Recognition (FG'19).
- Antitza Dantcheva co-organized the Robust Tattoo Detection and Retrieval Competition (RTDRC 2019) associated to the 10th IEEE International Conferencce on Biometrics: Theory, Applications and Systems (BTAS 2019).
- Antitza Dantcheva co-organized the special session on The Future of Biometrics beyond Recognition and Anti-Spoofing at the 12th IAPR International Conference on Biometrics (ICB'19).

9.1.1.3. Chair of Conference Program Committees

- François Brémond was part of the Organization Committee for the workshop on "Crowd analysis and applications: simulations meet video analytics"
- François Brémond was part of the AVSS'19 Organization Committee
- François Brémond was a Session Chair of AVSS - 17th IEEE International Conference on Advanced Video and Signal-Based Surveillance, Taipei, Taiwan, 18-21 September 2019.
- Elisabetta De Maria was Program chair of the international conference BIOINFORMATICS 2019 (10th International Conference on Bioinformatics Models, Methods, and Algorithms), which is part of BIOSTEC 2019 (12th International Joint Conference on Biomedical Engineering Systems and Technologies), Prague, Czech Republic.
- Elisabetta De Maria was Program chair of the international conference CsBio 2019 (10th International Conference on Computational Systems-Biology and Bioinformatics), Nice, France.
- Antitza Dantcheva was program Co-chair at the International Conference of the Biometrics Special Interest Group (BIOSIG) 2019, Darmstadt, Germany.

9.1.1.4. Member of the Conference Program Committees

- Monique Thonnat was program committee member of the conference ICPRAM 2020.
- Elisabetta De Maria was member of the program committee of the ICML Workshop on Computational Biology 2019, Long Beach, CA, USA.

9.1.1.5. Reviewer

- François Brémond was reviewer for the conferences: CVPR2019-20, ICCV2019, ICPRS-19, ICDP19, WACV 2020, AVSS19.
- François Brémond was reviewer for the Journal: IEEE International Conference on Systems, Man, and Cybernetics (SMC), IET Computer Vision, IEEE Transactions on Circuits and Systems for Video Technology
- Antitza Dantcheva was reviewer for IEEE Transactions on Information Forensics and Security (TIFS), IEEE Transactions on Biometrics, Behavior, and Identity Science (T-BIOM), IEEE Transactions on Circuits and Systems for Video Technology (TCSVT), Pattern Recognition and Neurocomputing.
- Srijan Das was reviewer for KCST 2019, ICAML 2019, AVSS 2019 and WACV 2020.

9.1.2. Journal

9.1.2.1. Member of the Editorial Boards

- François Brémond was handling editor of the international journal "Machine Vision and Application".
- François Brémond was handling editor for the MDPI special issue sensors Deep Learning for multi-sensor fusion.
- Elisabetta De Maria was guest editor of the JBCB journal (Journal of Bioinformatics and Computational Biology) for the review process of selected papers for the special issue on the conference BIOINFORMATICS 2019.
- Antitza Dantcheva has been in the Editorial Board of the Journal Multimedia Tools and Applications (MTAP) since 2017.

9.1.3. Invited Talks

- François Brémond was invited at the Data Science Riviera to give the talk “Cross domain residual transfer learning for person re-identification” in April 2019.
- François Brémond was invited to give a keynote speech on people tracking at the T4S Workshop in AVSS Taipei, 21 September 2019.
- François Brémond was invited in HealthCare and AI CITEDI at Tijuana, 23 August 2019.
- Monique Thonnat was invited as Speaker on AI and Health session to the CEO Forum at VivaTech, Paris, 16 May 2019.
- Monique Thonnat was invited to give a talk entitled Where to Focus on for Human Action Recognition? at the Franco-Mexican workshop on AI, Mexico, 27-29 August 2019.
- Monique Thonnat was invited by TEC Monterey for to give a talk on AI for Daily Living Activity recognition from videos at the AI Hub Launch, Guadalajara, 27 November 2019.
- Elisabetta De Maria was invited at *School of Electrical Engineering and Computer Science*, University of Ottawa, Canada in June 2019. Title of the talk: Parameter Learning for Spiking Neural Networks Modelled as Timed Automata.
- Elisabetta De Maria was invited at *Center of Modeling, Simulation, and Interactions (MSI)*, Université Côte d’Azur, France in September 2019. Title of the talk: Parameter Learning for Spiking Neural Networks Modelled as Timed Automata.
- Srijan Das was invited at the Data Science Riviera to give the talk “Spatio-temporal attention mechanism for Activities of Daily Living” in November.
- S L Happy was invited at the Data Science Riviera to give the talk “Apathy diagnosis by analyzing facial dynamics in videos” in April.
- Abhijit Das was invited at the Data Science Riviera to give the talk “Robust face analysis employing machine learning techniques for remote heart rate estimation and towards unbiased attribute analysis” in January.

9.1.4. Leadership within the Scientific Community

- François Brémond was part of the Evaluation Committee for new Inria team creation, Chorale.
- François Brémond was part of the Evaluation Committee for PINZ Axel research application for Austrian Science Fund.
- Monique Thonnat is member of the scientific board of ENPC, Ecole Nationale des Ponts et Chaussées since June 2008.
- Jean-Paul Rigault is an ISO C++ expert and the head of the French delegation at the ISO C++ standardization committee.

- Antitza Dantcheva serves in the Technical Activities Committee of the IEEE Biometrics Council since 2017
- Antitza Dantcheva serves in the EURASIP Biomedical Image & Signal Analytics (BISA) SAT 2018-2021
- Antitza Dantcheva is member of the European Reference Network for Critical Infrastructure Protection (ERNCIP), Thematic Group Extended Virtual Fencing - use of biometric and video technologies, since 2017
- Antitza Dantcheva is member of the European Association for Biometrics, since 2018

9.1.5. Scientific Expertise

Elisabetta De Maria was facilitator of the brainstorming of the strategic axis "Humain-Biologie" during the meeting of the I3S Laboratory, Fréjus, France.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Stars Team members (e.g. François Brémond) gave the class Master Data Science M2 in *Computer Vision and Deep Learning* from December 10, 2019 to February 25, 2020.

http://www-sop.inria.fr/members/Francois.Bremond/MSclass/deepLearningWinterSchool/index.html

9.2.2. Supervision

- PhD: U. Ujjwal, “Pedestrian detection to dynamically populate the map of a crossroad” [12], Thèses, Université Côte d’Azur, November 2019.
- PhD: I. Sarray, “Conception de systèmes de reconnaissance d’activités humaines” [11], Thèses, Université Côte d’Azur, March 2019.

  PhD in progress: Srijan Das, “Action recognition of daily living activities from RGB-D videos”, 2017, PhD codirected 50% François Brémond and Monique Thonnat.

  PhD in progress: Yaohui Wang, 2017, “Automated holistic human analysis”, Antitza Dantcheva.

  PhD in progress: Jen-Cheng Hou: “Quantified video analysis of seizure semiology in epilepsy”, 2018, PhD codirected 50% Monique Thonnat and Prof. Fabrice Bartolomei, PU-PH AMU/Inserm.

  PhD in progress: Juan Diego Gonzales Zuniga, 2018, “People Tracking using Deep Learning algorithms on embedded hardware”, 70% François Brémond and 30% Serge Tissot (Fellowship CIFRE - Kontron).

  PhD in progress: Thibaud L’Yvonnet, “Relations between human behaviour models and brain models - Application to serious games”, 2018, Sabine Moisan and Elisabetta De Maria.

  PhD in progress: Hao Chen, 2019, “People Re-identification using Deep Learning methods”, 70% François Brémond and 30% Benoit Lagadec (Fellowship CIFRE - ESI).

  PhD in progress: Rui Dai, 2019, “Action Detection for Untrimmed Videos based on Deep Neural Networks”, François Brémond.

  Abdorrahim Bahrami, “Modelling and verifying dynamical properties of biological neural networks in Coq”, Elisabetta De Maria.

Srijan Das was mentor for the Emerging Technology Business Incubator (ETBI) Led by NIT Rourkela, a platform envisaged transforming the start-up ecosystem of the region.

Srijan Das mentored for B.E.N.J.I. in GirlScript Summer of Code 2019 edition.

9.2.3. Juries

- François Brémond was jury member of Tenure Track Selection: committee member for permanent position, COS informatique, Lyon 2 University, 6 May 2019
- François Brémond was jury member for habilitation, Anthony Fleury, Lille University, 20 February 2019
- François Brémond was jury member for habilitation, Stefan Duffner, Lyon University, 5 April 2019
- François Brémond was jury member of the mid-term review for 6 PhDs - Nicolas Girard (May 3rd, 2019), Melissa Sanabria (May 21st, 2019), Lucas Pascal (July 11, 2019), Claire Labit (October 8, 2019), Renato Baptista (January 17 and August 28, 2019), Magali PAYNE (December 3, 2019).
- François Brémond was jury member of the following PhD theses:

  PhD, Jennifer Vandoni, Université de Paris Saclay, Saclay, 14 May 2019.

  PhD, Amr Alyafi, Grenoble Institute of Technology, 27 May 2019.

  PhD, Cristiano Massaroni, La Sapienza University in Rome, 13 December 2019.
- Monique Thonnat was reviewer for the PhD defense of Florent Lefevre, University of Lorraine, 4 December 2019
- Monique Thonnat was president for the PhD defense of Danny Francis, Sorbonne Université, 12 December 2019
- Jean-Paul Rigault was president of the HDR jury of Julien Deantoni.
- Elisabetta De Maria was member of the Ph.D. proposal defence jury of Abdorrahim Bahrami, University of Ottawa, Canada. Title of the thesis: Verifying Dynamic Properties of Neural Networks in Coq.
- Antitza Dantcheva was reviewer for the PhD defense of Mohamed Abdul Cader, Queensland University of Technology, Australia.

9.3. Popularization

9.3.1. Articles and contents

- François Brémond was interviewed for *Web Interview* on Facial recognition: limits and challenges for society, 16 Oct 2019.
- François Brémond was interviewed for *Graphical novel* about the challenges of AI, 29 Oct 2019.
- Antitza Dantcheva was interviewed for an article in *Science et Vie* on facial analysis in October 2019.
- Antitza Dantcheva was interviewed for an article in *Charlie Hebdo* on facial recognition in February 2019.

9.3.2. Interventions

- François Brémond, Thibaud L'Yvonnet, David Anghelone and Sandrine Boute represented STARS on the 19 October at the *La fête de la science* in Palais des Congrès d'Antibes Juan-les-Pins.
- STARS presented demos for Unlimitech Sport, Lyon, 18-21 September 2019.

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[8] A. RESSOUCHE, D. GAFFÉ.*Compilation Modulaire d'un Langage Synchrone*, in "Revue des sciences et technologies de l'information, série Théorie et Science Informatique", June 2011, vol. 4, n° 30, p. 441-471, http://hal.inria.fr/inria-00524499/en

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[12] U. UJJWAL.*Handling the speed-accuracy trade-off in deep-learning based pedestrian detection systems*, Inria Sophia Antipolis - Méditerranée ; Universite cote d'Azur, November 2019, https://hal.inria.fr/tel-02416418

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Project-Team TITANE

Geometric Modeling of 3D Environments

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Interaction and visualization

Table of contents

Project-Team TITANE

Creation of the Team: 2013 January 01, updated into Project-Team: 2014 January 01

Keywords:

Computer Science and Digital Science:

A5. - Interaction, multimedia and robotics
A5.3. - Image processing and analysis
A5.3.2. - Sparse modeling and image representation
A5.3.3. - Pattern recognition
A5.5.1. - Geometrical modeling
A5.6. - Virtual reality, augmented reality
A5.6.1. - Virtual reality
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A8.12. - Optimal transport
A9.2. - Machine learning

Other Research Topics and Application Domains:

B2.5. - Handicap and personal assistances
B3.3. - Geosciences
B5.1. - Factory of the future
B5.6. - Robotic systems
B5.7. - 3D printing
B8.3. - Urbanism and urban planning

1. Team, Visitors, External Collaborators

Research Scientists

Pierre Alliez [Team leader, Inria, Senior Researcher, HDR]
Florent Lafarge [Inria, Researcher, HDR]
Yuliya Tarabalka [Inria, Researcher, until Jan 2019]
Mathieu Desbrun [Caltech, International Chair, Advanced Research position until Mar 2019]

Technical Staff

Dmitry Anisimov [Inria, Engineer, until Apr 2019]
Fernando Ireta Munoz [Inria, Engineer]
Cédric Portaneri [Inria, Engineer]

PhD Students

Gaetan Bahl [IRT Saint-Exupéry, PhD Student, from Mar 2019]
Jean-Philippe Bauchet [Luxcarta, PhD Student]
Oussama Ennafii [IGN, PhD Student, until Sep 2019]
Hao Fang [Inria, PhD Student, until Jan 2019]
Nicolas Girard [Inria, PhD Student]
Muxingzi Li [Inria, PhD Student]
Lionel Matteo [Thales, PhD Student]
Flora Quilichini [Inria, PhD Student, until Jun 2019]

Onur Tasar [Inria, PhD Student]
Vincent Vadez [Dorea, PhD Student]
Julien Vuillamy [Dassault Systèmes, PhD Student]
Mulin Yu [Inria, PhD Student, from Nov 2019]
Tong Zhao [Inria, PhD Student, from Nov 2019]

Visiting Scientist
Jorg Peters [Uni. Florida, from Jun 2019 until Jul 2019]

Administrative Assistant
Florence Barbara [Inria, Administrative Assistant]

2. Overall Objectives

2.1. General Presentation

Our overall objective is the computerized geometric modeling of complex scenes from physical measurements. On the geometric modeling and processing pipeline, this objective corresponds to steps required for conversion from physical to effective digital representations: *analysis*, *reconstruction* and *approximation*. Another longer term objective is the *synthesis* of complex scenes. This objective is related to analysis as we assume that the main sources of data are measurements, and synthesis is assumed to be carried out from samples.

The related scientific challenges include i) being resilient to defect-laden data due to the uncertainty in the measurement processes and imperfect algorithms along the pipeline, ii) being resilient to heterogeneous data, both in type and in scale, iii) dealing with massive data, and iv) recovering or preserving the structure of complex scenes. We define the quality of a computerized representation by its i) geometric accuracy, or faithfulness to the physical scene, ii) complexity, iii) structure accuracy and control, and iv) amenability to effective processing and high level scene understanding.

3. Research Program

3.1. Context

Geometric modeling and processing revolve around three main end goals: a computerized shape representation that can be visualized (creating a realistic or artistic depiction), simulated (anticipating the real) or realized (manufacturing a conceptual or engineering design). Aside from the mere editing of geometry, central research themes in geometric modeling involve conversions between physical (real), discrete (digital), and mathematical (abstract) representations. Going from physical to digital is referred to as shape acquisition and reconstruction; going from mathematical to discrete is referred to as shape approximation and mesh generation; going from discrete to physical is referred to as shape rationalization.

Geometric modeling has become an indispensable component for computational and reverse engineering. Simulations are now routinely performed on complex shapes issued not only from computer-aided design but also from an increasing amount of available measurements. The scale of acquired data is quickly growing: we no longer deal exclusively with individual shapes, but with entire *scenes*, possibly at the scale of entire cities, with many objects defined as structured shapes. We are witnessing a rapid evolution of the acquisition paradigms with an increasing variety of sensors and the development of community data, as well as disseminated data.

In recent years, the evolution of acquisition technologies and methods has translated in an increasing overlap of algorithms and data in the computer vision, image processing, and computer graphics communities. Beyond the rapid increase of resolution through technological advances of sensors and methods for mosaicing images, the line between laser scan data and photos is getting thinner. Combining, e.g., laser scanners with panoramic cameras leads to massive 3D point sets with color attributes. In addition, it is now possible to generate dense point sets not just from laser scanners but also from photogrammetry techniques when using a well-designed acquisition protocol. Depth cameras are getting increasingly common, and beyond retrieving depth information we can enrich the main acquisition systems with additional hardware to measure geometric information about the sensor and improve data registration: e.g., accelerometers or GPS for geographic location, and compasses or gyrometers for orientation. Finally, complex scenes can be observed at different scales ranging from satellite to pedestrian through aerial levels.

These evolutions allow practitioners to measure urban scenes at resolutions that were until now possible only at the scale of individual shapes. The related scientific challenge is however more than just dealing with massive data sets coming from increase of resolution, as complex scenes are composed of multiple objects with structural relationships. The latter relate i) to the way the individual shapes are grouped to form objects, object classes or hierarchies, ii) to geometry when dealing with similarity, regularity, parallelism or symmetry, and iii) to domain-specific semantic considerations. Beyond reconstruction and approximation, consolidation and synthesis of complex scenes require rich structural relationships.

The problems arising from these evolutions suggest that the strengths of geometry and images may be combined in the form of new methodological solutions such as photo-consistent reconstruction. In addition, the process of measuring the geometry of sensors (through gyrometers and accelerometers) often requires both geometry process and image analysis for improved accuracy and robustness. Modeling urban scenes from measurements illustrates this growing synergy, and it has become a central concern for a variety of applications ranging from urban planning to simulation through rendering and special effects.

3.2. Analysis

Complex scenes are usually composed of a large number of objects which may significantly differ in terms of complexity, diversity, and density. These objects must be identified and their structural relationships must be recovered in order to model the scenes with improved robustness, low complexity, variable levels of details and ultimately, semantization (automated process of increasing degree of semantic content).

Object classification is an ill-posed task in which the objects composing a scene are detected and recognized with respect to predefined classes, the objective going beyond scene segmentation. The high variability in each class may explain the success of the stochastic approach which is able to model widely variable classes. As it requires a priori knowledge this process is often domain-specific such as for urban scenes where we wish to distinguish between instances as ground, vegetation and buildings. Additional challenges arise when each class must be refined, such as roof super-structures for urban reconstruction.

Structure extraction consists in recovering structural relationships between objects or parts of object. The structure may be related to adjacencies between objects, hierarchical decomposition, singularities or canonical geometric relationships. It is crucial for effective geometric modeling through levels of details or hierarchical multiresolution modeling. Ideally we wish to learn the structural rules that govern the physical scene manufacturing. Understanding the main canonical geometric relationships between object parts involves detecting regular structures and equivalences under certain transformations such as parallelism, orthogonality and symmetry. Identifying structural and geometric repetitions or symmetries is relevant for dealing with missing data during data consolidation.

Data consolidation is a problem of growing interest for practitioners, with the increase of heterogeneous and defect-laden data. To be exploitable, such defect-laden data must be consolidated by improving the data sampling quality and by reinforcing the geometrical and structural relations sub-tending the observed scenes. Enforcing canonical geometric relationships such as local coplanarity or orthogonality is relevant for registration of heterogeneous or redundant data, as well as for improving the robustness of the reconstruction process.

3.3. Approximation

Our objective is to explore the approximation of complex shapes and scenes with surface and volume meshes, as well as on surface and domain tiling. A general way to state the shape approximation problem is to say that we search for the shape discretization (possibly with several levels of detail) that realizes the best complexity / distortion trade-off. Such a problem statement requires defining a discretization model, an error metric to measure distortion as well as a way to measure complexity. The latter is most commonly expressed in number of polygon primitives, but other measures closer to information theory lead to measurements such as number of bits or minimum description length.

For surface meshes we intend to conceive methods which provide control and guarantees both over the global approximation error and over the validity of the embedding. In addition, we seek for resilience to heterogeneous data, and robustness to noise and outliers. This would allow repairing and simplifying triangle soups with cracks, self-intersections and gaps. Another exploratory objective is to deal generically with different error metrics such as the symmetric Hausdorff distance, or a Sobolev norm which mixes errors in geometry and normals.

For surface and domain tiling the term meshing is substituted for tiling to stress the fact that tiles may be not just simple elements, but can model complex smooth shapes such as bilinear quadrangles. Quadrangle surface tiling is central for the so-called *resurfacing* problem in reverse engineering: the goal is to tile an input raw surface geometry such that the union of the tiles approximates the input well and such that each tile matches certain properties related to its shape or its size. In addition, we may require parameterization domains with a simple structure. Our goal is to devise surface tiling algorithms that are both reliable and resilient to defect-laden inputs, effective from the shape approximation point of view, and with flexible control upon the structure of the tiling.

3.4. Reconstruction

Assuming a geometric dataset made out of points or slices, the process of shape reconstruction amounts to recovering a surface or a solid that matches these samples. This problem is inherently ill-posed as infinitely-many shapes may fit the data. One must thus regularize the problem and add priors such as simplicity or smoothness of the inferred shape.

The concept of geometric simplicity has led to a number of interpolating techniques commonly based upon the Delaunay triangulation. The concept of smoothness has led to a number of approximating techniques that commonly compute an implicit function such that one of its isosurfaces approximates the inferred surface. Reconstruction algorithms can also use an explicit set of prior shapes for inference by assuming that the observed data can be described by these predefined prior shapes. One key lesson learned in the shape problem is that there is probably not a single solution which can solve all cases, each of them coming with its own distinctive features. In addition, some data sets such as point sets acquired on urban scenes are very domain-specific and require a dedicated line of research.

In recent years the *smooth, closed case* (i.e., shapes without sharp features nor boundaries) has received considerable attention. However, the state-of-the-art methods have several shortcomings: in addition to being in general not robust to outliers and not sufficiently robust to noise, they often require additional attributes as input, such as lines of sight or oriented normals. We wish to devise shape reconstruction methods which are both geometrically and topologically accurate without requiring additional attributes, while exhibiting resilience to defect-laden inputs. Resilience formally translates into stability with respect to noise and outliers. Correctness of the reconstruction translates into convergence in geometry and (stable parts of) topology of the reconstruction with respect to the inferred shape known through measurements.

Moving from the smooth, closed case to the *piecewise smooth case* (possibly with boundaries) is considerably harder as the ill-posedness of the problem applies to each sub-feature of the inferred shape. Further, very few approaches tackle the combined issue of robustness (to sampling defects, noise and outliers) and feature reconstruction.

4. Application Domains

4.1. Domain 1

In addition to tackling enduring scientific challenges, our research on geometric modeling and processingis motivated by applications to computational engineering, reverse engineering, digital mapping and urbanplanning. The main deliverable of our research will be algorithms with theoretical foundations. Ultimatelywe wish to contribute making geometry modeling and processing routine for practitioners who deal with real-world data. Our contributions may also be used as a sound basis for future software and technology developments.

Our first ambition for technology transfer is to consolidate the components of our research experiments in the form of new software components for the CGAL (Computational Geometry Algorithms Library) library. Consolidation being best achieved with the help of an engineer, we will search for additional funding. Through CGAL, we wish to contribute to the “standard geometric toolbox”, so as to provide a generic answer to application needs instead of fragmenting our contributions. We already cooperate with the Inria spin-offcompany Geometry Factory, which commercializes CGAL, maintains it and provide technical support.

Our second ambition is to increase the research momentum of companies through advising Cifre Ph.D. thesesand postdoctoral fellows on topics that match our research program.

5. Highlights of the Year

5.1. Highlights of the Year

Pierre Alliez was program co-chair of the EUROGRAPHICS 2019 conference and of the Symposium on Solid and Physical Modeling (SPM). From February 2019 Yuliya Tarabalka is on leave to the Luxcarta company for two years.

5.1.1. Awards

Cédric Portaneri and Pierre Alliez obtained a best paper award at the ACM Conference on Multimedia Systems for a contribution to the progressive compression of textured meshes, in collaboration with the Draco team from Google. Jean-Philippe Bauchet obtained an award for the best presentation at a national workshop (GMTG 2019). Jean-Dominique Favreau received the best PhD thesis award 2019 (assessit prize) from IG-RV. Onur Tasar was part of the winning team of the tomtom AI summer school challenge organized in the Netherlands.

6. New Software and Platforms

6.1. CGAL Barycentric_coordinates_2

Module CGAL : Barycentric coordinates 2D

KEYWORD: Computational geometry

FUNCTIONAL DESCRIPTION: This package offers an efficient and robust implementation of two-dimensional closed-form generalized barycentric coordinates defined for simple two-dimensional polygons.

- Participants: Dmitry Anisimov and Pierre Alliez
- Contact: Pierre Alliez

6.2. dtk-nurbs-probing

KEYWORDS: Algorithm - CAD - Numerical algorithm - Geometric algorithms

FUNCTIONAL DESCRIPTION: This library offers tools for computing intersection between linear primitives and the constitutive elements of CAD objects (curves and surfaces). It is thus possible to compute intersections between a linear primitive with a trimmed or untrimmed NURBS surface, as well with Bezier surfaces. It is also possible, in the xy plane, to compute the intersections between linear primitives and NURBS curves as well as Bezier curves.

- Participants: Come Le Breton, Laurent Busé and Pierre Alliez
- Contact: Come Le Breton

6.3. Module CGAL : Point Set Processing

KEYWORD: Geometry Processing

FUNCTIONAL DESCRIPTION: This CGAL component implements methods to analyze and process unorganized point sets. The input is an unorganized point set, possibly with normal attributes (unoriented or oriented). The point set can be analyzed to measure its average spacing, and processed through functions devoted to the simplification, outlier removal, smoothing, normal estimation, normal orientation and feature edges estimation.

- Participants: Clément Jamin, Laurent Saboret and Pierre Alliez
- Contact: Pierre Alliez
- URL: http://doc.cgal.org/latest/Point_set_processing_3/index.html#Chapter_Point_Set_Processing

6.4. Module CGAL : Scale space surface reconstruction

KEYWORD: Geometric algorithms

SCIENTIFIC DESCRIPTION: This CGAL package implements a surface reconstruction method which takes as input an unordered point set and computes a triangulated surface mesh interpolating the point set. We assume that the input points were sampled from the surface of an object. The method can also process point sets sampled from the interior of the object, although we cannot provide guarantees on the output. This method can handle a decent amount of noise and outliers. The point set may greatly undersample the object in occluded regions, although no surface will be reconstructed to fill these regions.

FUNCTIONAL DESCRIPTION: This method allows to reconstruct a surface that interpolates a set of 3D points. This method provides an efficient alternative to the Poisson surface reconstruction method. The main difference in output is that this method reconstructs a surface that interpolates the point set (as opposed to approximating the point set). How the surface connects the points depends on a scale variable, which can be estimated semi-automatically.

- Participants: Pierre Alliez and Thijs Van Lankveld
- Contact: Pierre Alliez

6.5. Module Gudhi : Skeleton-Blockers

Skeleton-Blockers data-structure

KEYWORDS: C++ - Mesh - Triangulation - Topology - 3D

FUNCTIONAL DESCRIPTION: Skeleton-Blockers is a compact, efficient and generic data-structure that can represent any simplicial complex. The implementation is in C++11.

- Participant: David Salinas
- Contact: David Salinas
- URL: https://project.inria.fr/gudhi/software/

6.6. DPP

Delaunay Point Process for image analysis

KEYWORDS: Computer vision - Shape recognition - Delaunay triangulation - Stochastic process

FUNCTIONAL DESCRIPTION: The software extract 2D geometric structures (planar graphs, polygons...) from images

- Participants: Jean-Dominique Favreau, Florent Lafarge and Adrien Bousseau
- Contact: Florent Lafarge
- Publication: Extracting Geometric Structures in Images with Delaunay Point Processes

6.7. KIPPI

KInetic Polygonal Partitioning of Images

KEYWORDS: Computer vision - Computational geometry - Image segmentation

SCIENTIFIC DESCRIPTION: The scientific description of the algorithm is detailed in [Bauchet and Lafarge, KIPPI: KInetic Polygonal Partitioning of Images, CVPR 2018]

FUNCTIONAL DESCRIPTION: KIPPI decompose an image, or a bounded 2D space, into convex polygons. The method exploits a kinetic framework for propagating and colliding line-segments until forming convex polygons.

- Participants: Jean-Philippe Bauchet and Florent Lafarge
- Contact: Florent Lafarge

6.8. Module CGAL: 3D Point-Set Shape Detection

KEYWORD: CGAL

FUNCTIONAL DESCRIPTION: This package implements the efficient RANSAC method for shape detection, contributed by Schnabel et al. From an unstructured point set with unoriented normals, the algorithm detects a set of shapes. Five types of primitive shapes are provided by this package: plane, sphere, cylinder, cone and torus. Detecting other types of shapes is possible by implementing a class derived from a base shape.

- Participants: Clément Jamin, Pierre Alliez and Sven Oesau
- Contact: Pierre Alliez

6.9. CGAL module: Classification

KEYWORDS: Classification - Point cloud - Mesh

FUNCTIONAL DESCRIPTION: This CGAL module aims at classifying 3D data, typically point clouds, into arbitrary classes of interest. The module offers the user the possibility to segment data i) locally or globally, and ii) in an supervised or unsupervised way.

- Authors: Florent Lafarge and Simon Giraudot
- Contact: Florent Lafarge

6.10. SMICER

KEYWORDS: Geometric modeling - Computational geometry - Polyhedral meshes

FUNCTIONAL DESCRIPTION: The software allows the decomposition of a 3D domain into a polyhedra from a set of planar shapes

- Participants: Florent Lafarge and Pierre Alliez
- Contact: Florent Lafarge

6.11. Stochastic Vectorization

KEYWORDS: Vector graphics - Stochastic models

FUNCTIONAL DESCRIPTION: The software converts a line-drawing image into Bezier curves.

- Participants: Jean-Dominique Favreau, Florent Lafarge and Adrien Bousseau
- Contact: Florent Lafarge
- Publication: 01309271

7. New Results

7.1. Analysis

7.1.1. *Pyramid scene parsing network in 3D: improving semantic segmentation of point clouds with multi-scale contextual information*

Participants: Hao Fang, Florent Lafarge.

Analyzing and extracting geometric features from 3D data is a fundamental step in 3D scene understanding. Recent works demonstrated that deep learning architectures can operate directly on raw point clouds, i.e. without the use of intermediate grid-like structures. These architectures are however not designed to encode contextual information in-between objects efficiently. Inspired by a global feature aggregation algorithm designed for images, we propose a 3D pyramid module to enrich pointwise features with multi-scale contextual information. Our module can be easily coupled with 3D semantic segmantation methods operating on 3D point clouds. We evaluated our method on three large scale datasets with four baseline models. Experimental results show that the use of enriched features brings significant improvements to the semantic segmentation of indoor and outdoor scenes (See Figure 1). This work was published in the ISPRS journal of Remote Sensing and Photogrammetry [6].

7.1.2. *Low-power neural networks for semantic segmentation of satellite images*

Participants: Gaetan Bahl, Florent Lafarge.

In collaboration with Lionel Daniel and Matthieu Moretti (IRT Saint-Exupéry).

Semantic segmentation methods have made impressive progress with deep learning. However, while achieving higher and higher accuracy, state-of-the-art neural networks overlook the complexity of architectures, which typically feature dozens of millions of trainable parameters. As a result, these networks requires high computational resources and are mostly not suited to perform on edge devices with tight resource constraints, such as phones, drones, or satellites. In this work, we propose two highly-compact neural network architectures for semantic segmentation of images, which are up to 100 000 times less complex than state-of-the-art architectures while approaching their accuracy. To decrease the complexity of existing networks, our main ideas consist in exploiting lightweight encoders and decoders with depth-wise separable convolutions and decreasing memory usage with the removal of skip connections between encoder and decoder. Our architectures are designed to be implemented on a basic FPGA such as the one featured on the Intel Altera Cyclone V family. We demonstrate the potential of our solutions in the case of binary segmentation of remote sensing images, in particular for extracting clouds and trees from RGB satellite images. This work was published in the Low-Power Computer Vision ICCV workshop [13].

7.1.3. *A learning approach to evaluate the quality of 3D city models*

Participants: Oussama Ennafii, Florent Lafarge.

In collaboration with Arnaud Le Bris and Clément Mallet (IGN).

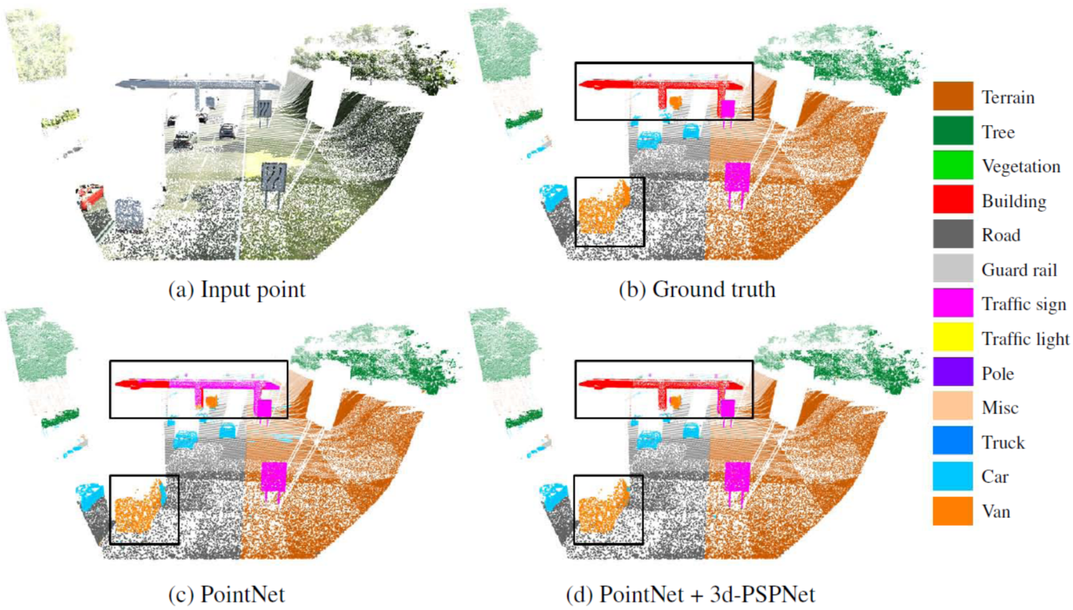

Figure 1. Semantic segmentation of a point cloud with and without our 3d-PSPNet module. Given an input point cloud (a), PointNet fails to predict correct labels for points describing large-scale objects (see rectangles in (c)). PointNet equipped with our 3d-PSPNet module gives better prediction results by enriching global contextual information (d).

The automatic generation of 3D building models from geospatial data is now a standard procedure. An abundant literature covers the last two decades and several softwares are now available. However, urban areas are very complex environments. Inevitably, practitioners still have to visually assess, at city-scale, the correctness of these models and detect frequent reconstruction errors. Such a process relies on experts, and is highly time-consuming with approximately two hours per square kilometer for one expert. This work proposes an approach for automatically evaluating the quality of 3D building models. Potential errors are compiled in a novel hierarchical and versatile taxonomy. This allows, for the first time, to disentangle fidelity and modeling errors, whatever the level of detail of the modeled buildings. The quality of models is predicted using the geometric properties of buildings and, when available, Very High Resolution images and Digital Surface Models. A baseline of handcrafted, yet generic, features is fed into a Random Forest classifier. Both multi-class and multi-label cases are considered: due to the interdependence between classes of errors, it is possible to retrieve all errors at the same time while simply predicting correct and erroneous buildings. The proposed framework was tested on three distinct urban areas in France with more than 3,000 buildings. $80\% - 99\%$ F-score values are attained for the most frequent errors. For scalability purposes, the impact of the urban area composition on the error prediction was also studied, in terms of transferability, generalization and representativeness of the classifiers. It shows the necessity of multimodal remote sensing data and mixing training samples from various cities to ensure stability of the detection ratios, even with very limited training set sizes. This work was presented at the IGARSS conference [16] and published in the PE&RS journal [5].

7.1.4. Robust joint image reconstruction from color and monochrome cameras

Participant: Muxingzi Li.

In collaboration with Peihan Tu (Uni. of Maryland) and Wolfgang Heidrich (KAUST).

Recent years have seen an explosion of the number of camera modules integrated into individual consumer mobile devices, including configurations that contain multiple different types of image sensors. One popular configuration is to combine an RGB camera for color imaging with a monochrome camera that has improved performance in low-light settings, as well as some sensitivity in the infrared. In this work we introduce a method to combine simultaneously captured images from such a two-camera stereo system to generate a high-quality, noise reduced color image. To do so, pixel-to-pixel alignment has to be constructed between the two captured monochrome and color images, which however, is prone to artifacts due to parallax. The joint image reconstruction is made robust by introducing a novel artifact-robust optimization formulation. We provide extensive experimental results based on the two-camera configuration of a commercially available cell phone. This work was presented at the BMVC conference [18].

7.1.5. Noisy supervision for correcting misaligned cadaster maps without perfect Ground Truth data

Participants: Nicolas Girard, Yuliya Tarabalka.

In collaboration with Guillaume Charpiat (Tau Inria project-team).

In machine learning the best performance on a certain task is achieved by fully supervised methods when perfect ground truth labels are available. However, labels are often noisy, especially in remote sensing where manually curated public datasets are rare. We study the multi-modal cadaster map alignment problem for which available annotations are misaligned polygons, resulting in noisy supervision. We subsequently set up a multiple-rounds training scheme which corrects the ground truth annotations at each round to better train the model at the next round. We show that it is possible to reduce the noise of the dataset by iteratively training a better alignment model to correct the annotation alignment. This work was presented at the IGARSS conference [10].

7.1.6. Incremental Learning for Semantic Segmentation of Large-Scale Remote Sensing Data

Participants: Onur Tasar, Pierre Alliez, Yuliya Tarabalka.

In spite of remarkable success of the convolutional neural networks on semantic segmentation, they suffer from catastrophic shortcomings: a significant performance drop for the already learned classes when new classes are added on the data having no annotations for the old classes. We propose an incremental learning methodology, enabling to learn segmenting new classes without hindering dense labeling abilities for the previous classes, although the entire previous data are not accessible. The key points of the proposed approach are adapting the network to learn new as well as old classes on the new training data, and allowing it to remember the previously learned information for the old classes. For adaptation, we keep a frozen copy of the previously trained network, which is used as a memory for the updated network in absence of annotations for the former classes. The updated network minimizes a loss function, which balances the discrepancy between outputs for the previous classes from the memory and updated networks, and the mis-classification rate between outputs for the new classes from the updated network and the new ground-truth. We either regularly feed samples from the stored, small fraction of the previous data or use the memory network, depending on whether the new data are collected from completely different geographic areas or from the same city (see Figure 2). Our experimental results prove that it is possible to add new classes to the network, while maintaining its performance for the previous classes, despite the whole previous training data are not available. This work was published in the IEEE journal of Selected Topics in Applied Earth Observations and Remote Sensing [9].

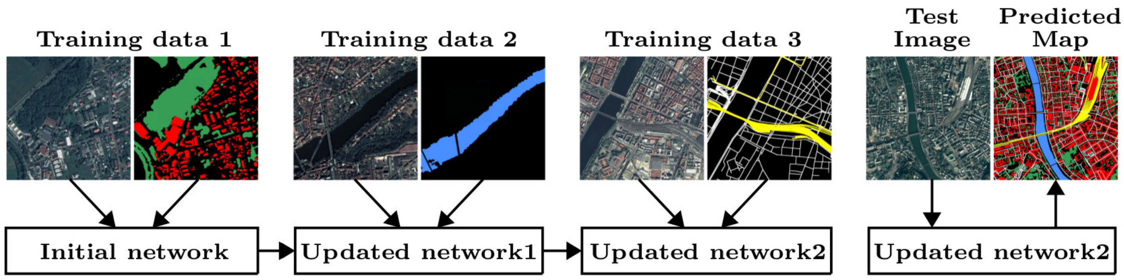

Figure 2. An example of an incremental learning scenario. Firstly, satellite images as well as their label maps for building and high vegetation classes are fed to the network. Then, from the second training data, the network learns the water class without forgetting building and high vegetation classes. Finally, road and railway classes are taught to the network. Whenever new training data are obtained, we store only a small part of the previous ones for the network to remember. When a new test image is provided, the network is able to detect all the classes.

7.1.7. Multi-Task Deep Learning for Satellite Image Pansharpening and Segmentation

Participants: Onur Tasar, Yuliya Tarabalka.

In collaboration with Andrew Khalel (Cairo University), Guillaume Charpiat (Inria, TAU team)

In this work, we propose a novel multi-task framework, to learn satellite image pansharpening and segmentation jointly (Figure 3). Our framework is based on the encoder-decoder architecture, where both tasks share the same encoder but each one has its own decoder. We compare our framework against single-task models with different architectures. Results show that our framework outperforms all other approaches in both tasks. This work was presented at the IGARSS conference [11].

7.1.8. A Generic Framework for Combining Multiple Segmentations in Geographic Object-Based Image Analysis

Participant: Onur Tasar.

In collaboration with Sébastien Lefèvre (Université Bretagne Sud, IRISA) and David Sheeren (DYNAFOR, University of Toulouse, INRA)

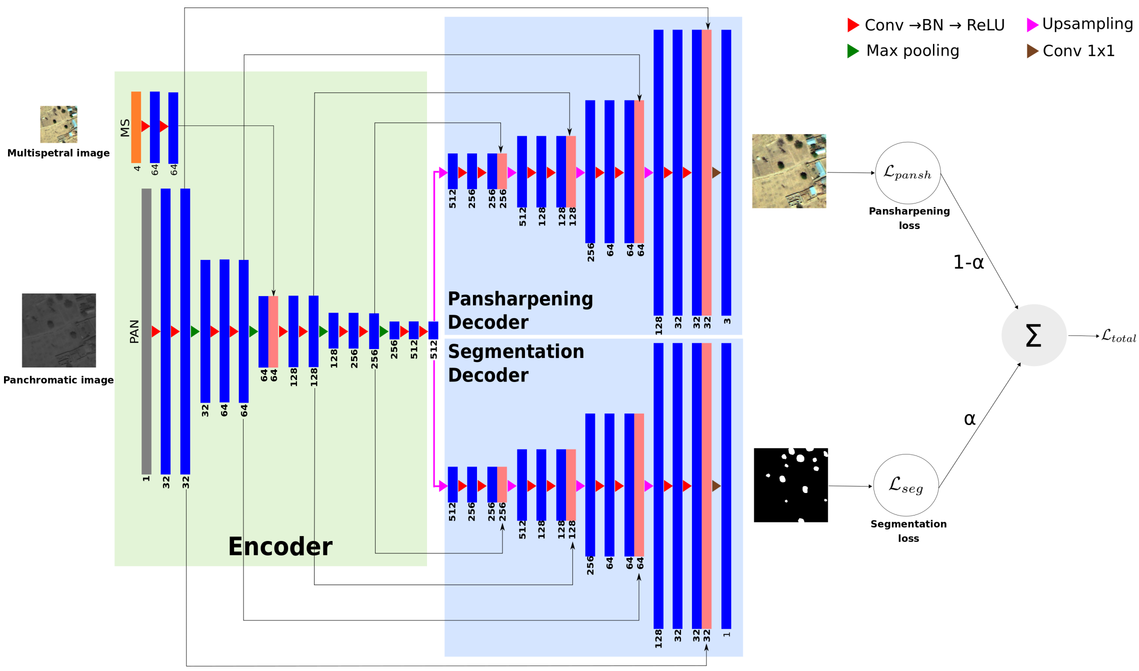

Figure 3. The overall pansharpening and segmentation framework.

The Geographic Object-Based Image Analysis (GEOBIA) paradigm relies strongly on the segmentation concept, i.e., partitioning of an image into regions or objects that are then further analyzed. Segmentation is a critical step, for which a wide range of methods, parameters and input data are available. To reduce the sensitivity of the GEOBIA process to the segmentation step, here we consider that a set of segmentation maps can be derived from remote sensing data. Inspired by the ensemble paradigm that combines multiple weak classifiers to build a strong one, we propose a novel framework for combining multiple segmentation maps (Figure 4). The combination leads to a fine-grained partition of segments (super-pixels) that is built by intersecting individual input partitions, and each segment is assigned a segmentation confidence score that relates directly to the local consensus between the different segmentation maps. Furthermore, each input segmentation can be assigned some local or global quality score based on expert assessment or automatic analysis. These scores are then taken into account when computing the confidence map that results from the combination of the segmentation processes. This means the process is less affected by incorrect segmentation inputs either at the local scale of a region, or at the global scale of a map. In contrast to related works, the proposed framework is fully generic and does not rely on specific input data to drive the combination process. We assess its relevance through experiments conducted on ISPRS 2D Semantic Labeling. Results show that the confidence map provides valuable information that can be produced when combining segmentations, and fusion at the object level is competitive w.r.t. fusion at the pixel or decision level. This work was published in the ISPRS journal of Geo-Information [8].

7.2. Reconstruction

7.2.1. City Reconstruction from Airborne Lidar: A Computational Geometry Approach

Participants: Jean-Philippe Bauchet, Florent Lafarge.

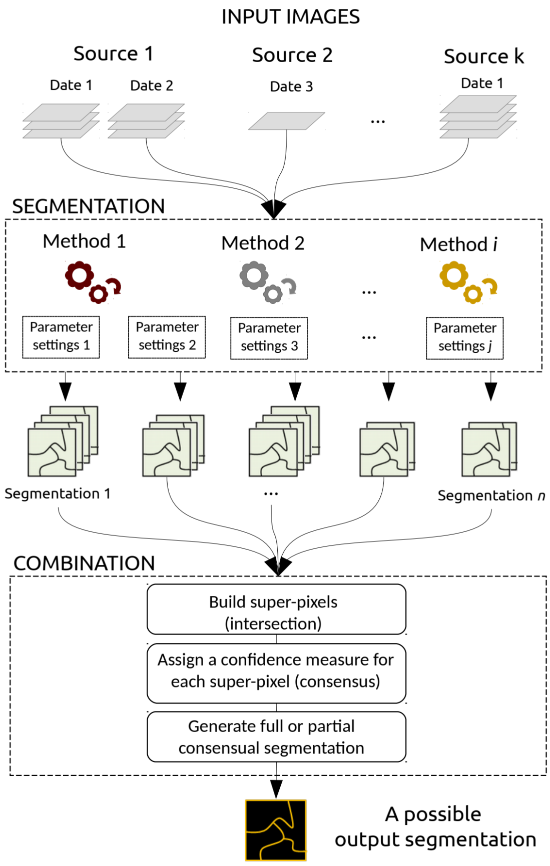

Figure 4. Our generic framework to combine multiple segmentations in the GEOBIA paradigm. Segmentations can come from different data sources (e.g., optical and radar sensors) and be acquired at different dates. They may also be produced using different methods (e.g., region-based or edge-based) relying on different parameter values.

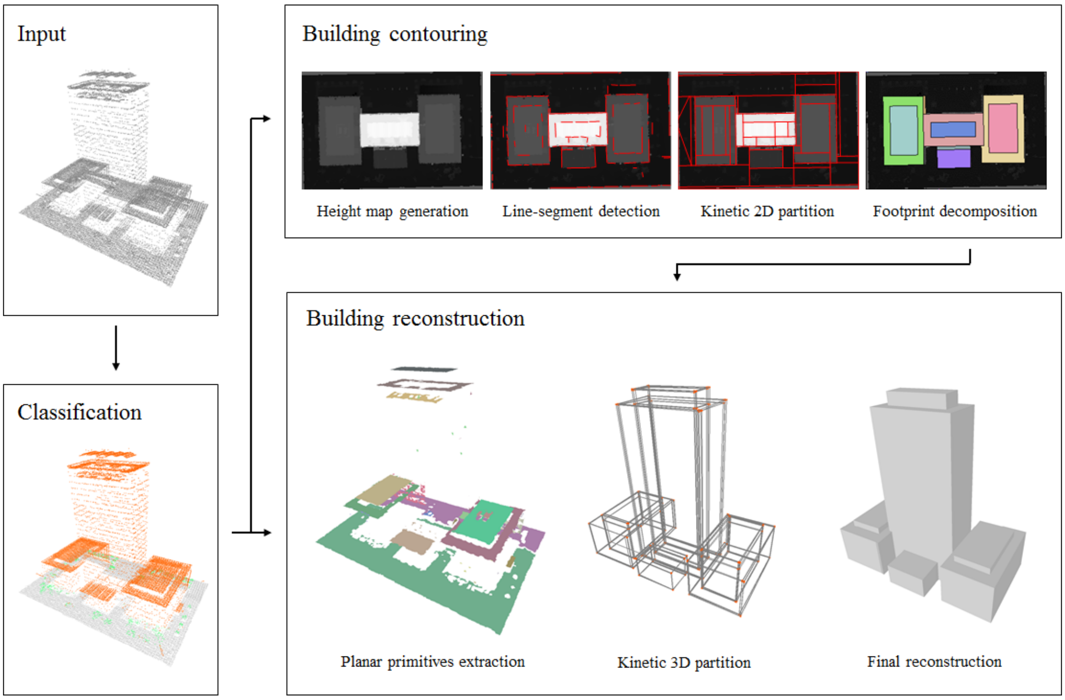

Figure 5. City Reconstruction from Airborne Lidar. Our method consists of three main steps. We first label points of the LiDAR scan as ground, vegetation or roof. Then, we apply a contouring algorithm to the height map, revealing the facades initially absent in the point set. Finally, we extract and propagate planar primitives from the point cloud, dividing the space into polyhedra that are labeled to obtain a 3D reconstruction of buildings.

We introduce a pipeline that reconstructs buildings of urban environments as concise polygonal meshes from airborne LiDAR scans. It consists of three main steps: classification, building contouring, and building reconstruction, the two last steps being achieved using computational geometry tools. Our algorithm demonstrates its robustness, flexibility and scalability by producing accurate and compact 3D models over large and varied urban areas in a few minutes only (See Figure 5). This work was published in the ISPRS international conference 3D GeoInfo [14].

7.2.2. Extracting geometric structures in images with Delaunay point processes

Participant: Florent Lafarge.

In collaboration with Jean-Dominique Favreau (Ekinnox), Adrien Bousseau (GraphDeco Inria team) and Alex Auvolat (Wide Inria team).

We introduce Delaunay Point Processes, a framework for the extraction of geometric structures from images. Our approach simultaneously locates and groups geometric primitives (line segments, triangles) to form extended structures (line networks, polygons) for a variety of image analysis tasks. Similarly to traditional point processes, our approach uses Markov Chain Monte Carlo to minimize an energy that balances fidelity to the input image data with geometric priors on the output structures. However, while existing point processes struggle to model structures composed of interconnected components, we propose to embed the point process into a Delaunay triangulation, which provides high-quality connectivity by construction. We further leverage key properties of the Delaunay triangulation to devise a fast Markov Chain Monte Carlo sampler. We demonstrate the flexibility of our approach on a variety of applications, including line network extraction, object contouring, and mesh-based image compression (See Figure 6). This work was published in the IEEE journal TPAMI [7].

Figure 6. Example applications of Delaunay Point Processes to extract planar graphs representing blood vessels in retina images (left), and complex polygons representing object silhouettes (right). The point distribution creates a dynamic Delaunay triangulation while edge and facet labels specify the geometric structure (see red edges on close-ups).

7.3. Approximation

7.3.1. Cost-driven framework for progressive compression of textured meshes

Participants: Cédric Portaneri, Pierre Alliez.

In collaboration with Michael Hemmer (Google X), Lukas Birklein and Elmar Schoemer (Uni. of Mainz).

Recent advances in digitization of geometry and radiometry generate in routine massive amounts of surface meshes with texture or color attributes. This large amount of data can be compressed using a progressive approach which provides at decoding low complexity levels of details (LoDs) that are continuously refined until retrieving the original model. The goal of such a progressive mesh compression algorithm is to improve the overall quality of the transmission for the user, by optimizing the rate-distortion trade-off. In this paper,

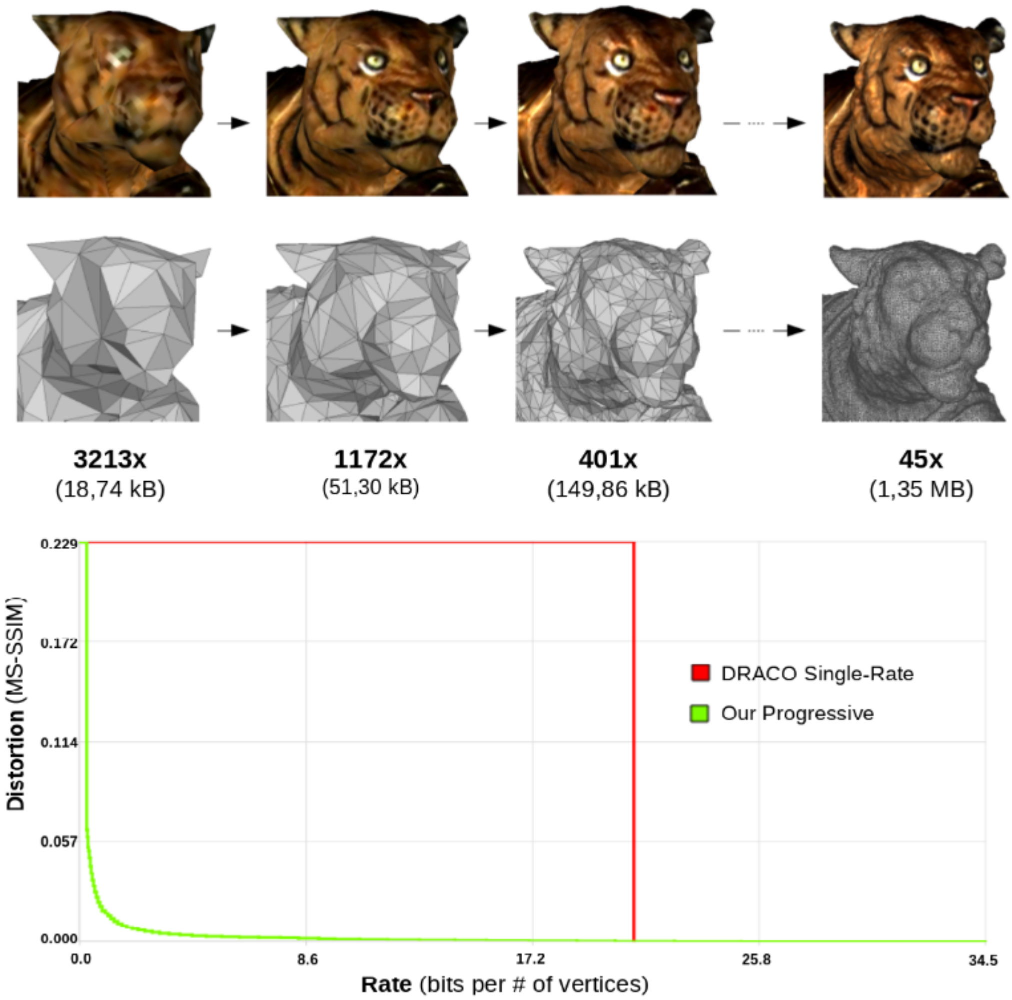

Figure 7. Progressive decompression of a textured surface triangle mesh. Top: key levels of detail with their size and compression rate compared to the raw obj file (texture data not included). Bottom: Distortion against the bit consumption, in bits per vertex, where the number of vertices refers to the input mesh. Green is our progressive approach, red is the state-of-the-art single-rate DRACO encoder.

we introduce a novel meaningful measure for the cost of a progressive transmission of a textured mesh by observing that the rate-distortion curve is in fact a staircase, which enables an effective comparison and optimization of progressive transmissions in the first place. We contribute a novel generic framework which utilizes the cost function to encode triangle surface meshes via multiplexing several geometry reduction steps (mesh decimation via half-edge or full-edge collapse operators, xyz quantization reduction and uv quantization reduction). This framework can also deal with textures by multiplexing an additional texture reduction step. We also design a texture atlas that enables us to preserve texture seams during decimation while not impairing the quality of resulting LODs. For encoding the inverse mesh decimation steps we further contribute a significant improvement over the state-of-the-art in terms of rate-distortion performance and yields a compression-rate of 22:1, on average. Finally, we propose a unique single-rate alternative solution using a selection scheme of a subset among LODs, optimized for our cost function, and provided with our atlas that enables interleaved progressive texture refinements (see Figure 7). This work was presented at the ACM Multimedia Systems conference [19] and obtained the best paper award.

7.3.2. Selective padding for Polycube-based hexahedral meshing

Participant: Pierre Alliez.

In collaboration with Gianmarco Cherchi and Riccardo Scateni from University of Cagliari (Sardinia), Max Lyon from University of Aachen and David Bommes from University of Bern.

Hexahedral meshes generated from polycube mapping often exhibit a low number of singularities but also poor quality elements located near the surface. It is thus necessary to improve the overall mesh quality, in terms of the minimum Scaled Jacobian (MSJ) or average Scaled Jacobian (ASJ). Improving the quality may be obtained via global padding (or pillowing), which pushes the singularities inside by adding an extra layer of hexahedra on the entire domain boundary. Such a global padding operation suffers from a large increase of complexity, with unnecessary hexahedra added. In addition, the quality of elements near the boundary may decrease. We propose a novel optimization method which inserts sheets of hexahedra so as to perform selective padding, where it is most needed for improving the mesh quality. A sheet can pad part of the domain boundary, traverse the domain and form singularities. Our global formulation, based on solving a binary problem, enables us to control the balance between quality improvement, increase of complexity and number of singularities. We show in a series of experiments that our approach increases the MSJ value and preserves (or even improves) the ASJ, while adding fewer hexahedra than global padding. (See Figure 8). This work was published in an international journal and was presented at the EUROGRAPHICS conference [4].

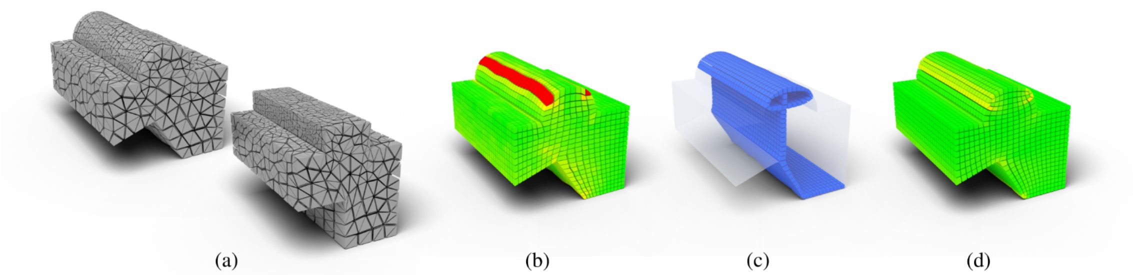

Figure 8. Polycube-based hexahedral meshing. Our pipeline takes as input a model and its polycube mapping (a); we compute the relative hex-mesh and locate the surface areas in need of padding analyzing the mapping quality (b); we set and solve a binary problem to find a set of facets to extrude in order to create a selective padding layer (c); we compute and analyze the mapping with the new hex-mesh structure (d).

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Google X

Participants: Cédric Portaneri, Pierre Alliez.

We developed a novel approach and software prototype for the compression of 3D models. Our main focus is on progressive compression of surface triangle meshes with color textures, with emphasis on fine grain, genericity and flexible metric. The proposed methodology is to turn the input models into a stream of refinements, in which both mesh and texture refinement details are multiplexed in accordance to rate-distortion principles. Fine grain control is achieved through considering all components, local as well as non-local, from both the mesh and its textures: mesh complexity, vertex accuracy, texture definition and accuracy. We leveraged the recent advances on perceptual metrics to improve the visual appearance, and performed joint consolidation and encoding of the models to further optimize the rate-distortion tradeoffs and visual perception.

8.1.2. Dorea technology

Participants: Vincent Vadez, Pierre Alliez.

In collaboration with SME Dorea Technology, our objective is to advance the knowledge on the radiative thermal simulation of satellites, via geometric model reduction. The survival of a satellite is related to the temperature of its components, the variation of which must be controlled within safety intervals. In this context, the thermal simulation of the satellite for its design is crucial to anticipate the reality of its operation. This CIFRE project started in August 2018, for a total duration of 3 years.

8.1.3. Luxcarta

Participants: Jean-Philippe Bauchet, Florent Lafarge.

The goal of this collaboration is to design automated approaches for producing city models from the last generation of satellites. In particular, this project investigates geometric representations for images and 3D data that are more compact and meaningful than traditional pixel and voxel grids, the intuition being to synthesize massive satellite data to reconstruct objects in 3D in a more scalable manner than existing methods. This CIFRE project started in October 2016, for a total duration of 3 years.

8.1.4. CNES and Acri-ST

Participants: Onur Tasar, Yuliya Tarabalka, Pierre Alliez.

The aim is to devise efficient representations for satellite images. The project started in October 2017, for a total duration of 3 years.

8.1.5. CSTB

Participants: Hao Fang, Mulin Yu, Florent Lafarge.

This collaboration takes the form of two independent contracts. The first project investigated the automatic conversion of raw 3D data to polyhedral surfaces that approximate man-made objects at some key structural representation scales. This project started in March 2016, for a total duration of 3 years. The second project investigates the design of as-automatic-as-possible algorithms for repairing and converting Building Information Modeling (BIM) models of buildings in different urban-specific CAD formats using combinatorial maps. This project started November 2019, for a total duration of 3 years.

8.1.6. IRT Saint-Exupéry

Participants: Gaetan Bahl, Florent Lafarge.

This project investigates low-power deep learning architectures for detecting, localizing and characterizing changes in temporal satellite images. These architectures are designed to be exploited on-board satellites with low computational resources. The project started in March 2019, for a total duration of 3 years.

8.1.7. Dassault Systèmes

Participants: Julien Vuillamy, Pierre Alliez, Florent Lafarge.

This project investigates algorithms for reconstructing city models from multi-sourced data. 3D objects are reconstructed by filtering, parsing and assembling planar shapes. The project started in April 2018, for a total duration of 3 years.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

9.1.1.1. PISCO: Perceptual Levels of Detail for Interactive and Immersive Remote Visualization of Complex 3D Scenes

Participants: Pierre Alliez [contact], Flora Quilichini, Florent Lafarge.

The way of consuming and visualizing this 3D content is evolving from standard screens to Virtual and Mixed Reality (VR/MR). Our objective is to devise novel algorithms and tools allowing interactive visualization, in these constrained contexts (Virtual and Mixed reality, with local/remote 3D content), with a high quality of user experience. Partners: Inria, LIRIS INSA Lyon Institut National des Sciences Appiquées (coordinator), Laboratoire d'Informatique en Images et Systèmes d'Information LS2N Nantes University. Total budget 550 KE, 121 KE for TITANE. The PhD thesis of Flora Quilichini is funded by this project which started in January 2018, for a total duration of 4 years.

9.1.1.2. LOCA-3D: Localization Orientation and 3D CArtography

Participants: Fernando Ireta Munoz, Florent Lafarge, Pierre Alliez [contact].

This project is part of the ANR Challenge MALIN LOCA-3D (Localization, orientation and 3D cartography). The challenge is to develop and experiment accurate location solutions for emergency intervention officers and security forces. These solutions must be efficient inside buildings and in conditions where satellite positioning systems do not work satisfactorily. Our solution is based on an advanced inertial system, where part of the inertial sensor drift is compensated by a vision system. Partners: SME INNODURA TB (coordinator), IBISC laboratory (Evry university) and Inria. Total budget: 700 KE, 157 KE for TITANE. The engineer position of Fernando Ireta Munoz is funded by this project which started in January 2018, for a total duration of 4 years.

9.1.1.3. EPITOME: efficient representation to structure large-scale satellite images

Participants: Nicolas Girard, Yuliya Tarabalka [PI].

The goal of this young researcher project is to devise an efficient multi-scale vectorial representation, which would structure the content of large-scale satellite images. More specifically, we seek for a novel effective representation for large-scale satellite images, that would be generic, i.e., applicable for images worldwide and for a wide range of applications, and structure-preserving, i.e. best representing the meaningful objects in the image scene. To address this challenge, we plan to bridge the gap between advanced machine learning and geometric modeling tools to devise a multi-resolution vector-based representation, together with the methods for its effective generation and manipulation. Total budget: 225 KE for TITANE. The PhD thesis of Nicolas Girard is funded by this project which started in October 2017, for a total duration of 4 years.

9.1.1.4. Faults_R_GEMS: Properties of FAULTS, a key to Realistic Generic Earthquake Modeling and hazard Simulation

Participants: Lionel Matteo, Yuliya Tarabalka [contact].

The goal of the project is to study the properties of seismic faults, using advanced math tools including learning approaches. The project is in collaboration with Geoazur lab (coordinator), Arizona State University, CALTECH, Ecole Centrale Paris, ENS Paris, ETH Zurich, Geosciences Montpellier, IFSTTAR, IPGP Paris, IRSN Fontenay-aux-Roses, LJAD Nice, UNAVCO Colorado and Pisa University. The PhD thesis of Lionel Matteo is funded by this project which started in October 2017, for a total duration of 4 years.

9.1.1.5. BIOM: Building Indoor and Outdoor Modeling

Participants: Muxingzi Li, Pierre Alliez, Florent Lafarge [contact].

The BIOM project aims at automatic, simultaneous indoor and outdoor modelling of buildings from images and dense point clouds. We want to achieve a complete, geometrically accurate, semantically annotated but nonetheless lean 3D CAD representation of buildings and objects they contain in the form of a Building Information Models (BIM) that will help manage buildings in all their life cycle (renovation, simulation, deconstruction). The project is in collaboration with IGN (coordinator), Ecole des Ponts Paristech, CSTB and INSA-ICube. Total budget: 723 KE, 150 KE for TITANE. The PhD thesis of Muxingzi Li is funded by this project which started in February 2018, for a total duration of 4 years.

9.2. International Initiatives

9.2.1. Inria International Partners

9.2.1.1. Declared Inria International Partners

We collaborated with David Bommes from Bern University (Switzerland), Gianmarco Cherchi and Riccardo Scateni from University of Cagliary (Sardinia), and Elmar Schoemer from Johannes Gutenberg Universität Mainz.

9.3. International Research Visitors

9.3.1. Visits of International Scientists

- Michael Hemmer, research engineer at Google X, visited us in June.
- Jorg Peters, Professor at University of Florida, visited us in June.

9.3.2. Visits to International Teams

- Pierre Alliez visited the Google X team for one week in April.
- Florent Lafarge visited the Institute of Computer Graphics and Vision at TU Graz in March.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events: Organisation

10.1.1.1. General Chair, Scientific Chair

Pierre Alliez was program co-chair of the EUROGRAPHICS conference and of the Symposium on Solid and Physical Modeling (SPM).

10.1.2. Scientific Events: Selection

10.1.2.1. Member of the Conference Program Committees

- Pierre Alliez: member of the advisory board for EUROGRAPHICS 2020.
- Florent Lafarge: EUROGRAPHICS
- Yuliya Tarabalka: ICCV

10.1.2.2. Reviewer

- Pierre Alliez: ACM SIGGRAPH, SIGGRAPH Asia, Symposium on Geometry processing.
- Florent Lafarge: CVPR, ICCV, SIGGRAPH.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- Pierre Alliez: associate editor of the Computer Graphics Forum, Computer-Aided Geometric Design and Computer-Aided Design. He is also a member of the editorial board of the CGAL open source project.
- Florent Lafarge: associate editor of The Visual Computer and the Revue Française de Photogrammétrie et de Télédétection, and member of the Editorial Advisory Board of the ISPRS Journal of Photogrammetry and Remote Sensing

10.1.3.2. Reviewer - Reviewing Activities

- Pierre Alliez: reviewer for Computer Graphics Forum and ACM Transactions on Graphics.
- Florent Lafarge: reviewer for the ISPRS Journal of Photogrammetry and Remote Sensing and the International Journal of Computer Vision.

10.1.4. Invited Talks

Pierre Alliez gave invited talks at Cambridge university, Google X and UCLA.

10.1.5. Leadership within the Scientific Community

Pierre Alliez is a member of the Steering Committees of the EUROGRAPHICS Symposium on Geometry Processing, EUROGRAPHICS Workshop on Graphics and Cultural Heritage and Executive Board Member for the Solid Modeling Association.

10.1.6. Scientific Expertise

Pierre Alliez was a reviewer for the European commission and ANR, and is a scientific advisory board member for the Bézout Labex in Paris (Models and algorithms: from the discrete to the continuous).

10.1.7. Research Administration

Pierre Alliez is Head of Science of the Inria Sophia Antipolis center and a member of the scientific committee of the 3IA Côte d'Azur.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master: Pierre Alliez, Florent Lafarge and Gaétan Bahl, advanced machine learning, 21h, M2, university Nice Sophia Antipolis, France.

Master: Pierre Alliez, data visualization, 3h, M2, university Côte d'Azur, France.

Master: Pierre Alliez and Florent Lafarge, 3D Meshes and Applications, 32h, M2, Ecole des Ponts ParisTech, France.

Master: Florent Lafarge, Traitement d'images numériques, 6h, M2, university Nice Sophia Antipolis, France.

Master: Pierre Alliez and Florent Lafarge, Interpolation numérique, 60h, M1, university Nice Sophia Antipolis, France.

Master: Florent Lafarge, Mathématiques pour la géométrie, 20h, M1, EFREI, France.

Master: Yuliya Tarabalka, Discrete inference and learning, 12h, M2 MVA, ENS Paris-Saclay & CentraleSupelec, France.

10.2.2. Supervision

PhD defended January 16th: Hao Fang, Geometric modeling of man-made objects at different level of details, since March 2016, Florent Lafarge.

PhD defended December 6th: Jean-Philippe Bauchet, Kinetic data structures for the geometric modeling of urban environments, since October 2016, Florent Lafarge.

PhD in progress: Julien Vuillamy, city reconstruction from multi-sourced data, since April 2018, Pierre Alliez and Florent Lafarge.

PhD in progress: Muxingzi Li, indoor reconstruction from a smartphone, since February 2018, Florent Lafarge.

PhD in progress: Lionel Matteo: From Pleiades images to very high resolution topography in complex zones, since September 2017, Yuliya Tarabalka and Isabelle Manighetti.

PhD in progress: Onur Tasar, Using deep learning approaches to devise an efficient representation for large-scale satellite images, since October 2017, Yuliya Tarabalka and Pierre Alliez.

PhD in progress: Nicolas Girard, How to structure satellite data, since November 2017, Yuliya Tarabalka.

PhD in progress: Vincent Vadez, Geometric simplification of satellites for thermal simulation, since August 2018, Pierre Alliez.

PhD in progress: Gaétan Bahl, low-power neural networks, since March 2019, Florent Lafarge.

PhD in progress: Mulin Yu, remeshing urban-specific CAD formats, since November 2019, Florent Lafarge.

PhD in progress: Tong Zhao, shape reconstruction, since November 2019, Pierre Alliez and Laurent Busé (from the Aromath Inria project-team).

PhD stopped after one year: Flora Quilichini, Geometry Compression, between January 2018 and June 2019, Pierre Alliez and Guillaume Lavoué (INSA Lyon).

10.2.3. Juries

- Pierre Alliez was a PhD committee member for Siargey Kachanovich and Jean-Philippe Bauchet (Inria Sophia Antipolis). He was a reviewer for the habilitation committee of Sébastien Valette (INSA Lyon).
- Florent Lafarge was a PhD thesis reviewer for Romain Rombourg (University of Grenoble Alpes) and Thomas Holzmann (TU Graz, Austria).

10.3. Popularization

10.3.1. Interventions

- Pierre Alliez gave a talk on geometric modeling in a high school in Cannes, April 26th.

11. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] J.-P. BAUCHET. *Kinetic data structures for the geometric modeling of urban environments*, Université Côte d'Azur, Inria, France, December 2019, https://hal.inria.fr/tel-02432386

[2] H. FANG.*Geometric modeling of man-made objects at different level of details*, Université Côte d'Azur, January 2019, https://tel.archives-ouvertes.fr/tel-02406834

Articles in International Peer-Reviewed Journal

[3] P. ALLIEZ, R. DI COSMO, B. GUEDJ, A. GIRAULT, M.-S. HACID, A. LEGRAND, N. P. ROUGIER.*Attributing and Referencing (Research) Software: Best Practices and Outlook from Inria*, in "Computing in Science & Engineering", 2019, p. 1-14, https://arxiv.org/abs/1905.11123 [*DOI :* 10.1109/MCSE.2019.2949413], https://hal.archives-ouvertes.fr/hal-02135891

[4] G. CHERCHI, P. ALLIEZ, R. SCATENI, M. LYON, D. BOMMES.*Selective Padding for Polycube-Based Hexahedral Meshing*, in "Computer Graphics Forum", January 2019 [*DOI :* 10.1111/CGF.13593], https://hal.inria.fr/hal-01970790

[5] O. ENNAFII, A. LE BRIS, F. LAFARGE, C. MALLET.*A learning approach to evaluate the quality of 3D city models*, in "Photogrammetric engineering and remote sensing", 2019, forthcoming, https://hal.archives-ouvertes.fr/hal-02193116

[6] H. FANG, F. LAFARGE.*Pyramid Scene Parsing Network in 3D: improving semantic segmentation of point clouds with multi-scale contextual information*, in "ISPRS Journal of Photogrammetry and Remote Sensing", 2019, forthcoming, https://hal.inria.fr/hal-02159279

[7] J.-D. FAVREAU, F. LAFARGE, A. BOUSSEAU, A. AUVOLAT.*Extracting Geometric Structures in Images with Delaunay Point Processes*, in "IEEE Transactions on Pattern Analysis and Machine Intelligence", 2019 [*DOI :* 10.1109/TPAMI.2018.2890586], https://hal.inria.fr/hal-01950791

[8] S. LEFÈVRE, D. SHEEREN, O. TASAR.*A Generic Framework for Combining Multiple Segmentations in Geographic Object-Based Image Analysis*, in "ISPRS International Journal of Geo-Information", 2019, vol. 8, n^{o} 2 [*DOI :* 10.3390/IJGI8020070], https://hal.archives-ouvertes.fr/hal-02083265

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Invited Conferences

[10] N. GIRARD, G. CHARPIAT, Y. TARABALKA.*Noisy Supervision for Correcting Misaligned Cadaster Maps Without Perfect Ground Truth Data*, in "IGARSS 2019 - IEEE International Geoscience and Remote Sensing Symposium", Yokohama, Japan, July 2019, https://arxiv.org/abs/1903.06529 , https://hal.inria.fr/hal-02065211

[11] A. KHALEL, O. TASAR, G. CHARPIAT, Y. TARABALKA.*Multi-Task Deep Learning for Satellite Image Pansharpening and Segmentation*, in "IGARSS 2019 - IEEE International Geoscience and Remote Sensing Symposium", Yokohama, Japan, July 2019, https://hal.inria.fr/hal-02276549

[12] O. TASAR, Y. TARABALKA, P. ALLIEZ.*Continual Learning for Dense Labeling of Satellite Images*, in "IGARSS 2019 - IEEE International Geoscience and Remote Sensing Symposium", Yokohama, Japan, July 2019, https://hal.inria.fr/hal-02276543

International Conferences with Proceedings

[13] G. BAHL, L. DANIEL, M. MORETTI, F. LAFARGE.*Low-power neural networks for semantic segmentation of satellite images*, in "ICCV Workshop on Low-Power Computer Vision", Seoul, South Korea, October 2019, https://hal.inria.fr/hal-02277061

[14] J.-P. BAUCHET, F. LAFARGE.*City Reconstruction from Airborne Lidar: A Computational Geometry Approach*, in "3D GeoInfo 2019 - 14thConference 3D GeoInfo", Singapore, Singapore, September 2019, https://hal.inria.fr/hal-02295768

[15] G. CHARPIAT, N. GIRARD, L. FELARDOS, Y. TARABALKA.*Input Similarity from the Neural Network Perspective*, in "Neural Information Processing Systems (NeurIPS)", Vancouver, Canada, December 2019, https://hal.inria.fr/hal-02394647

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[20] V. VADEZ, F. BRUNETTI, P. ALLIEZ.*First steps of numerical simulation using Artificial Intelligence*, in "European Space Thermal Engineering Workshop 2019", Amsterdam, Netherlands, October 2019, https://hal.inria.fr/hal-02367540

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[21] D. COHEN-STEINER, A. LIEUTIER, J. VUILLAMY.*Lexicographic optimal chains and manifold triangulations*, Inria Sophia-Antipolis Méditerranée, December 2019, https://hal.archives-ouvertes.fr/hal-02391190

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[24] O. TASAR, S. L. HAPPY, Y. TARABALKA, P. ALLIEZ.*ColorMapGAN: Unsupervised Domain Adaptation for Semantic Segmentation Using Color Mapping Generative Adversarial Networks*, November 2019, working paper or preprint, https://hal.inria.fr/hal-02382155

[25] O. TASAR, Y. TARABALKA, P. ALLIEZ, A. GIROS, S. CLERC.*From Satellite Images to Vector Representations*, November 2019, JC2 - 14èmes Journées CNES Jeunes Chercheurs, Poster, https://hal.inria.fr/hal-02367545

Team TOSCA

TO Simulate and CAlibrate stochastic models

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTERS
Sophia Antipolis - Méditerranée
Nancy - Grand Est

THEME
Stochastic approaches

Table of contents

Team TOSCA

Creation of the Team: 2019 January 01

Keywords:

Computer Science and Digital Science:

A6.1.2. - Stochastic Modeling
A6.1.3. - Discrete Modeling (multi-agent, people centered)
A6.1.4. - Multiscale modeling
A6.2.2. - Numerical probability
A6.2.3. - Probabilistic methods
A6.2.4. - Statistical methods
A6.4.2. - Stochastic control

Other Research Topics and Application Domains:

B1.1.6. - Evolutionnary biology
B1.1.8. - Mathematical biology
B1.2.1. - Understanding and simulation of the brain and the nervous system
B3.2. - Climate and meteorology
B3.3.4. - Atmosphere
B4.3.2. - Hydro-energy
B4.3.3. - Wind energy
B9.5.2. - Mathematics
B9.11. - Risk management
B9.11.1. - Environmental risks
B9.11.2. - Financial risks

1. Team, Visitors, External Collaborators

Research Scientists

Mireille Bossy [Inria, Senior Researcher, HDR]
Denis Talay [Team leader, Inria, Senior Researcher, HDR]
Christophe Henry [Inria, Starting Research Position]
Etienne Tanré [Inria, Researcher]
Olivier Faugeras [Inria, Emeritus Senior Researcher, also member of the team MATHNEURO, HDR]
Nicolas Champagnat [Inria, Senior Researcher, HDR]
Madalina Deaconu [Inria, Researcher, HDR]
Coralie Fritsch [Inria, Researcher]
Antoine Lejay [Inria, Senior Researcher, HDR]

Faculty Member

Denis Villemonais [Univ. de Lorraine, Associate Professor, HDR]

External Collaborators

Jeremie Bec [CNRS, Senior Researcher at CEMEF, Sophia Antipolis, from Mar. 2019]
Areski Cousin [Univ. de Claude Bernard, Professor]
Marcos Di Iorio [Marine Energy Research and Innovation Centre, Engineer, from May 2019 to Aug. 2019]
Jean-Francois Jabir [University of Edinburgh, Assistant Professor]

Nadia Maïzi [Ecole Nationale Supérieure des Mines de Paris, Professor, from Feb. 2019]
Samuel Herrmann [Univ. de Bourgogne, HDR]
Émilie Soret [Univ. Côte d'Azur]

Technical Staff

Radu Maftei [Inria, Engineer, HDR]
Victor Martin Lac [Inria, Engineer, until Jun. 2019]

PhD Students

Sofia Allende Contador [Univ. Côte d'Azur, from Mar. 2019]
Lorenzo Campana [Univ. Côte d'Azur]
Quentin Cormier [Univ. Côte d'Azur]
Aurore Dupre [Laboratoire de météorologie dynamique]
Pascal Helson [Univ. Côte d'Azur]
Alexis Anagnostakis [Univ. Lorraine]
Vincent Hass [Inria]
Rodolphe Loubaton [Univ. Lorraine]

Post-Doctoral Fellows

Igor Honore [Inria]
Kerlyns Martinez Rodriguez [Inria, from Oct. 2019]
Hector Olivero-Quinteros [Univ. Côte d'Azur]
Ulysse Herbach [Inria]
Édouard Strickler [Inria, since Oct. 2019]

Visiting Scientists

Kerlyns Martinez Rodriguez [CIMFAV, Valparaiso, Chile, PhD student, until Sep. 2019]
Cyril Mokrani [Marine Energy Research and Innovation Centre, Post-doc]
Alvin Tse [University of Edinburgh, PhD student, from Feb. 2019 until Mar. 2019]

Administrative Assistants

Isabelle Blanchard [Inria]
Laurence Briffa [Inria, from Jan. 2019 to Sep. 2019]
Sandrine Boute [Inria, since Aug. 2019]

2. Overall Objectives

2.1. Overall Objectives

TOSCA aims to significantly contribute to discern and explore new horizons for stochastic modeling. To this end we need to better understand the issues of stochastic modeling and the objectives pursued by practitioners who need them: we thus need to deeply understand other scientific fields than ours (e.g., Fluid Mechanics, Ecology, Biophysics) and to take scientific risks. Indeed, these risks are typified by the facts that often new and complex models do not behave as expected, mathematical and numerical difficulties are harder to overcome than forecast, and the increase of our knowledge in target fields is slower than wished.

In spite of these risks we think that our scientific approach is relevant for the following reasons:

- On the one hand, physicists, economists, biologists and engineers use a stochastic model because they cannot describe the physical, economical, biological, etc., experiment under consideration with deterministic systems, either because the experiment has a huge complexity, or because accurate calibrations of the parameters of the models would be impossible. However it is far from being enough to add noise to a dynamical system or to substitute random variables as parameters: the probability distribution of the random noises and parameters themselves is a modeling issue and, in addition, the qualitative behavior of the model may dramatically change as a function of this choice; in other terms, adding randomness to capture uncertainties may increase uncertainty instead of aiding. This issue is not so well understood in the literature, where most often probabilistic structures are given A PRIORI rather than studied as questionable choices. **Therefore our works, which concern application fields where stochastic modeling is still in its very beginning, include analysis of the limitations of the models we are elaborating. This analysis is based, either on theoretical estimates, or on our unique experience in stochastic simulations.**
- On the other hand, STOCHASTIC COMPUTATIONAL MODELS are being developed here and there, including by our team, with a fully different point of view from classical modeling approaches: these models are aimed to approximate complex physical laws (e.g. Fluid Mechanics laws for turbulent flows or folding processes for proteins) by statistical properties of artificial objects (e.g. particles interacting with turbulent flows or low dimensional stochastic systems having suitable correlation structures). The design of the stochastic dynamics of these objects is part of the problem to deal with, and the complexity of the underlying physical phenomena leads to huge simulation difficulties. **Therefore we are exploring new frontiers for stochastic numerical methods and developing advanced techniques far beyond our previous works and most of the literature.**

To bring relevant analytical and numerical answers to the preceding problems, we feel necessary to attack in parallel several problems arising from different fields. Each one of these problems contributes to our better understanding of the advantages and limitations of stochastic models and algorithms.

Of course, this strategy allows each researcher in the team to have her/his own main topic. However **we organize the team in order to maximize internal collaborations**. We consider this point, which justifies the existence of Inria project-teams, as essential to the success of our programme of research. It relies on the fact that, to develop our mathematical and numerical studies, we share a common interest for collaborations with engineers, practitioners, physicists, biologists and numerical analysts, and we also share the following common toolbox:

- Stochastic differential calculus;
- Mathematical combinations of both partial differential equations (PDEs) analysis and stochastic analysis for deterministic non-linear PDEs, notably stochastic control equations and McKean-Vlasov-Fokker-Planck equations;
- Original stochastic numerical analysis techniques to get theoretical estimates on stochastic numerical methods, and numerical experiments to calibrate these methods.

We finally emphasize that the unifying theme of our research is to develop analytical tools that can be effectively applied to various problems that come from extremely diverse subjects. For example, as described in more detail below, we study: branching processes and their simulation with the view of advancing our understanding of population dynamics, molecular dynamics, and cancer models; the theory and numerical analysis of McKean-Vlasov interacting particle systems in order to develop our models in biology, computational fluid dynamics, coagulation and fragmentation; hitting times of domains by stochastic processes so that we can improve on the current methods and theory used in finance and neuroscience.

3. Research Program

3.1. Research Program

Most often physicists, economists, biologists and engineers need a stochastic model because they cannot describe the physical, economical, biological, etc., experiment under consideration with deterministic systems, either because of its complexity and/or its dimension or because precise measurements are impossible. Therefore, they abandon trying to get the exact description of the state of the system at future times given its initial conditions, and try instead to get a statistical description of the evolution of the system. For example, they desire to compute occurrence probabilities for critical events such as the overstepping of a given thresholds by financial losses or neuronal electrical potentials, or to compute the mean value of the time of occurrence of interesting events such as the fragmentation to a very small size of a large proportion of a given population of particles. By nature such problems lead to complex modelling issues: one has to choose appropriate stochastic models, which require a thorough knowledge of their qualitative properties, and then one has to calibrate them, which requires specific statistical methods to face the lack of data or the inaccuracy of these data. In addition, having chosen a family of models and computed the desired statistics, one has to evaluate the sensitivity of the results to the unavoidable model specifications. The TOSCA team, in collaboration with specialists of the relevant fields, develops theoretical studies of stochastic models, calibration procedures, and sensitivity analysis methods.

In view of the complexity of the experiments, and thus of the stochastic models, one cannot expect to use closed form solutions of simple equations in order to compute the desired statistics. Often one even has no other representation than the probabilistic definition (e.g., this is the case when one is interested in the quantiles of the probability law of the possible losses of financial portfolios). Consequently the practitioners need Monte Carlo methods combined with simulations of stochastic models. As the models cannot be simulated exactly, they also need approximation methods which can be efficiently used on computers. The TOSCA team develops mathematical studies and numerical experiments in order to determine the global accuracy and the global efficiency of such algorithms.

The simulation of stochastic processes is not motivated by stochastic models only. The stochastic differential calculus allows one to represent solutions of certain deterministic partial differential equations in terms of probability distributions of functionals of appropriate stochastic processes. For example, elliptic and parabolic linear equations are related to classical stochastic differential equations (SDEs), whereas nonlinear equations such as the Burgers and the Navier–Stokes equations are related to McKean stochastic differential equations describing the asymptotic behavior of stochastic particle systems. In view of such probabilistic representations one can get numerical approximations by using discretization methods of the stochastic differential systems under consideration. These methods may be more efficient than deterministic methods when the space dimension of the PDE is large or when the viscosity is small. The TOSCA team develops new probabilistic representations in order to propose probabilistic numerical methods for equations such as conservation law equations, kinetic equations, and nonlinear Fokker–Planck equations.

4. Application Domains

4.1. Application domains

TOSCA is interested in developing stochastic models and probabilistic numerical methods. Our present motivations come from models with singular coefficients, with applications in Geophysics, Molecular Dynamics and Neurosciences; Lagrangian modeling in Fluid Dynamics and Meteorology; Population Dynamics, Evolution and Genetics; Neurosciences; and Financial Mathematics.

4.1.1. Stochastic models with singular coefficients: Analysis and simulation

Stochastic differential equations with discontinuous coefficients arise in Geophysics, Chemistry, Molecular Dynamics, Neurosciences, Oceanography, etc. In particular, they model changes of diffusion of fluids, or diffractions of particles, along interfaces.

For practioners in these fields, Monte Carlo methods are popular as they are easy to interpret — one follows particles — and are in general easy to set up. However, dealing with discontinuities presents many numerical and theoretical challenges. Despite its important applications, ranging from brain imaging to reservoir simulation, very few teams in mathematics worldwide are currently working in this area. The Tosca project-team has tackled related problems for several years providing rigorous approach. Based on stochastic analysis as well as interacting with researchers in other fields, we developed new theoretical and numerical approaches for extreme cases such as Markov processes whose generators are of divergence form with discontinuous diffusion coefficient.

The numerical approximation of singular stochastic processes can be combined with backward stochastic differential equations (BSDEs) or branching diffusions to obtain Monte Carlo methods for quasi-linear PDEs with discontinuous coefficients. The theory of BSDEs has been extensively developed since the 1980s, but the general assumptions for their existence can be quite restrictive. Although the probabilistic interpretation of quasi-linear PDEs with branching diffusions has been known for a long time, there have been only a few works on the related numerical methods.

Another motivation to consider stochastic dynamics in a discontinuous setting came to us from time evolution of fragmentation and coagulation phenomena, with the objective to elaborate stochastic models for the avalanche formation of soils, snow, granular materials or other geomaterials. Most of the models and numerical methods for avalanches are deterministic and involve a wide variety of physical parameters such as the density of the snow, the yield, the friction coefficient, the pressure, the basal topography, etc. One of these methods consists in studying the safety factor (or limit load) problem, related to the shallow flow of a visco-plastic fluid/solid with heterogeneous thickness over complex basal topography. The resulting nonlinear partial differential equation of this last theory involves many singularities, which motivates us to develop an alternative stochastic approach based on our past works on coagulation and fragmentation. Our approach consists in studying the evolution of the size of a typical particle in a particle system which fragments in time.

4.1.2. Stochastic Lagrangian modeling in Computational Fluid Dynamics

Stochastic Lagrangian models were introduced in the eighties to simulate complex turbulent flows, particularly two-phase flows. In Computational Fluid Dynamics (CFD), they are intensively used in the so-called Probability Density Functions (PDF) methods in order to model and compute the reaction-phase terms in the fundamental equations of fluid motions. The PDF methods are currently developed in various laboratories by specialists in scientific computation and physicists. However, to our knowledge, we are innovating in two ways:

- our theoretical studies are the pioneering mathematical analysis of Lagrangian stochastic models in CFD;
- our work on the Stochastic Downscaling Method (SDM) for wind simulation is the first attempt to solve the fundamental equations themselves by a fully 3D stochastic particle method.

We emphasize that our numerical analysis is essential to the SDM development which takes benefits from our deep expertise on numerical schemes for McKean-Vlasov-non-linear SDEs.

4.1.3. Population Dynamics, Evolution and Genetics

The activity of the team on stochastic modeling in population dynamics and genetics mainly concerns application in adaptive dynamics, a branch of evolutionary biology studying the interplay between ecology and evolution, ecological modeling, population genetics in growing populations, and stochastic control of population dynamics, with applications to cancer growth modeling. Stochastic modeling in these areas mainly considers individual-based models, where the birth and death of each individual is described. This class of model is well-developed in Biology, but their mathematical analysis is still fragmentary. Another important topic in population dynamics is the study of populations conditioned to non-extinction, and of the corresponding stationary distributions, called quasi-stationary distributions (QSD). This domain has been the object of a lot of studies since the 1960's, but we made recently significant progresses on the questions of existence, convergence and numerical approximation of QSDs using probabilistic tools rather than the usual spectral tools.

Our activity in population dynamics also involves a fully new research project on cancer modeling at the cellular level by means of branching processes. In 2010 the International Society for Protons Dynamics in Cancer was launched in order to create a critical mass of scientists engaged in research activities on Proton Dynamics in Cancer, leading to the facilitation of international collaboration and translation of research to clinical development. Actually, a new branch of research on cancer evolution is developing intensively; it aims in particular to understand the role of proteins acting on cancerous cells' acidity, their effects on glycolysis and hypoxia, and the benefits one can expect from controlling pH regulators in view of proposing new therapies.

4.1.4. Stochastic modeling in Neuroscience

It is generally accepted that many different neural processes that take place in the brain involve noise. Indeed, one typically observes experimentally underlying variability in the spiking times of an individual neuron in response to an unchanging stimulus, while a predictable overall picture emerges if one instead looks at the average spiking time over a whole group of neurons. Sources of noise that are of interest include ionic currents crossing the neural membrane, synaptic noise, and the global effect of the external environment (such as other parts of the brain).

It is likely that these stochastic components play an important role in the function of both the neurons and the networks they form. The characterization of the noise in the brain, its consequences at a functional level and its role at both a microscopic (individual neuron) level and macroscopic level (network of thousands of neurons) is therefore an important step towards understanding the nervous system.

To this end, a large amount of current research in the neuroscientific literature has involved the addition of noise to classical purely deterministic equations resulting in new phenomena being observed. The aim of the project is thus to rigorously study these new equations in order to be able to shed more light on the systems they describe.

4.1.5. Stochastic modeling in Financial Mathematics

4.1.5.1. Technical Analysis

In the financial industry, there are three main approaches to investment: the fundamental approach, where strategies are based on fundamental economic principles; the technical analysis approach, where strategies are based on past price behavior; and the mathematical approach where strategies are based on mathematical models and studies. The main advantage of technical analysis is that it avoids model specification, and thus calibration problems, misspecification risks, etc. On the other hand, technical analysis techniques have limited theoretical justifications, and therefore no one can assert that they are risk-less, or even efficient.

4.1.5.2. Financial Risks Estimation and Hedging

Popular models in financial mathematics usually assume that markets are perfectly liquid. In particular, each trader can buy or sell the amount of assets he/she wants at the same price (the "market price"). They moreover assume that the decision taken by the trader does not affect the price of the asset (the small investor assumption). In practice, the assumption of perfect liquidity is never satisfied but the error due to liquidity is generally negligible with respect to other sources of error such as model error or calibration error, etc.

Derivatives of interest rates are singular for at least two reasons: firstly the underlying (interest rate) is not directly exchangeable, and secondly the liquidity costs usually used to hedge interest rate derivatives have large variation in times.

Due to recurrent crises, the problem of risk estimation is now a crucial issue in finance. Regulations have been enforced (Basel Committee II). Most asset management software products on the markets merely provide basic measures (VaR, Tracking error, volatility) and basic risk explanation features (e.g., "top contributors" to risk, sector analysis, etc).

4.1.5.3. Energy and Carbon Markets

With the rise of renewable energy generation (from solar, wind, waves...), engineers face new challenges which heavily rely on stochastic and statistical problems.

Besides, in the context of the beginning of the second phase (the Kyoto phase) in 2008 of the European carbon market, together with the fact that French carbon tax was scheduled to come into law on Jan. 1, 2010, the year 2009 was a key year for the carbon price modeling. Our research approach adopts the point of view of the legislator and energy producers. We used both financial mathematical tools and a game theory approach. Today, with the third phase of the EU-ETS, that didn't yet start, and the report form the Cour des Comptes (October 2013) that pointed out (among many others point) the lack of mathematical modeling on such carbon market design, we continue our research in this direction.

4.1.5.4. Optimal Stopping Problems

The theory of optimal stopping is concerned with the problem of taking a decision at the best time, in order to maximise an expected reward (or minimise an expected cost). We work on the general problem of optimal stopping with random discounting and additional cost of observation.

4.1.5.5. First hitting times distributions

Diffusion hitting times are of great interest in finance (a typical example is the study of barrier options) and also in Geophysics and Neurosciences. On the one hand, analytic expressions for hitting time densities are well known and studied only in some very particular situations (essentially in Brownian contexts). On the other hand, the study of the approximation of the hitting times for stochastic differential equtions is an active area of research since very few results still are available in the literature.

5. New Software and Platforms

5.1. diamss

KEYWORDS: High-performance calculation - Computation - Stochastic process

FUNCTIONAL DESCRIPTION: Numerical resolution of Keller-Segel equations and everal numerical tests.

- Participants: Denis Talay, Hector Olivero-Quinteros and Milica Tomasevic
- Contact: Denis Talay

5.2. ExitBM

FUNCTIONAL DESCRIPTION: The exitbm library provides methods to simulate random variables related to the first exit time and position of the Brownian motion from simple domains, namely intervals, squares and rectangles.

- Participants: Antoine Lejay and Madalina Deaconu
- Contact: Antoine Lejay
- URL: http://exitbm.gforge.inria.fr/

5.3. MOC

Models Of Chemostat

KEYWORD: Simulator

FUNCTIONAL DESCRIPTION: MOC (for Models of Chemostat) is a Python simulator of four chemostat models: a mass-structured stochastic individual based model, a mass-structured integro-differential model, the Crump-Young model and a system of ordinary differential equations. This software allows to simulate one or several of those models with different parameters, to plot graphics of evolution of biomass concentration, number of bacteria and substrate concentration as well as the phase portrait, to determine the law of the extinction time of the bacterial population in case of population extinction.

- Participants: Coralie Fritsch and Fabien Campillo
- Contact: Coralie Fritsch
- URL: https://github.com/coraliefritsch/modelsOfChemostat

5.4. SDM

Stochastic Downsaling Method

FUNCTIONAL DESCRIPTION: The computation of the wind at small scale and the estimation of its uncertainties is of particular importance for applications such as wind energy resource estimation. To this aim, starting in 2005, we have developed a new method based on the combination of an existing Numerical Weather Prediction model providing a coarse prediction, and a Lagrangian Stochastic Model for turbulent flows. This Stochastic Downscaling Method (SDM) requires a specific modeling of the turbulence closure, and involves various simulation techniques whose combination is totally original (such as Poisson solvers, optimal transportation mass algorithm, original Euler scheme for confined Langevin stochastic processes, and stochastic particle methods).

- Participants: Antoine Rousseau, Antoine Rousseau, Claire Chauvin, Frederic Bernardin and Mireille Bossy
- Contact: Mireille Bossy

5.5. SDM-Log

- Participants: Antoine Rousseau, Claire Chauvin, Frederic Bernardin, Jacques Morice and Mireille Bossy
- Contact: Mireille Bossy

5.6. WindPoS-SDM-LAM

KEYWORDS: Numerical simulations - 3D - Fluid mechanics

FUNCTIONAL DESCRIPTION: Software platform for wind modeling.

- Authors: Antoine Rousseau, Cristian Paris Ibarra, Jacques Morice, Mireille Bossy and Sélim Kraria
- Contact: Mireille Bossy
- URL: https://windpos.inria.fr

5.7. WindPoS-ATM

KEYWORDS: 3D - Co-simulation - Fluid mechanics

- Authors: Philippe Drobinski, Antoine Rousseau, Mireille Bossy, Jacques Morice and Thomas Dubos
- Partners: Ecole Polytechnique - Laboratoire de Météorologie Dynamique
- Contact: Mireille Bossy
- URL: https://windpos.inria.fr/projects/windpos/

5.8. WindPoS-CIV

WinsPoS-CIV (Configuration Interface and Visualization)

- Authors: Sélim Kraria, Antoine Rousseau and Mireille Bossy
- Contact: Mireille Bossy

5.9. SBM

Skew Brownian Motion

KEYWORDS: Monte-Carlo methods - Skew Brownian Motion

FUNCTIONAL DESCRIPTION: SBM is a code allowing exact or approximated simulations of the Skew Brownian Motion. This code is used for the simulation, with a Monte-Carlo approach, of a 1D diffusion process with a discontinuous diffusion coefficient. Several benchmark tests are also implemented.

NEWS OF THE YEAR: - Refactoring and Cmake compilation - Automatic non regression tests on ci-inria.fr - Full documentation - Open source project on gitlab-inria

- Authors: Antoine Lejay and Géraldine Pichot
- Contact: Antoine Lejay
- Publication: Simulating diffusion processes in discontinuous media: Benchmark tests
- URL: https://gitlab.inria.fr/lejay/sbm

6. New Results

6.1. Probabilistic numerical methods, stochastic modeling and applications

Participants: Sofia Allende Contador, Alexis Anagnostakis, Mireille Bossy, Lorenzo Campana, Nicolas Champagnat, Quentin Cormier, Madalina Deaconu, Aurore Dupre, Coralie Fritsch, Vincent Hass, Pascal Helson, Christophe Henry, Ulysse Herbach, Igor Honore, Antoine Lejay, Rodolphe Loubaton, Radu Maftei, Kerlyns Martinez Rodriguez, Victor Martin Lac, Hector Olivero-Quinteros, Édouard Strickler, Denis Talay, Etienne Tanré, Denis Villemonais.

6.1.1. Published works and preprints

- H. AlRachid (Orléans University), M. Bossy, C. Ricci (University of Florence) and L. Szpruch (University of Edinburgh and The Alan Turing Institute, London) introduced several new particle representations for *ergodic* McKean-Vlasov SDEs. They construct new algorithms by leveraging recent progress in weak convergence analysis of interacting particle system. In [12] they present detailed analysis of errors and associated costs of various estimators, highlighting key differences between long-time simulations of linear (classical SDEs) versus non-linear (McKean-Vlasov SDEs) process.
- M. Di Iorio (Marine Energy Research and Innovation Center, Santiago, Chile), M. Bossy, C. Mokrani (Marine Energy Research and Innovation Center, Santiago, Chile), and A. Rousseau (LEMON team) obtained advances in stochastic Lagrangian approaches for the simulation of hydrokinetic turbines immersed in complex topography [42].
- M. Bossy, J.-F. Jabir (University of Edinburgh) and K. Martinez (University of Valparaiso) consider the problem of the approximation of the solution of a one-dimensional SDE with non-globally Lipschitz drift and diffusion coefficients behaving as x^α, with $\alpha > 1$ [44]. They propose an (semi-explicit) exponential-Euler scheme and study its convergence through its weak approximation error. To this aim, they analyze the $C^{1,4}$ regularity of the solution of the associated backward Kolmogorov PDE using its Feynman-Kac representation and the flow derivative of the involved processes. From this, under some suitable hypotheses on the parameters of the model ensuring the control of its positive moments, they recover a rate of weak convergence of order one for the proposed exponential Euler scheme. Numerical experiments are analyzed in order to complement their theoretical result.
- L. Campana et al. developed some Lagrangian stochastic model for anisotropic particles in turbulent flow [35]. Suspension of anisotropic particles can be found in various industrial applications. Microscopic ellipsoidal bodies suspended in a turbulent fluid flow rotate in response to the velocity gradient of the flow. Understanding their orientation is important since it can affect the optical or rheological properties of the suspension (e.g. polymeric fluids). The equations of motion for the orientation of microscopic ellipsoidal particles was obtained by Jeffery. But so far this description has been always investigated in the framework of direct numerical simulations (DNS) and experimental measurements. In this work, the orientation dynamics of rod-like tracer particles, i.e. long ellipsoidal

particles (in the limit of infinite aspect-ratio) is studied. The size of the rod is assumed smaller than the Kolmogorov length scale but sufficiently large that its Brownian motion need not be considered. As a result, the local flow around a particle can be considered as inertia-free and Stokes flow solutions can be used to relate particle rotational dynamics to the local velocity gradient. The orientation of rod can be described as the normalised solution of the linear ordinary differential equation for the separation vector between two fluid tracers, under the action of the velocity gradient tensor. In this framework, the rod orientation is described by a Lagrangian stochastic model where cumulative velocity gradient fluctuations are represented by a white-noise tensor such that the incompressibility condition is preserved. A numerical scheme based on the decomposition into skew/symmetric part of the process dynamics is proposed.

- Together with M. Andrade-Restrepo (Univ. Paris Diderot) and R. Ferrière (Univ. Arizona and École Normale Supérieure), N. Champagnat studied deterministic and stochastic spatial eco-evolutionary dynamics along environmental gradients. This work focuses on numerical and analytical analysis of the clustering phenomenon in the population, and on the patterns of invasion fronts [13].
- Together with M. Benaïm (Univ, Neuchâtel), N. Champagnat and D. Villemonais studied stochastic algorithms to approximate quasi-stationary distributions of diffusion processes absorbed at the boundary of a bounded domain. They study a reinforced version of the diffusion, which is resampled according to its occupation measure when it reaches the boundary. They show that its occupation measure converges to the unique quasi-stationary distribution of the diffusion process [43].
- N. Champagnat, C. Fritsch and S. Billiard (Univ. Lille) studied models of food web adaptive evolution. They identified the biomass conversion efficiency as a key mechanism underlying food webs evolution and discussed the relevance of such models to study the evolution of food webs [51].
- N. Champagnat and J. Claisse (Univ. Paris-Dauphine) studied the ergodic and infinite horizon controls of discrete population dynamics with almost sure extinction in finite time. This can either correspond to control problems in favor of survival or of extinction, depending on the cost function. They have proved that these two problems are related to the quasi-stationary distribution of the processes controled by Markov controls [18].
- N. Champagnat and B. Henry (Univ. Lille 1) studied a probabilistic approach for the Hamilton-Jacobi limit of non-local reaction-diffusion models of adaptive dynamics when mutations are small. They used a Feynman-Kac interpretation of the partial differential equation and large deviation estimates to obtain a variational characterization of the limit. They also studied in detail the case of finite phenotype space with exponentially rare mutations, where they were able to obtain uniqueness of the limit [19].
- N. Champagnat and D. Villemonais solved a general conjecture on the Fleming-Viot particle systems approximating quasi-stationary distributions (QSD): in cases where several quasi-stationary distributions exist, it is expected that the stationary distributions of the Fleming-Viot processes approach a particular QSD, called minimal QSD. They proved that this holds true for general absorbed Markov processes with soft obstacles [20].
- N. Champagnat and D. Villemonais studied the geometric convergence of normalized unbounded semigroups. They proved in [47] that general criteria for this convergence can be easily deduced from their recent results on the theory of quasi-stationary distributions.
- N. Champagnat, S. Méléard (École Polytechnique) and V.C. Tran (Univ. Paris Est Marne-la-Vallée) studied evolutionary models of bacteria with horizontal transfer. They considered in [46] a scaling of parameters taking into account the influence of negligible but non-extinct populations, allowing them to study specific phenomena observed in these models (re-emergence of traits, cyclic evolutionary dynamics and evolutionary suicide).
- M. Bahlali (CEREA, France) , C. Henry and B. Carissimo (CEREA, France) clarify issues related to the expression of Lagrangian stochastic models used for atmospheric dispersion applications. They showed that accurate simulations are possible only if two aspects are properly addressed: the respect of the well-mixed criterion (related to the incorporation of the mean pressure-gradient term in the

mean drift-term) and the consistency between Eulerian and Lagrangian turbulence models (regarding turbulence models, boundary and divergence-free conditions).

- A. Lejay and A. Brault have continued their work on rough flows, which provides an unified framework to deal with the theory of rough paths from the point of view of flows. In particular, they have studied consistency, stability and generic properties of rough differential equations [45].
- A. Lejay and P. Pigato have provided an estimator of a discontinuous drift coefficients [30], which follows their previous work on the oscillating Brownian motion and its application to financial models.
- A. Lejay and H. Mardones (U. la Serenan, Chile), have completed their work on the Monte Carlo simulation of the Navier-Stockes equations based on a new representation by Forward-Backward Stochastic Differential Equations [53].
- O. Faugeras, E. Soret and E. Tanré have obtained a Mean-Field description of thermodynamics limits of large population of neurons with random interactions. They have obtained the asymptotic behaviour for an asymmetric neuronal dynamics in a network of linear Hopfield neurons. They have a complete description of this limit with Gaussian processes. Furthermore, the limit object is not a Markov process [50].
- E. Tanré, P. Grazieschi (Univ. Warwick), M. Leocata (Univ. Pisa), C. Mascart (Univ. Côte d'Azur), J. Chevallier (Univ. of Grenoble) and F. Delarue (Univ. Côte d'Azur) have extended the previous work [9] to sparse networks of interacting neurons. They have obtained a precise description of the limit behavior of the mean field limit according to the probability of (random) interactions between two individual LIF neurons [24].
- P. Helson has studied the learning of an external signal by a neural network and the time to forget it when this network is submitted to noise. He has constructed an estimator of the initial signal thanks to the synaptic currents, which are Markov chains. The mathematical study of the Markov chains allow to obtain a lower bound on the number of external stimuli that the network can receive before the initial signal is forgotten [52].
- Q. Cormier and E. Tanré studied with Romain Veltz (team MATHNEURO) the long time behavior of a McKean-Vlasov SDE modeling a large assembly of neurons. A convergence to the unique (in this case) invariant measure is obtained assuming that the interactions between the neurons are weak enough. The key quantity in this model is the "firing rate": it gives the average number of jumps per unit of times of the solution of the SDE. They derive a non-linear Volterra equation satisfied by this rate. They used methods from integral equation to control finely the long time behavior of this firing rate [21].
- E. Tanré has worked with Nicolas Fournier (Sorbonne Université) and Romain Veltz (MATHNEURO Inria team) on a network of spiking networks with propagation of spikes along the dendrites. Consider a large number n of neurons randomly connected. When a neuron spikes at some rate depending on its electric potential, its membrane potential is set to a minimum value v_{min}, and this makes start, after a small delay, two fronts on the dendrites of all the neurons to which it is connected. Fronts move at constant speed. When two fronts (on the dendrite of the same neuron) collide, they annihilate. When a front hits the soma of a neuron, its potential is increased by a small value w_n. Between jumps, the potentials of the neurons are assumed to drift in $[v_{min}, \infty)$, according to some well-posed ODE. They prove the existence and uniqueness of a heuristically derived mean-field limit of the system when $n \to \infty$ [23].
- O. Faugeras, James Maclaurin (Univ. of Utah) and E. Tanré have worked on the asymptotic behavior of a model of neurons in interaction with correlated gaussian synaptic weights. They have obtained the limit equation as a singular non-linear SDE and a Large Deviation Principle for the law of the finite network [49].
- E. Tanré has worked with Alexandre Richard (Centrale-Supelec) and Soledad Torres (Universidad de Valparaíso, Chile) on a one-dimensional fractional SDE with reflection. They have proved the existence of the reflected SDE with a penalization scheme (suited to numerical approximation). Penalization also gives an algorithm to approach this solution [55].

- The Neutron Transport Equation (NTE) describes the flux of neutrons over time through an inhomogeneous fissile medium. A probabilistic solution of the NTE is considered in order to demonstrate a Perron-Frobenius type growth of the solution via its projection onto an associated leading eigenfunction. The associated eigenvalue, denoted k_{eff}, has the physical interpretation as being the ratio of neutrons produced (during fission events) to the number lost (due to absorption in the reactor or leakage at the boundary) per typical fission event. Together with A. M. G. Cox, E. L. Horton and A. E. Kyprianou (Univ. Bath), D. Villemonais developed the stochastic analysis of the NTE by giving a rigorous probabilistic interpretation of k_{eff} [48].
- In [34], D. Villemonais obtained a lower bound for the coarse Ricci curvature of continuous-time pure-jump Markov processes, with an emphasis on interacting particle systems. Applications to several models are provided, with a detailed study of the herd behavior of a simple model of interacting agents.
- In collaboration with C. Coron (Univ. Paris Sud) and S. Méléard (École Polytechnique), D. Villemonais studied in [22] the way alleles extinctions and fixations occur for a multiple allelic proportions model based on diffusion processes. It is proved in particular that alleles extinctions occur successively and that a 0-1 law holds for fixation and extinction: depending on the population dynamics near extinction, either fixation occurs before extinction, or the converse, almost surely.
- Mean telomere length in human leukocyte DNA samples reflects the different lengths of telomeres at the ends of the 23 chromosomes and in an admixture of cells. Together with S. Toupance (CHRU Nancy), D. Germain (Univ. Lorraine), A. Gégout-Petit (Univ. Lorraine and BIGS Inria team), E. Albuisson (CHRU Nancy) and A. Benetos (CHRU Nancy), D. Villemonais analysed telomere length distributions dynamics in adults individuals. It is proved in [33] that the shape of this distribution is stable over the lifetime of individuals.
- J. Bion-Nadal (Ecole Polytechnique) and D. Talay have pursued their work on their Wasserstein-type distance on the set of the probability distributions of strong solutions to stochastic differential equations. This new distance is defined by restricting the set of possible coupling measures and can be expressed in terms of the solution to a stochastic control problem, which allows one to deduce a priori estimates or to obtain numerical evaluations [15].

  A notable application concerns the following modeling issue: given an exact diffusion model, how to select a simplified diffusion model within a class of admissible models under the constraint that the probability distribution of the exact model is preserved as much as possible? The objective being to select a model minimizing the above distance to a target model, approximations of the optimal model have been established. The construction and analysis of an efficient stochastic algorithm are being in progress.
- D. Talay and M. Tomašević have continued to work on their new type of stochastic interpretation of the parabolic-parabolic Keller-Segel systems. It involves an original type of McKean-Vlasov interaction kernel. At the particle level, each particle interacts with all the past of each other particle. D. Talay and M. Tomašević are studying the well-posedness and the propagation of chaos of the particle system related to the two-dimensional parabolic-parabolic Keller-Segel system.
- V. Martin Lac, R. Maftei D. Talay and M. Tomašević have continued to work on theoretical and algorithmic questions related to the simulation of the Keller–Segel particle systems. The library DIAMSS has been developed.
- H. Olivero (Inria, now University of Valparaiso, Chile) and D. Talay have continued to work on their hypothesis test which helps to detect when the probability distribution of complex stochastic simulations has an heavy tail and thus possibly an infinite variance. This issue is notably important when simulating particle systems with complex and singular McKean-Vlasov interaction kernels whick make it extremely difficult to get a priori estimates on the probability laws of the mean-field limit, the related particle system, and their numerical approximations. In such situations the standard limit theorems do not lead to effective tests. In the simple case of independent and identically distributed sequences the procedure developed this year and its convergence analysis are based on deep tools coming from the statistics of semimartingales.

- I. Honoré and D. Talay have worked on statistical issues related to numerical approximations of invariant probability measures of ergodic diffusions. These approximations are based on the simulation of one single trajectory up to long time horizons. I. Honoré and D. Talay handle the critical situations where the asymptotic variance of the normalized error is infinite.
- V. Martin Lac, H. Olivero-Quinteros and D. Talay have worked on theoretical and algorithmic questions related to the simulation of large particle systems under singular interactions and to critical numerical issues related to the simulation of independent random variables with heavy tails. A preliminary version of a library has been developed.
- C. Graham (École Polytechnique) and D. Talay have ended the second volume of their series on Mathematical Foundation of Stochastic Simulation to be published by Springer.

6.1.2. Other works in progress

- K. Martinez, M. Bossy, C. Henry, R. Maftei and S. Sherkarforush work on a refined algorithm for macroscopic simulations of particle agglomeration using population balance equations (PBE). More precisely, their study is focused on identifying regions with non-homogeneous spatial distribution of particles. This is indeed a major drawback of PBE formulations which require a well-mixed condition to be satisfied. The developed algorithm identifies higher/lower density regions to treat them separately.
- S. Allende (CEMEF, France), J. Bec (CEMEF, France), M. Bossy, L. Campana, M. Ferrand (EDF, France), C. Henry and J.P. Minier (EDF, France) work together on a macroscopic model for the dynamics of small, flexible, inextensible fibers in a turbulent flow. Following the model developed at Inria, they perform numerical simulations of the orientation of such fibers in wall-bounded turbulent flows and compare it to microscopic simulations obtained with Direct Numerical Simulation (DNS). This work is performed under the POPART project.
- N. Champagnat, C. Fritsch and U. Herbach are working with A. Harlé (Institut de Cancérologie de Lorraine), J.-L. Merlin (ICL), E. Pencreac'h (CHRU Strasbourg), A. Gégout-Petit, P. Vallois, A. Muller-Gueudin (Inria BIGS team) and A. Kurtzmann (Univ. Lorraine) within an ITMO Cancer project on modeling and parametric estimation of dynamical models of circulating tumor DNA (ctDNA) of tumor cells, divided into several clonal populations. The goal of the project is to predict the emergence of a clonal population resistant to a targeted therapy in a patient's tumor, so that the therapy can be modulated more efficiently.
- N. Champagnat and R. Loubaton are working with P. Vallois (Univ. Lorraine and Inria BIGS team) and L. Vallat (CHRU Strasbourg) on the inference of dynamical gene networks from RNAseq and proteome data.
- N. Champagnat, E. Strickler and D. Villemonais are working on the characterization of convergence in Wasserstein distance of conditional distributions of absorbed Markov processes to a quasi-stationary distribution.
- N. Champagnat and V. Hass are studying evolutionary models of adaptive dynamics under an assumption of large population and small mutations. They expect to recover variants of the canonical equation of adaptive dynamics, which describes the long time evolution of the dominant phenotype in the population, under less stringent biological assumptions than in previous works.
- Q. Cormier, E. Tanré and Romain Veltz (team MATHNEURO) are working on the local stability of a stationary solution of some McKean-Vlasov equation. They also obtain spontaneous oscillation of the solution for critical values of the external currents or the interactions.
- M. Deaconu, A. Lejay and E. Mordecki (U. de la República, Uruguay) are studying an optimal stopping problem for the Snapping Out Brownian motion.
- M. Deaconu and A. Lejay are currently working on the simulation and the estimation of the fragmentation equation through its probabilistic representation.

- S. Allende (CEMEF, France) , C. Henry and J. Bec (CEMEF, France) work on the dynamics of small, flexible, inextensible fibers in a turbulent flow. They show that the fragmentation of fibers smaller than the smallest fluid scale in a turbulent flow occurs through tensile fracture (i.e. when the fiber is stretched along its main axis) or through flexural failure (i.e. when the fiber curvature is too high as it buckles under compressive load). Statistics of such events are provide together with measures of the rate of fragmentation and daughter size distributions, which are basic ingredients for macroscopic fragmentation models.
- C. Henry and M.L. Pedrotti (LOV, France) are working together on the topic of sedimentation of plastic that are populated by biological organisms (this is called biofouling). Biofouling modifies the density of plastic debris in the ocean and can lead to their sedimentation towards deeper regions. This work is done under the PLAISE project, which comprises measurements (by the LOV) and simulations (by C. Henry).
- C. Fritsch is working with A. Gégout-Petit (Univ. Lorraine and EPI BIGS), B. Marçais (INRA, Nancy) and M. Grosdidier (INRA, Avignon) on a statistical analysis of a Chalara Fraxinea model.
- C. Fritsch is working with Tanjona Ramiadantsoa (Univ. Wisconsin-Madison) on a model of extinction of orphaned plants.
- A. Lejay and M. Clausel (U. Lorraine) are studing the clustering method based on the use of the signature and the iterated integrals of time series. It is based on asymmetric spectral clustering [41].
- In collaboration with L. Lenotre (postdoc at IECL between Oct. 2018 and Sep. 2019), A. Gégout-Petit (Univ. Lorraine and Inria BIGS team) and O. Coudray (Master degree student), D. Villemonais conducted preliminary researches on branching models for the telomeres' length dynamics across generations.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- M. Bossy is the Coordinator of the POPART Industrial partnership project at UCA-JEDI on the modeling of fibre transport in turbulent flows. This partnership is granted by EDF and by UCA, and in collaboration with CEMEF (J. Bec and S. Allende).
- M. Bossy is member of a MERIC project (MERIC is the marine energy research & innovation center in Chile) on stochastic Lagrangian models to better estimate energy production variability with water turbine, granted with the LEMON Inria Team.

8. Partnerships and Cooperations

8.1. Regional Initiatives

- C. Henry is the coordinator of the PAIRE project, a TREMPLIN-COMPLEX project funded by University of Côte d'Azur. The project aims at creating new international and cross-sector collaborations to foster innovative solutions for particle contamination in the environment. This will be achieved by bringing together partners in a consortium to submit a research proposal to the European MSCA-RISE-2019 and MSCA-RISE-2020 calls.
- A. Lejay is a member of the Executive board of LUE Impact digistrust on citizens' trust in the digital world (grant of the i-site, U. Lorraine), since 2018.

8.2. National Initiatives

8.2.1. ANR

- N. Champagnat was member of the ANR NONLOCAL (Phénomènes de propagation et équations non locales), coordinated by F. Hamel (Univ. Aix-Marseille), which ended in October.
- C. Henry is the coordinator of the PACE project, a MRSEI project funded by the ANR to help prepare European projects. As for PAIRE, the project aims at creating new international and cross-sector collaborations to foster innovative solutions for particle contamination in the environment. This will be achieved by bringing together partners in a consortium to submit a research proposal to the European MSCA-RISE-2019 and MSCA-RISE-2020 calls.
- U. Herbach is member of the ANR SinCity (Analyses transcriptomiques sur cellules uniques dont la généalogie est identifiée au cours d'un processus de différentiation), coordinated by O. Gandrillon (ENS Lyon).

8.2.2. GDR

A. Lejay is leader of the GdR Project TRAG on rough paths founded by INSMI in 2019.

8.2.3. ITMO Cancer

N. Champagnat, C. Fritsch and U. Herbach are involved in an ITMO Cancer project (INSERM funding) on "Modeling ctDNA dynamics for detecting targeted therapy resistance" (2017-2020), involving researchers from IECL (Institut Elie Cartan de Lorraine), the Inria teams BIGS and TOSCA, ICL (Institut de Cancérologie de Lorraine), CRAN (Centre de Recherche en Automatique de Nancy) and CHRU Strasbourg (Centre Hospitalier Régional Universitaire). This project is coordinated by N. Champagnat.

8.2.4. PEPS

The project SECURE of C. Fritsch obtained a PEPS I3A (Intelligence Artificielle et Apprentissage Automatique).

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

Program: FP7

Project acronym: HBP

Project title: The Human Brain Project

Duration: April 2018 - Mars 2020 (third part)

Coordinator: EPFL

Other partners: see the webpage of the project.

Tosca contact: Etienne Tanré

Abstract: Understanding the human brain is one of the greatest challenges facing 21st century science. If we can rise to the challenge, we can gain profound insights into what makes us human, develop new treatments for brain diseases and build revolutionary new computing technologies. Today, for the first time, modern ICT has brought these goals within sight. The goal of the Human Brain Project, part of the FET Flagship Programme, is to translate this vision into reality, using ICT as a catalyst for a global collaborative effort to understand the human brain and its diseases and ultimately to emulate its computational capabilities. The Human Brain Project will last ten years and will consist of a ramp-up phase (from month 1 to month 36) and subsequent operational phases. This Grant Agreement covers the ramp-up phase. During this phase the strategic goals of the project will be to design, develop and deploy the first versions of six ICT platforms dedicated to Neuroinformatics, Brain Simulation, High Performance Computing, Medical Informatics, Neuromorphic Computing and Neurorobotics, and create a user community of research groups from within and outside the HBP, set up a European Institute for Theoretical Neuroscience, complete a set of pilot projects providing a first demonstration of the scientific value of the platforms and the Institute, develop the scientific and technological capabilities required by future versions of the platforms, implement a policy of Responsible Innovation, and a programme of transdisciplinary education, and develop a framework for collaboration that links the partners under strong scientific leadership and professional project management, providing a coherent European approach and ensuring effective alignment of regional, national and European research and programmes. The project work plan is organized in the form of thirteen subprojects, each dedicated to a specific area of activity. A significant part of the budget will be used for competitive calls to complement the collective skills of the Consortium with additional expertise.

M. Bossy and C. Henry are involved in the VIMMP H2020 project, started in January 2018. M. Bossy is responsible for the partner Inria. VIMMP is a four years development for a software platform and simulation market place on the topic of complex multiscale CFD simulations.

8.4. International Initiatives

8.4.1. Participation in Other International Programs

Math AmSud SARC

Title: Stochastic and Statistics analysis for Stochastic Differential equations driven by fractional Brownian motion with non regular coefficients.

International Partner (Institution - Laboratory - Researcher):

Universidade Estadual de Campinas (Brasil)

Universidad de Valparaiso (Chile) - CIMFAV – Facultad de Ingenieria

PI: C. Olivera (Brasil), E. Tanré (France), S. Torrès (Chile)

Duration: 2019 - 2020

Start year: 2019

Keywords: Stochastic differential equations, fractional Brownian motion, Malliavin calculus, Bayesian parametric, and nonparametric statistics.

BRN

Title: Biostochastic Research Network

International Partner (Institution - Laboratory - Researcher):

Universidad de Valparaiso (Chile) - CIMFAV – Facultad de Ingenieria - Soledad Torres, Rolando Rebolledo

CNRS, Inria & IECL - Institut Élie Cartan de Lorraine (France) - N. Champagnat, A. Lejay, D. Villemonnais, R. Schott.

Duration: 2018 - 2022

Start year: 2018

8.5. International Research Visitors

8.5.1. Visits of International Scientists

- E. Horton (University of Bath) spent one week in IECL in April to work with D. Villemonais.
- E. Mordecki (U. de la República, Uruguay) spent 3 months in IECL, with an invited professor position (*poste rouge CNRS*).
- H. Olivero Quintos spent one month at Sophia Antipolis.

8.5.1.1. Internships

- Loubna Ben Allal

  subject: processus de Hawkes

  date: sept. 2019 - june 2020

  institution: École des Mines de Nancy
- Wejdene Ben Nasr

  subject: méthodes de signature pour les séries temporelles multi-variées

  date: sept. 2019 - june 2020

  institution: Master IMSD, U. Lorraine.
- Olivier Coudray

  subject: transmission de la longueur de télomères entre générations

  date: apr. 2019 - aug. 2019

  institution: École Polytechnique, Master Mathématiques de l'aléatoire
- Rémi Maréchal

  subject: processus de fragmentation pour les avalanches

  date: sept. 2019 - june 2020

  institution: École des Mines de Nancy
- Seyedafshin Shekarforush

  subject: particles in the environment: the adaptative grid generation problem in particle agglomeration and fragmentation dynamics

  date: apr. 2019 - aug. 2019

  institution: Université Nice Sophia Antipolis

8.5.2. Visits to International Teams

8.5.2.1. Sabbatical programme

D. Villemonais obtained a *délégation CNRS* which ended in August.

9. Dissemination

9.1. Promotion of Mathematics in the industry

- A. Lejay is member of the board of AMIES (Agence Mathématiques en Intéractions avec l'Entreprise et la Société). A. Lejay is editor of the *success stories* project.
- D. Talay continued to serve as a member of the Scientific Committee of the AMIES National Agency aimed to promote interactions between Mathematics and Industry.
- D. Talay continued to serve as the Vice-President of the Fondation d'Entreprise Natixis which aims to contribute to develop research in quantitative finance. He also serves as a member of the Scientific Committee of the Foundation.

9.2. Promoting Scientific Activities

9.2.1. Scientific Events: Organisation

- C. Fritsch organizes with Pascal Moyal (Univ. de Lorraine) the weekly Seminar of Probability and Statistics of IECL, Nancy.
- C. Fritsch organized with Constantin Morarescu (CRAN) a scientific day of the *Fédération Charles Hermite* about multiscale models. (IECL, Nancy, 21 June 2019)

9.2.1.1. Member of the Organizing Committees

- N. Champagnat is member of the organizing committee of the conference *Mathematical Models in Evolutionary Biology*, part of the Thematic Month on Mathematical Issues in Biology (CIRM, Luminy, 10–14 Feb. 2020).
- N. Champagnat was member of the organizing committee of the conference ReaDiNet 2019 *Mathematical Analysis for Biology and Ecology* (Inria Nancy – Grand Est, 23–25 Sep.).
- N. Champagnat and U. Herbach organized the workshop *Modélisation de l'hétérogénéité tumorale et thérapies ciblées* (IECL, Univ. Lorraine, 21–22 Oct.).
- C. Fritsch was member of the organizing committee of the conference *51es Journées de Statistiques* (Nancy, 3–7 June).
- A. Lejay organized the conference *TRAG 2019* (Nancy, 9–11 Oct.).
- E. Tanré and R. Veltz organized the workshop on *Mean-field approaches to the dynamics of neuronal networks* (EITN, 3–4 April).

9.2.1.2. Member of the Conference Program Committees

- M. Bossy is member of the SMAI2019 Conference Scientific Committee and MASCOT NUM 2020 Conference.
- D. Talay is serving as a member of the scientific commitee for MasterKesm (Masterclass from kinetic equations to statistical mechanics) summer school to be held in Saint Jean de Monts in 2020.

9.2.2. Journal

9.2.2.1. Member of the Editorial Boards

- A. Lejay is one of the three editors of the *Séminaire de Probabilités* and *Mathematics and Computers in Simulation* (MATCOM).
- N. Champagnat serves as an associate editor of *Stochastic Models*.
- N. Champagnat serves as co-editor-in-chief with Béatrice Laurent-Bonneau (IMT Toulouse) of *ESAIM: Probability & Statistics*.
- D. Talay serves as an Area Editor of *Stochastic Processes and their Applications*, and as an Associate Editor of *Journal of the European Mathematical Society*, *Probability, Uncertainty and Quantitative Risk*, *ESAIM Probability and Statistics*, *Stochastics and Dynamics*, *Journal of Scientific Computing*, *Monte Carlo Methods and Applications*, *SIAM Journal on Scientific Computing*, *Communications in Applied Mathematics and Computational Science*, *Éditions de l'École Polytechnique*. He also served as Co-editor in chief of *MathematicS in Action*.

9.2.2.2. Reviewer - Reviewing Activities

- N. Champagnat wrote reviews for *Stochastic Processes and their Applications* (three times this year), *Electronic Journal of Probability* and *Frontiers of Mathematics in China*.
- C. Fritsch wrote reviews for *PCI Ecology*.
- C. Henry wrote reviews for *Annals of Nuclear Energy*, *Aerosol Science and Technology*, *Building and Environment* and *Journal of Aerosol Science*.

- A. Lejay wrote reviews for *Annals of Institut Henri Poincaré*, *Statistical Inference for Stochastic Processes*, *Journal of Computational and Applied Mathematics*, *Physical Review E*, *Bernoulli*, *Electronic Journal of Probability*, *ESAIM PS*, *Journal Theoretical Probability*, *SIAM Journal on Control and Optimization*, *Applied Probability Journals*, *Journal of Functional Analysis*.
- E. Strickler wrote reviews for *Stochastic Models* and *Stochastic Processes and their Applications*.
- E. Tanré wrote reviews for *The Annals of Applied Probability*, *Electronic Journal of Probability*, *ESAIM PS*, *The Bulletin of the London Mathematical Society*, *Finance and Stochastics*, *The Journal of Mathematical Neuroscience*, *Stochastic Processes and their Applications*.
- E. Tanré serves has a permanent reviewer of *Mathematical Reviews of the American Mathematical Society (MathSciNet)*.
- D. Villemonais wrote reviews for *Markov processes and related fields*, *Electronic communication in Probabilty* (twice), *The Annals of Applied Probability*, *Stochastic processes and Applications*, *Journal of Statistical Physics* and *Electronic Journal of Probability*.
- D. Talay reported on applications to the Swiss National Science Foundation (SNSF).
- D. Talay reported on applications to the Research Grants Council (RGC) of Hong Kong.

9.2.3. Invited Talks

- M. Bossy has been invited to give talks at the conference Simulation and Optimization for Renewable Marine Energies, at Roscoff in July.
- N. Champagnat has been invited to give a Colloquium talk at the Department of Mathematics and Computer Science of the University of Technology in Eindhoven in February.
- N. Champagnat gave a talk at the Journée Charles Hermite *Modélisation fine versus outils d'analyse et simulation, un problème d'échelle* in Nancy in June.
- Q. Cormier has been invited to give a talk at the workshop on *Mean-field approaches to the dynamics of neuronal networks* at EITN in April.
- Q. Cormier and P. Helson have presented posters at the *International Conference on Mathematical Neuroscience* in Copenhagen in June.
- Q. Cormier and E. Tanré have been invited to give talks at the workshop "Nonlinear Processes and their Applications" in St. Etienne in July.
- C. Fritsch has been invited to give a talk at the workshop of the *MAMOVI* group in September.
- C. Fritsch gave a talk at the *Journées de Statistiques* in Nancy in June and at the *Mathematical Models in Ecology and Evolution* conference in Lyon in July.
- V. Hass presented a poster at the conference ReaDiNet 2019 *Mathematical Analysis for Biology and Ecology* in Nancy in September.
- U. Herbach has been invited to give talks at the Journée Charles Hermite *Méthodes et Modèles pour comprendre les réseaux biologiques* in January, at the spring school of *chaire MMB (Modélisation Mathématique et Biodiversité)* in Aussois in May, at the *Journée du RIS (Réseau Interdisciplinaire autour de la Statistique)* in Paris in September and at the workshop *Modélisation de l'hétérogénéité tumorale et thérapies ciblées* in Nancy in October.
- U. Herbach gave seminar talks at the *Séminaire de probabilités et statistiques de l'IECL* in Nancy in April, at the *Groupe de travail Maths-Bio* in Orléans in May, at the *Séminaire CIML (Centre d'immunologie de Marseille-Luminy)* in Marseille in May, at the *Groupe de travail du LBMC (Laboratoire de Biologie et Modélisation de la Cellule)* in Lyon in November, at the *Séminaire de probabilités* in Grenoble in November and at the *Groupe de travail Maths-Bio* in Grenoble in November.
- U. Herbach presented a poster at the conference *Probabilistic Modeling in Genomics* in Aussois in October.

- A. Lejay have been invited to give a mini-talk *A short introduction to Rough Paths* at Ritsumeikan University (Kyoto, Japan) in February.
- A. Lejay gave a talk at the conference *TRAG 2019* (Nancy) in October.
- E. Strickler gave seminar talks at the *Séminaire de probabilités* in Toulouse in October and at the *Séminaire de probabilités et statistiques de l'IECL* in Nancy in November.
- D. Villemonais gave seminar talks at the *Séminaire de Probabilités* of Univ. Paris 13 in April and at the *Probability Seminar* of Zurich Univ. in March.
- D. Villemonais has bee invited to give talks at the *Journées du réseau A2* (Paris-Sorbonne Univ.) in October and at the *Conference ReaDiNet 2019* (Inria Nancy – Grand Est) in September.
- E. Soret has given an invited talk at ICMNS in Copenhagen in June.
- D. Talay was an invited speaker at the Conference in Honor of Philip Protter, Columbia University, New York, USA, September 2019.
- D. Talay was an invited speaker at the Conference in Honor of Nicole El Karoui, Sorbonne University, Paris, 21-24 May 2019.
- D. Talay was an invited speaker at the 'Stochastic Analysis and Related Topics' International Conference, Bucarest, Romania, 6-9 May 2019.
- D. Talay chaired a session at the 'Journées de l'Académie des Sciences en région', Nice and Sophia Antipolis, 2-21 June 2019.
- D. Talay gave a seminar talk at École des Ponts ParisTech on 27 November 2019.

9.2.4. Leadership within the Scientific Community

- M. Bossy was serving as a vice president of the Inria Evaluation Committee until September 2019.
- A. Lejay is head of the Probability and Statistics team of Institut Élie Cartan de Lorraine.
- D. Talay continued to chair the Scientific Council of the French Applied Math. Society SMAI.
- D. Talay is a member of the scientific committee of the 'Institut Mathématiques de la Planète Terre' project suppirted by INSMI-CNRS.
- D. Talay served as a member of the scientific council of the Complex System academy of the Université Côte d'Azur Idex.
- D. Talay is serving as a member of the CMUP Advisory Commission (University of Porto).
- D. Talay is a member of the Comité National Français de Mathématiciens.

9.2.5. Scientific Expertise

- N. Champagnat evaluated a research project submitted to the ANR.
- C. Fritsch is member of the Ph.D. monitoring committee of Léo Darrigade (INRA).
- D. Talay served as a member of the committee for positions in Applied Mathematics at the Ecole Polytechnique.
- D. Talay chaired the HCERES evaluation committee for the Toulouse Mathematics Institute (IMT).
- D. Talay is serving as a member of the evaluation committee of the Charles University (Prague, Czech Republic).

9.2.6. Research Administration

- N. Champagnat is a member of the *Comité de Centre*, the *COMIPERS* and the *Commission Information Scientifique et Technique* of Inria Nancy - Grand Est, *Responsable Scientifique* for the library of Mathematics of the IECL, member of the *Conseil du laboratoire* of IECL (as *responsable scientifique* of the library). He is also local correspondent of the COERLE (*Comité Opérationel d'Évaluation des Risques Légaux et Éthiques*) for the Inria Research Center of Nancy - Grand Est.

- C. Fritsch is member of the *Commission du Développement Technologique* of Inria Nancy - Grand Est, of the *Commission du personnel* and the *Commission Parité-Égalité* of IECL. She is the local Raweb correspondent for the Inria Research Center of Nancy - Grand Est.
- A. Lejay is member of the Executive board of *LUE Impact project digistrust* (Univ. Lorraine), of the Conseil de Pôle AM2I (Univ. Lorraine) and of the CUMI (Inria NGE).
- D. Villemonais is responsible of the “Ingénierie Mathématique” cursus of École des Mines de Nancy and is elected member of the conseil de l’École des Mines de Nancy.

9.3. Teaching - Supervision - Juries

9.3.1. Teaching

Master: N. Champagnat, *Introduction to Quantitative Finance*, 18h, M1, École des Mines de Nancy, France.

Master: N. Champagnat, *Introduction to Quantitative Finance*, 13.5h, M2, École des Mines de Nancy, France.

Master: N. Champagnat, *Problèmes inverses*, 22.5h, M1, École des Mines de Nancy, France.

Master: C. Fritsch, *Probability theory*, 40h, L3, École des Mines de Nancy, France.

Master: A. Lejay, *Probabilités*, 9h, 1st year Mines de Nancy, France.

Master: A. Lejay, *Simulation des marchés financiers*, 29h, M2, Master PSA, Université de Lorraine, France.

Master: E. Tanré (courses and exercices), *Advanced Numerics for Computational Finance*, 30h (20h + 10h), M2, Univ. Côte d’Azur (Mathmods Erasmus Mundus), France.

Master: E. Tanré, *Mathematical Methods for Neurosciences*, 20h, M2, ENS - Master MVA / Paris 6 - Master Maths-Bio, France.

Master: E. Tanré (courses) *Stochastic models in neurocognition*, 15h (7h30 + 7h30), M2, Univ. Côte d’Azur (Master 2), France.

Master: D. Talay *Invariant measures of diffusion processes*, 18h, M2 Probabilité et Applications, Université Paris 6, France.

9.3.2. Supervision

HdR: Denis Villemonais, *Convergence exponentielle vers une distribution quasi-stationnaire et applications*, Université de Lorraine, 28/11/2019.

PhD in progress: Alexis Anagnostakis, *Étude du mouvement brownien collant*, Université de Lorraine, Octobre 2018, A. Lejay and D. Villemonais.

PhD in progress: Lorenzo Campana, *Stochastic modeling of non-spherical particles transport and deposition by turbulent flow*, Université Côte d’Azur, December 2017, M. Bossy.

PhD in progress: Quentin Cormier, *Biological Networks of Spiking Neurons*, September 2017, E. Tanré and R. Veltz (MATHNEURO Inria team).

PhD in progress: Vincent Hass, *Individual-based models in adaptive dynamics and long time evolution under assumptions of rare advantageous mutations*, Université de Lorraine, October 2018, N. Champagnat.

PhD in progress: Pascal Helson, *Plasticity in networks of spiking neurons in interaction*, October 2016, E. Tanré and R. Veltz (MATHNEURO Inria team).

PhD in progress: Rodolphe Loubaton, *Caractérisation des cibles thérapeutiques dans un programme génique tumoral*, Université de Lorraine, October 2018, N. Champagnat and L. Vallat (CHRU Strasbourg).

9.3.3. Juries

- M. Bossy served as a referee for the Ph.D. thesis of Pierre Antoine Joulin, *Modélisation à fine échelle des interactions entre parcs éoliens et météorologie locale* at Institut National Polytechnique de Toulouse, December 2019.
- M. Bossy served as an examiner for the Ph.D. theses of Victor Marx, *Diffusive processes on the Wasserstein space: Coalescing models, Regularization properties and McKean-Vlasov equations*, Université Côte d'Azur, November 2019, and Sebastian Reyes Riffo, *Méthodes mathématiques pour l'extraction d'énergie marine*, PSL University November 2019.
- N. Champagnat will serve as an examiner for the habilitation thesis of Nicolas Gast, *Refinements of Mean Field Approximation*, Univ. de Grenoble, 30/01/2020.
- N. Champagnat served as a referee for the Ph.D. thesis of Paulien Jeunesse, *Estimation non paramétrique du taux de mort dans un modèle de population générale : théorie et applications*, Univ. Paris Dauphine, 08/01/2019.
- N. Champagnat served as an examiner for the Ph.D. theses of Frédérique Robin, *Modeling and analysis of cell population dynamics: application to the early development of ovarian follicles*, Univ. Paris Saclay, 26/09/2019, William Oçafrain, *Quasi-stationarité avec frontières mobiles*, Univ. Toulouse 3, 4/07/2019, Martin Andrade-resptrepo, *Mathematical modeling and evolutionary processes*, Univ. Paris 7, 26/06/2019 and Edouard Strickler, *Persistance de processus de Markov déterministes par morceaux*, Univ. Neuchâtel, 21/03/2019.
- A. Lejay served as an examiner for the habilitation thesis of Nicolas Marie, *Quelques contributions à la contrainte et à la statistique des équations différentielles dirigées par le mouvement brownien fractionnaire ainsi qu'à la sélection de modèle*, Université Paris Nanterre, November 2019.
- A. Lejay served as an examiner for the Ph.D. thesis of Carlo Bellingeri, *Itô formulae on stochastic heat equation via regularity structures and rough paths*, Sorbonne Université, July 2019.
- D. Talay served as a referee for the Ph.D. thesis of Grégoire Ferré, *Large Deviations Theory in Statistical Physics: Some Theoretetical and Numerical Aspects*, Université Paris Est and École des Ponts ParisTech, 27 November 2019.
- D. Talay served as a referee for the habilitation thesis of Adrien Richou, *Quelques Résultats sur les Equations Différentielles Rétrogrades et les Principes de Grandes Déviations pour les Estimateurs de Paramètres de Diffusions*, université de Bordeaux, 4 November 2019.

9.4. Popularization

9.4.1. Interventions

C. Henry gave a presentation at the Inria Café In on the topic of breakup of elongated particles such as spaghettis.

9.4.2. Creation of media or tools for science outreach

- A. Lejay is editor of the project *Success Stories* (AMIES and FSMP) dedicated to create 2-page sheets to present successful interactions between industry and academia.

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Major publications by the team in recent years

[1] L. BEZNEA, M. DEACONU, O. LUPASCU.*Branching processes for the fragmentation equation*, in "Stochastic Processes and their Applications", 2015, vol. 125, p. 1861-1885 [*DOI :* 10.1016/J.SPA.2014.11.016], https://hal.inria.fr/hal-00948876

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Publications of the year

Articles in International Peer-Reviewed Journal

[12] H. ALRACHID, M. BOSSY, C. RICCI, Ł. SZPRUCH.*New particle representations for ergodic McKean-Vlasov SDEs*, in "ESAIM: Proceedings and Surveys", 2019, vol. 65, p. 68-83, https://arxiv.org/abs/1901.05507 [*DOI :* 10.1051/PROC/201965068], https://hal.inria.fr/hal-02059785

[13] M. ANDRADE-RESTREPO, N. CHAMPAGNAT, R. FERRIÈRE.*Spatial eco-evolutionary dynamics along environmental gradients: multi-stability and cluster dynamics*, in "Ecology Letters", May 2019, vol. 22, n^{o} 5, p. 767-777, https://hal.inria.fr/hal-01732325

[14] M. L. BAHLALI, C. HENRY, B. CARISSIMO.*On the Well-Mixed Condition and Consistency Issues in Hybrid Eulerian/Lagrangian Stochastic Models of Dispersion*, in "Boundary-Layer Meteorology", October 2019 [*DOI :* 10.1007/S10546-019-00486-9], https://hal.inria.fr/hal-02374779

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Project-Team WIMMICS

Web-Instrumented Man-Machine Interactions, Communities and Semantics

IN COLLABORATION WITH: Laboratoire informatique, signaux systèmes de Sophia Antipolis (I3S)

IN PARTNERSHIP WITH:
CNRS

Université Nice - Sophia Antipolis

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Data and Knowledge Representation and Processing

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1. Team, Visitors, External Collaborators

Research Scientists

Fabien Gandon [Team leader, Inria, Senior Researcher, HDR]
Olivier Corby [Inria, Researcher]
Alain Giboin [Inria, Researcher, until Apr 2019]
Serena Villata [CNRS, Researcher, HDR]

Faculty Members

Elena Cabrio [Univ de Nice - Sophia Antipolis, Associate Professor]
Michel Buffa [Univ de Nice - Sophia Antipolis, Associate Professor, HDR]
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Clément Jonquet [Univ Montpellier II, Associate Professor, HDR]
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Peter Sander [Univ de Nice - Sophia Antipolis, Professor]
Andrea Tettamanzi [Univ de Nice - Sophia Antipolis, Professor]

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Claude Frasson [Univ. of Montreal, Professor]
Freddy Lecue [Thales, Research Engineer]
Roque Lopez Condori [Univ. of New York, Associate Professor, until Jan 2019]
Jean-Marie Dormoy [Inria, Internship, from Jun 2019 until Aug 2019]

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Franck Michel [CNRS, Research Engineer]
Pinar Arslan [Inria, Engineer, until May 2019]
Anna Bobasheva [Inria, Engineer, from Feb 2019]
Michele Corazza [Inria, Engineer, until Oct 2019]
Hai Huang [Inria, Engineer]
Elmahdi Korfed [CNRS, Engineer, until Nov 2019]
Emilie Palagi [Inria, Engineer, from Feb 2019 until Mar 2019]
Oscar Rodríguez Rocha [Inria, Engineer, until Sep 2019, granted by Université Numérique Francophone des Sciences de la Santé et du Sport]

PhD Students

Molka Dhouib [Inria, SILEX]
Ahmed El Amine Djebri [Univ de Nice - Sophia Antipolis]
Antonia Ettorre [Univ Côte d'Azur, from Oct 2019]
Michael Fell [CNRS]
Raphaël Gazzotti [SynchroNext]
Nicholas Halliwell [Inria, from Feb 2019]
Tobias Mayer [Univ Côte d'Azur]
Thu Huong Nguyen [Univ de Nice - Sophia Antipolis]
Mahamadou Toure [UGB]
Vorakit Vorakitphan [Inria]

Post-Doctoral Fellow

Jérôme Delobelle [Inria]

Visiting Scientists

Laura Alonso Alemany [Univ. of Cordoba, Professor, Jul 2019]
Aissa Bensattalah [Univ. of Tiaret, Associate Professor, Dec 2019]
Cristian Cardellino [Univ. of Cordoba, Associate Professor, from May 2019 until Jun 2019]
Johanna Frau [Univ. of Cordoba, Argentina, PhD Student, from May 2019 until Jul 2019]
Marco Guerini [FBK-IRST, Trento, Italy, Researcher, Jun 2019]
Yimin Hu [Chinese Science Academy, Associate Professor, from May 2019]

Dario Malchiodi [Univ. of Milan, Associate Professor, from Mar 2019]
Philippe Martin [Univ. of La Réunion, Associate Professor, from Feb 2019 until Jul 2019]
Yuting Sun [Univ. of Shanghai, Master student, from Nov 2019]
Milagro Teruel [Univ. of Cordoba, PhD student, from May 2019 until Jul 2019]

Administrative Assistants

Christine Foggia [Inria]
Lionel Tavanti [I3S]

2. Overall Objectives

2.1. Context and Objectives

The Web became a virtual place where persons and software interact in mixed communities. The Web has the potential of becoming the collaborative space for natural and artificial intelligence, raising the problem of supporting these worldwide interactions. These large scale mixed interactions create many problems that must be addressed with multidisciplinary approaches [60]. One particular problem is to reconcile formal semantics of computer science (e.g. logics, ontologies, typing systems, protocols, etc.) on which the Web architecture is built, with soft semantics of people (e.g. posts, tags, status, relationships, etc.) on which the Web content is built.

Wimmics proposes models and methods to bridge formal semantics and social semantics on the Web [59] in order to address some of the challenges in building a Web as a universal space linking many different kinds of intelligence.

From a formal modeling point of view, one of the consequences of the evolutions of the Web is that the initial graph of linked pages has been joined by a growing number of other graphs. This initial graph is now mixed with sociograms capturing the social network structure, workflows specifying the decision paths to be followed, browsing logs capturing the trails of our navigation, service compositions specifying distributed processing, open data linking distant datasets, etc. Moreover, these graphs are not available in a single central repository but distributed over many different sources. Some sub-graphs are small and local (e.g. a user's profile on a device), some are huge and hosted on clusters (e.g. Wikipedia), some are largely stable (e.g. thesaurus of Latin), some change several times per second (e.g. social network statuses), etc. And each type of network of the Web is not an isolated island. Networks interact with each other: the networks of communities influence the message flows, their subjects and types, the semantic links between terms interact with the links between sites and vice-versa, etc.

Not only do we need means to represent and analyze each kind of graphs, we also do need the means to combine them and to perform multi-criteria analysis on their combination. Wimmics contributes to this understanding by: (1) proposing multidisciplinary approaches to analyze and model the many aspects of these intertwined information systems, their communities of users and their interactions; (2) formalizing and reasoning on these models using graphs-based knowledge representation from the semantic Web to propose new analysis tools and indicators, and to support new functionalities and better management. In a nutshell, the first research direction looks at models of systems, users, communities and interactions while the second research direction considers formalisms and algorithms to represent them and reason on their representations.

2.2. Research Topics

The research objectives of Wimmics can be grouped according to four topics that we identify in reconciling social and formal semantics on the Web:

Topic 1 - users modeling and designing interaction on the Web: The general research question addressed by this objective is "*How do we improve our interactions with a semantic and social Web more and more complex and dense ?*". Wimmics focuses on specific sub-questions: "How can we capture and model the users' characteristics?" "How can we represent and reason with the users' profiles?" "How can we adapt the system behaviors as a result?" "How can we design new interaction means?" "How can we evaluate the quality of the interaction designed?"

Topic 2 - communities and social interactions analysis on the Web: The general question addressed in this second objective is "*How can we manage the collective activity on social media?*". Wimmics focuses on the following sub-questions: "How do we analyze the social interaction practices and the structures in which these practices take place?" "How do we capture the social interactions and structures?" "How can we formalize the models of these social constructs?" "How can we analyze and reason on these models of the social activity ?"

Topic 3 - vocabularies, semantic Web and linked data based knowledge representation and Artificial Intelligence formalisms on the Web: The general question addressed in this third objective is "*What are the needed schemas and extensions of the semantic Web formalisms for our models?*". Wimmics focuses on several sub-questions: "What kinds of formalism are the best suited for the models of the previous section?" "What are the limitations and possible extensions of existing formalisms?" "What are the missing schemas, ontologies, vocabularies?" "What are the links and possible combinations between existing formalisms?" In a nutshell, an important part of this objective is to formalize as typed graphs the models identified in the previous objectives in order for software to exploit them in their processing (in the next objective).

Topic 4 - artificial intelligence processing: learning, analyzing and reasoning on heterogeneous semantic graphs on the Web: The general research question addressed in this last objective is "*What are the algorithms required to analyze and reason on the heterogeneous graphs we obtained?*". Wimmics focuses on several sub-questions: "How do we analyze graphs of different types and their interactions?" "How do we support different graph life-cycles, calculations and characteristics in a coherent and understandable way?" "What kind of algorithms can support the different tasks of our users?".

3. Research Program

3.1. Users Modeling and Designing Interaction on the Web

Wimmics focuses on interactions of ordinary users with ontology-based knowledge systems, with a preference for semantic Web formalisms and Web 2.0 applications. We specialize interaction design and evaluation methods to Web application tasks such as searching, browsing, contributing or protecting data. The team is especially interested in using semantics in assisting the interactions. We propose knowledge graph representations and algorithms to support interaction adaptation, for instance for context-awareness or intelligent interactions with machine. We propose and evaluate Web-based visualization techniques for linked data, querying, reasoning, explaining and justifying. Wimmics also integrates natural language processing approaches to support natural language based interactions. We rely on cognitive studies to build models of the system, the user and the interactions between users through the system, in order to support and improve these interactions. We extend the user modeling technique known as *Personas* where user models are represented as specific, individual humans. *Personas* are derived from significant behavior patterns (i.e., sets of behavioral variables) elicited from interviews with and observations of users (and sometimes customers) of the future product. Our user models specialize *Personas* approaches to include aspects appropriate to Web applications. Wimmics also extends user models to capture very different aspects (e.g. emotional states).

3.2. Communities and Social Interactions Analysis

The domain of social network analysis is a whole research domain in itself and Wimmics targets what can be done with typed graphs, knowledge representations and social models. We also focus on the specificity of social Web and semantic Web applications and in bridging and combining the different social Web data structures and semantic Web formalisms. Beyond the individual user models, we rely on social studies to build models of the communities, their vocabularies, activities and protocols in order to identify where and when formal semantics is useful. We propose models of collectives of users and of their collaborative functioning extending the collaboration personas and methods to assess the quality of coordination interactions and the quality of coordination artifacts. We extend and compare community detection algorithms to identify and label communities of interest with the topics they share. We propose mixed representations containing social semantic representations (e.g. folksonomies) and formal semantic representations (e.g. ontologies) and propose operations that allow us to couple them and exchange knowledge between them. Moving to social interaction we develop models and algorithms to mine and integrate different yet linked aspects of social media contributions (opinions, arguments and emotions) relying in particular on natural language processing and argumentation theory. To complement the study of communities we rely on multi-agent systems to simulate and study social behaviors. Finally we also rely on Web 2.0 principles to provide and evaluate social Web applications.

3.3. Vocabularies, Semantic Web and Linked Data Based Knowledge Representation and Artificial Intelligence Formalisms on the Web

For all the models we identified in the previous sections, we rely on and evaluate knowledge representation methodologies and theories, in particular ontology-based modeling. We also propose models and formalisms to capture and merge representations of different levels of semantics (e.g. formal ontologies and social folksonomies). The important point is to allow us to capture those structures precisely and flexibly and yet create as many links as possible between these different objects. We propose vocabularies and semantic Web formalizations for all the aspects that we model and we consider and study extensions of these formalisms when needed. The results have all in common to pursue the representation and publication of our models as linked data. We also contribute to the transformation and linking of existing resources (informal models, databases, texts, etc.) to be published on the Semantic Web and as Linked Data. Examples of aspects we formalize include: user profiles, social relations, linguistic knowledge, business processes, derivation rules, temporal descriptions, explanations, presentation conditions, access rights, uncertainty, emotional states, licenses, learning resources, etc. At a more conceptual level we also work on modeling the Web architecture with philosophical tools so as to give a realistic account of identity and reference and to better understand the whole context of our research and its conceptual cornerstones.

3.4. Artificial Intelligence Processing: Learning, Analyzing and Reasoning on Heterogeneous Semantic Graphs

One of the characteristics of Wimmics is to rely on graph formalisms unified in an abstract graph model and operators unified in an abstract graph machine to formalize and process semantic Web data, Web resources, services metadata and social Web data. In particular Corese, the core software of Wimmics, maintains and implements that abstraction. We propose algorithms to process the mixed representations of the previous section. In particular we are interested in allowing cross-enrichment between them and in exploiting the life cycle and specificity of each one to foster the life-cycles of the others. Our results all have in common to pursue analyzing and reasoning on heterogeneous semantic graphs issued from social and semantic Web applications. Many approaches emphasize the logical aspect of the problem especially because logics are close to computer languages. We defend that the graph nature of Linked Data on the Web and the large variety of types of links that compose them call for typed graphs models. We believe the relational dimension is of paramount importance in these representations and we propose to consider all these representations as fragments of a typed graph formalism directly built above the Semantic Web formalisms. Our choice of a graph based programming approach for the semantic and social Web and of a focus on one graph based formalism is also an efficient way to support interoperability, genericity, uniformity and reuse.

4. Application Domains

4.1. Social Semantic Web

A number of evolutions have changed the face of information systems in the past decade but the advent of the Web is unquestionably a major one and it is here to stay. From an initial wide-spread perception of a public documentary system, the Web as an object turned into a social virtual space and, as a technology, grew as an application design paradigm (services, data formats, query languages, scripting, interfaces, reasoning, etc.). The universal deployment and support of its standards led the Web to take over nearly all of our information systems. As the Web continues to evolve, our information systems are evolving with it.

Today in organizations, not only almost every internal information system is a Web application, but these applications more and more often interact with external Web applications. The complexity and coupling of these Web-based information systems call for specification methods and engineering tools. From capturing the needs of users to deploying a usable solution, there are many steps involving computer science specialists and non-specialists.

We defend the idea of relying on Semantic Web formalisms to capture and reason on the models of these information systems supporting the design, evolution, interoperability and reuse of the models and their data as well as the workflows and the processing.

4.2. Linked Data on the Web and on Intranets

With billions of triples online (see Linked Open Data initiative), the Semantic Web is providing and linking open data at a growing pace and publishing and interlinking the semantics of their schemas. Information systems can now tap into and contribute to this Web of data, pulling and integrating data on demand. Many organisations also started to use this approach on their intranets leading to what is called linked enterprise data.

A first application domain for us is the publication and linking of data and their schemas through Web architectures. Our results provide software platforms to publish and query data and their schemas, to enrich these data in particular by reasoning on their schemas, to control their access and licenses, to assist the workflows that exploit them, to support the use of distributed datasets, to assist the browsing and visualization of data, etc.

Examples of collaboration and applied projects include: SMILK Joint Laboratory, Corese, DBpedia.fr.

4.3. Assisting Web-based Epistemic Communities

In parallel with linked open data on the Web, social Web applications also spread virally (e.g. Facebook growing toward 1.5 billion users) first giving the Web back its status of a social read-write media and then putting it back on track to its full potential of a virtual place where to act, react and interact. In addition, many organizations are now considering deploying social Web applications internally to foster community building, expert cartography, business intelligence, technological watch and knowledge sharing in general.

By reasoning on the Linked Data and the semantics of the schemas used to represent social structures and Web resources, we provide applications supporting communities of practice and interest and fostering their interactions in many different contexts (e-learning, business intelligence, technical watch, etc.).

We use typed graphs to capture and mix: social networks with the kinds of relationships and the descriptions of the persons; compositions of Web services with types of inputs and outputs; links between documents with their genre and topics; hierarchies of classes, thesauri, ontologies and folksonomies; recorded traces and suggested navigation courses; submitted queries and detected frequent patterns; timelines and workflows; etc.

Our results assist epistemic communities in their daily activities such as biologists exchanging results, business intelligence and technological watch networks informing companies, engineers interacting on a project, conference attendees, students following the same course, tourists visiting a region, mobile experts on the field, etc. Examples of collaboration and applied projects: EduMICS, OCKTOPUS, Vigiglobe, Educlever, Gayatech.

4.4. Linked Data for a Web of Diversity

We intend to build on our results on explanations (provenance, traceability, justifications) and to continue our work on opinions and arguments mining toward the global analysis of controversies and online debates. One result would be to provide new search results encompassing the diversity of viewpoints and providing indicators supporting opinion and decision making and ultimately a Web of trust. Trust indicators may require collaborations with teams specialized in data certification, cryptography, signature, security services and protocols, etc. This will raise the specific problem of interaction design for security and privacy. In addition, from the point of view of the content, this requires to foster the publication and coexistence of heterogeneous data with different points of views and conceptualizations of the world. We intend to pursue the extension of formalisms to allow different representations of the world to co-exist and be linked and we will pay special attention to the cultural domain and the digital humanities. Examples of collaboration and applied projects: Zoomathia, Seempad, SMILK,

4.5. Artificial Web Intelligence

We intend to build on our experience in artificial intelligence (knowledge representation, reasoning) and distributed artificial intelligence (multi-agent systems - MAS) to enrich formalisms and propose alternative types of reasoning (graph-based operations, reasoning with uncertainty, inductive reasoning, non-monotonic, etc.) and alternative architectures for linked data with adequate changes and extensions required by the open nature of the Web. There is a clear renewed interest in AI for the Web in general and for Web intelligence in particular. Moreover distributed AI and MAS provide both new architectures and new simulation platforms for the Web. At the macro level, the evolution accelerated with HTML5 toward Web pages as full applications and direct Page2Page communication between browser clearly is a new area for MAS and P2P architectures. Interesting scenarios include the support of a strong decentralization of the Web and its resilience to degraded technical conditions (downscaling the Web), allowing pages to connect in a decentralized way, forming a neutral space, and possibly going offline and online again in erratic ways. At the micro level, one can imagine the place RDF and SPARQL could take as data model and programming model in the virtual machines of these new Web pages and, of course, in the Web servers. RDF is also used to serialize and encapsulate other languages and becomes a pivot language in linking very different applications and aspects of applications. Example of collaboration and applied projects: MoreWAIS, Corese, Vigiglobe collaboration.

4.6. Human-Data Interaction (HDI) on the Web

We need more interaction design tools and methods for linked data access and contribution. We intend to extend our work on exploratory search coupling it with visual analytics to assist sense making. It could be a continuation of the Gephi extension that we built targeting more support for non experts to access and analyze data on a topic or an issue of their choice. More generally speaking SPARQL is inappropriate for common users and we need to support a larger variety of interaction means with linked data. We also believe linked data and natural language processing (NLP) have to be strongly integrated to support natural language based interactions. Linked Open Data (LOD) for NLP, NLP for LOD and Natural Dialog Processing for querying, extracting and asserting data on the Web is a priority to democratize its use. Micro accesses and micro contributions are important to ensure public participation and also call for customized interfaces and thus for methods and tools to generate these interfaces. In addition, the user profiles are being enriched now with new data about the user such as her current mental and physical state, the emotion she just expressed or her cognitive performances. Taking into account this information to improve the interactions, change the behavior of the system and adapt the interface is a promising direction. And these human-data interaction means should also be available for “small data”, helping the user to manage her personal information and to link it to public or collective one, maintaining her personal and private perspective as a personal Web of data. Finally, the continuous knowledge extractions, updates and flows add the additional problem of representing, storing, querying and interacting with dynamic data. Examples of collaboration and applied projects: QAKIS, Sychonext collaboration, ALOOF, DiscoveryHub, WASABI, MoreWAIS.

Web-augmented interactions with the world: The Web continues to augment our perception and interaction with reality. In particular, Linked Open Data enable new augmented reality applications by providing data sources on almost any topic. The current enthusiasm for the Web of Things, where every object has a corresponding Web resource, requires evolutions of our vision and use of the Web architecture. This vision requires new techniques as the ones mentioned above to support local search and contextual access to local resources but also new methods and tools to design Web-based human devices interactions, accessibility, etc. These new usages are placing new requirements on the Web Architecture in general and on the semantic Web models and algorithms in particular to handle new types of linked data. They should support implicit requests considering the user context as a permanent query. They should also simplify our interactions with devices around us jointly using our personal preferences and public common knowledge to focus the interaction on the vital minimum that cannot be derived in another way. For instance the access to the Web of data for a robot can completely change the quality of the interactions it can offer. Again, these interactions and the data they require raise problems of security and privacy. Examples of collaboration and applied projects: ALOOF, AZKAR, MoreWAIS.

5. Highlights of the Year

5.1. Highlights of the Year

28th International Joint Conference on Artificial Intelligence (IJCAI-2019) Runner-up (second place) for the Application Impact Award for the paper “DISPUTool – A tool for the Argumentative Analysis of Political Debates”, for Shohreh Haddadan, Serena Villata and Elena Cabrio [22].

Best Poster Runners-Up at the 34th ACM/SIGAPP Symposium On Applied Computing (SAC 2019), for the paper: Pinar Arslan, Michele Corazza, Elena Cabrio, Serena Villata, *Overwhelmed by negative emotions?: maybe you are being cyber-bullied!* [7].

Hai Huang and Fabien Gandon received the Université Côte d’Azur Research Award.

Fabien Gandon, Andrea Tettamanzi and Serena Villata were nominated Fellow of the 3IA Côte d’Azur.

5.1.1. Awards

BEST PAPERS AWARDS :

[24]

H. HUANG, F. GANDON.*Learning URI Selection Criteria to Improve the Crawling of Linked Open Data*, in "ESWC2019 - 16th Extended Semantic Web Conference", Portoroz, Slovenia, June 2019, https://hal.inria.fr/hal-02073854

[33]

S. REN, S. LETZ, Y. ORLAREY, R. MICHON, D. FOBER, M. BUFFA, E. AMMARI, J. LEBRUN.*FAUST online IDE: dynamically compile and publish FAUST code as WebAudio Plugins*, in "WAC 2019 - 5th Web Audio Conference", Trindheim, Norway, December 2019, https://hal.inria.fr/hal-02366725

6. New Software and Platforms

6.1. CORESE

COnceptual REsource Search Engine

KEYWORDS: Semantic Web - Search Engine - RDF - SPARQL

FUNCTIONAL DESCRIPTION: Corese is a Semantic Web Factory, it implements W3C RDF, RDFS, OWL RL, SHACL, SPARQL 1 .1 Query and Update as well as RDF Inference Rules.

Furthermore, Corese query language integrates original features such as approximate search and extended Property Path. It provides STTL: SPARQL Template Transformation Language for RDF graphs. It also provides LDScript: a Script Language for Linked Data. Corese provides distributed federated query processing.

- Participants: Erwan Demairy, Fabien Gandon, Fuqi Song, Olivier Corby, Olivier Savoie and Virginie Bottollier
- Partners: I3S - Mnemotix
- Contact: Olivier Corby
- URL: http://wimmics.inria.fr/corese

6.2. DBpedia

KEYWORDS: RDF - SPARQL

FUNCTIONAL DESCRIPTION: DBpedia is an international crowd-sourced community effort to extract structured information from Wikipedia and make this information available on the semantic Web as linked open data. The DBpedia triple stores then allow anyone to solve sophisticated queries against Wikipedia extracted data, and to link the different data sets on these data. The French chapter of DBpedia was created and deployed by Wimmics and is now an online running platform providing data to several projects such as: QAKIS, Izipedia, zone47, Sépage, HdA Lab., JocondeLab, etc.

RELEASE FUNCTIONAL DESCRIPTION: The new release is based on updated Wikipedia dumps and the inclusion of the DBpedia history extraction of the pages.

- Participants: Fabien Gandon and Elmahdi Korfed
- Contact: Fabien Gandon
- URL: http://wiki.dbpedia.org/

6.3. Discovery Hub

Discovery Hub Exploratory Search Engine

KEYWORD: Search Engine

FUNCTIONAL DESCRIPTION: Recommandation system on top of DBpedia

- Participants: Alain Giboin, Emilie Palagi, Fabien Gandon and Nicolas Marie
- Partner: Alcatel-Lucent
- Contact: Fabien Gandon
- URL: http://discoveryhub.co/

6.4. Fuzzy labelling argumentation module

Fuzzy labelling algorithm for abstract argumentation

KEYWORDS: Artificial intelligence - Multi-agent - Knowledge representation - Algorithm

FUNCTIONAL DESCRIPTION: The goal of the algorithm is to compute the fuzzy acceptability degree of a set of arguments in an abstract argumentation framework. The acceptability degree is computed from the trustworthiness associated with the sources of the arguments.

- Participant: Serena Villata
- Contact: Serena Villata

6.5. Qakis

Question-Answering wiki framework based system

KEYWORD: Natural language

FUNCTIONAL DESCRIPTION: The QAKiS system implements question answering over DBpedia. QAKiS allows end users to submit a query to an RDF triple store in English and to obtain the answer in the same language, hiding the complexity of the non-intuitive formal query languages involved in the resolution process. At the same time, the expressiveness of these standards is exploited to scale to the huge amounts of available semantic data. Its major novelty is to implement a relation-based match for question interpretation, to convert the user question into a query language (e.g. SPARQL). English, French and German DBpedia chapters are the RDF data sets to be queried using a natural language interface.

- Participants: Alessio Palmero Aprosio, Amine Hallili, Elena Cabrio, Fabien Gandon, Julien Cojan and Serena Villata
- Contact: Elena Cabrio
- URL: http://www.qakis.org/

7. New Results

7.1. Users Modeling and Designing Interaction

7.1.1. Design of a User-Centered Evaluation Method for Exploratory Search Systems: Consolidation of the CheXplore plugin

Participants: Alain Giboin, Jean-Marie Dormoy, Emilie Palagi, Fabien Gandon.

Designed and implemented in the context of the PhD of Emilie Palagi [64], CheXplore is a Chrome plugin that supports the user-centered evaluation of exploratory search systems. This year, CheXplore has been consolidated, i.e., in particular, refactoring of the source code – from jQuery to JavaScript; addition of some new functionalities mentioned in Emilie Palagi's PhD thesis.

7.1.2. User Evaluation of the WASABI demonstrators

Participants: Alain Giboin, Michel Buffa, Elmahdi Korfed.

In the context of the ANR project WASABI, and in collaboration with Guillaume Pellerin (IRCAM), we specified a generic methodological framework for evaluating the WASABI musical demonstrators through their use. The demonstrators are targeted to six kinds of users: composers, musicologists, journalists, content providers, music school students and teachers, and sound-engineers.

7.1.3. Territoriality-theory-based Rules and Method for Designing Multi-device Games

Participant: Alain Giboin.

A research action performed in the context of a collaboration with Anne-Marie Dery-Pinna, Philippe Renevier (I3S, Sparks team) and Sophie Lepreux (UVHC, LAMIH Lab). Observing that "territorial behavior" occurs during human interaction at a table – i.e. that humans engaged in a collaborative task partition the table workspace into different zones (so-called personal territory, group territory and storage territory), in order to get collaborative benefits –, Scott and Carpendale [65] proposed to rely on a tabletop territoriality (or workspace partitioning) theory to support the design of collaborative digital tabletop applications. Concerned by competitive game applications involving multiple devices (e.g., tabletop, tablet, smartphone), we adapted Scott and Carpendale's theory, and, based on this adapted theory, we developed a set of rules and a method for designing the user interfaces of these multi-device applications [57]. This year, we refined this set of rules and this method after having tested them [58].

7.1.4. Linked Data Visualization

Participants: Yun Tian, Olivier Corby.

We started a collaboration with M. Winckler from I3S, UNS, on Linked Data visualization with Yun Tian, a Polytech'Nice Master internship. During this internship, we have connected the HAL open data server [0] with the MGExplorer graphic library. The result is a graphic browser for copublications. This work resulted in a server prototype [0].

7.1.5. Linked Data Path Finder

Participants: Marie Destandeau, Olivier Corby, Alain Giboin.

We started a collaboration with the ILDA Inria team from Saclay where we developped an algorithm to explore the content of remote Semantic Web triple stores.

7.2. Communities and Social Interactions Analysis

7.2.1. Fake News Detection

Participants: Elena Cabrio, Serena Villata, Jérôme Delobelle.

This work is part of the DGA project RAPID CONFIRMA (COntre argumentation contre les Fausses InfoRMAtion) aiming to automatically detect fake news and limit their diffusion. In this purpose, a framework is developed to detect fake news, to reduce their propagation and to propose the best response strategies. Thus, in addition to identifying the communities propagating these fake news, our goal is to propose a method to convince a person that the information is actually false is a key element in fighting the spread of such a kind of dangerous information. To achieve this goal, we orientate our research towards the generation of counter-argumentation. Counter-argumentation is a process aiming to put forward counter-arguments in order to provide evidences against a certain argument previously proposed. In the case of fake news, in order to convince a person that the (fake) information is true, the author of the fake news will use different methods of persuasion via arguments. Thus, identifying these arguments and attacking them by using carefully constructed arguments from safe sources is a way to fight this phenomenon and its spread along the social network. More precisely, we have identified four steps to address the counter-argumentation process: (1) Identifying the arguments used in the fake news (Argument mining); (2) Determining, for each of the arguments, whether it is for or against the topic of the fake news (Stance detection); (3) Identifying the key arguments that our system must attack (Classification task); and (4) Providing a set of arguments from safe sources to attack the targeted fake arguments (Counter-Argumentation).

We are also interested in studying, from a formal point of view, how to cast the notion of interpretability (i.e. the degree to which an observer can understand the cause(s) of a result) in abstract argumentation so that the reasons leading to the acceptability of one or a set of arguments in a framework (returned by a particular semantics) may be explicitly assessed [13]. More precisely, this research question breaks down into the following sub-questions: *(i)* how to formally define and characterise the notion of *impact* of an argument with respect to the acceptability of the other arguments in the framework? and *(ii)* how does this impact play a role in the interpretation process of the acceptability of arguments in the framework?

7.2.2. Hate Speech Detection

Participants: Elena Cabrio, Alain Giboin, Sara Tonelli, Michele Corazza, Pinar Arslan, Stefano Menini.

On the topic of cyberbullying event detection and hate speech detection, we proposed a message-level cyberbullying annotation on an Instagram dataset. Moreover, we used the correlations on the Instagram dataset annotated with emotion, sentiment and bullying labels. Finally, we built a message-level emotion classifier automatically predicting emotion labels for each comment in the Vine bullying dataset. We built a session-based bullying classifier with the use of n-grams, emotion, sentiment and concept-level features. For

[0] http://sparql.archives-ouvertes.fr/sparql
[0] http://sparks-vm9.i3s.unice.fr:8080/index.html

both emotion and bullying classifiers, we used Linear Support Vector Classification. Our results showed that "anger" and "negative" labels have a positive correlation with the presence of bullying. Concept-level features, emotion and sentiment features in different levels contribute to the bullying classifier, especially to the bullying class. Our best performing bullying classifier with n-grams and concept-level features (e.g., polarity, averaged polarity intensity, moodtags and semantics features) reached to an F1-score of 0.65 for bullying class and a macro average F1-score of 0.7520. The results of this research have been published at SAC 2019 [7].

Together with some colleagues at FBK Trento, we performed a comparative evaluation on datasets for hate speech detection in Italian, extracted from four different social media platforms, i.e. Facebook, Twitter, Instagram and WhatsApp. We showed that combining such platform-dependent datasets to take advantage of training data developed for other platforms is beneficial, although their impact varies depending on the social network under consideration. The results of this research have been published at SAC 2019 [11].

7.3. Vocabularies, Semantic Web and Linked Data Based Knowledge Representation and Artificial Intelligence Formalisms on the Web

7.3.1. Semantic Web for Biodiversity

Participants: Franck Michel, Catherine Faron Zucker, Antonia Ettorre.

The development of an activity related to biodiversity data sharing and integration is going on through the sustained collaboration with the "Muséum National d'Histoire Naturelle" of Paris (MNHN).

First, at the very end of 2018, we published a journal paper about the SPARQL Micro-Services architecture and how this can be useful in the biodiversty domain [62]. Then, through the internship of a Ubinet master student, we explored how SPARQL Micro-Services can help biologists in editing taxonomic information by confronting multiple, heterogeneous biodiversity-related data sources. We presented some results of this work at the Biodiversty_Next conference 2019 [28].

Within the same internship we continued the work meant to publish biodiversity data as linked data (TAXREF-LD [0]). The goal is to extend the dataset from simple taxonomic data to new types of data: species interactions, multi-lingual names, conservation and legal statuses. This work should lead to a publication in 2020.

During the last two years, we have lead the biodiversity task within the Bioschemas.org W3C community group that seeks the definition and adoption of common biology-related markup terms. We proposed the creation of the Taxon term [0] whose adoption in Schema.org is under discussion. The work now starts bearing fruits as 180.000+ webpages of the MNHN are now annotated with the Taxon term, paving the way to more biodiversity resources being published as structured data that search engines can process to provide more accurate search results.

7.3.2. Semantic Web for eEducation

Participants: Catherine Faron Zucker, Géraud Fokou Pelap.

In the framework of the EduMICS project we developed and populated an ontology to represent the students' activity on the Educlever learning platform.

7.3.3. Semantic Web for B2B applications

Participants: Molka Dhouib, Catherine Faron Zucker, Andrea Tettamanzi.

In the framework of the collaborative project with Silex France company aiming to model the social network of service providers and companies, as a preliminary step, we developed an ontology alignment approach combining word embedding and the radius measure to detect matching concepts and determining equivalence or hierarchical relations between them. We report and discuss the results of the evaluation of our approach on the OAEI complex alignment benchmark and on the SILEX use case: aligning reference vocabularies to annotate B2B services (ESCO to Cigref, ESCO to ROME, NAF to kompass and NAF to Silex activity domains) [35].

[0] http://agroportal.lirmm.fr/ontologies/TAXREF-LD
[0] http://bioschemas.org/devSpecs/Taxon/

7.3.4. Integration of Heterogeneous Data Sources

Participants: Franck Michel, Catherine Faron Zucker, Fabien Gandon.

With the incentive of fostering the integration of Linked Data and non RDF data sources, we continued the work initiated around the SPARQL Micro-Service architecture that harnesses the Semantic Web standards to enable automatic combination of Linked Data and data residing in Web APIs. We published a paper at the LDOW workshop of the Web Conference that explores how we can leverage Schema.org to enable web-scale discovery and querying of Web APIs using SPARQL micro-services [27].

7.3.5. Uncertainty in the Semantic Web

Participants: Ahmed El Amine Djebri, Fabien Gandon, Andrea Tettamanzi.

In the framework of Ahmed El Amine Djebri's thesis, we proposed an approach to publishing uncertainty on the Semantic Web [15] and to link and negote uncertainty theories [14].

7.3.6. Uncertainty in Human Geography

Participant: Andrea Tettamanzi.

In the framework of the Incertimmo collaborative project between Université Côte d'Azur and Kinaxia, we applied machine learning and urban morphology theory to the investigation of the influence of the urban environment on the value of residential real estate [6].

7.3.7. Ontology Design Rule

Participants: Olivier Corby, Catherine Faron Zucker, Philippe Martin.

We worked on the topic of Ontology Design Rules with Philippe Martin, from université de la Réunion, during his visit to the Wimmics team. This work resulted in a publication at Semantics [25].

7.3.8. Suggestion of Data Sources for SPARQL Queries over Linked Open Data

Participants: Hai Huang, Fabien Gandon.

For querying processing over Linked Open Data, suggestion of relevant data sources with respect to a SPARQL query is crucial since it highly affects the performance of querying. In this work, we focus on the problem of suggesting k relevant data sources with respect to a SPARQL query. We propose a summarization method which models the RDF graph of linked data sources and query graphs as sets of feature paths (star, sink and chain paths) and an effective algorithm to extract these feature paths for data sources and query graphs. To obtain candidate data sources we propose a time and space efficient search algorithm based on locality sensitive hashing. We perform a large-scale experiment on real world linked datasets which shows that our algorithm outperforms existing baselines.

7.4. Analyzing and Reasoning on Heterogeneous Semantic Graphs

7.4.1. SPARQL Function

Participant: Olivier Corby.

We wrote a SHACL interpreter with the LDScript language. Within the SPARQL Function LDScript [56] language we intoduced new datatypes for JSON and XML DOM. We have written a technical documentation for the whole language: http://ns.inria.fr/sparql-extension.

7.4.2. Ontology alignement approach based on Embedded Space

Participants: Molka Dhouib, Catherine Faron Zucker, Andrea Tettamanzi.

In the framework of a collaborative project with Silex France company aiming to model the social network of service providers and companies, as a preliminary step, we developed last year a dedicated vocabulary of competences and fields of activities to semantically annotate B2B service offers. This year, we proposed a new ontology alignment approach based on a set of rules exploiting the embedded space and measuring clusters of labels to discover the relationship between concepts. We tested our system on the OAEI conference complex alignment benchmark track and then applied it to aligning ontologies in a real-world case study of Silex company. The experimental results show that the combination of word embedding and the radius measure make it possible to determine, with good accuracy, not only equivalence relations, but also hierarchical relations between concepts. This work has been presented at the 15th International Conference, SEMANTiCS 2019 [35].

7.4.3. Argument Mining and Argumentation Theory

Participants: Elena Cabrio, Shohreh Haddadan, Tobias Mayer, Milagro Teruel, Laura Alonso Alemany, Johanna Frau.

We have proposed an Argument Mining approach to political debates [23]. We have addressed this task in an empirical manner by annotating 39 political debates from the last 50 years of US presidential campaigns, creating a new corpus of 29k argument components, labeled as premises and claims. We then proposed two tasks: (1) identifying the argumentative components in such debates, and (2) classifying them as premises and claims. We showed that feature-rich SVM learners and Neural Network architectures outperform standard baselines in Argument Mining over such complex data. We released the new corpus USElecDeb60To16 and the accompanying software under free licenses to the research community. As a result of these findings, we have also realized the DISPUTool system [22]. The results of this research have been published at ACL 2019 and IJCAI 2019.

We have contributed to the definition of the ACTA tool, aiming at applying argument mining to clinical text, given the importance of argument-based decision making in medicine [26]. ACTA is a tool for automating the argumentative analysis of clinical trials. The tool is designed to support doctors and clinicians in identifying the document(s) of interest about a certain disease, and in analyzing the main argumentative content and PICO elements. The results of this research have been published at IJCAI 2019.

Finally, together with Laura Alonso Alemany (Univ. Cordoba), Johanna Frau (Univ. Cordoba) and Milagro Teruel (Univ. Cordoba), we evaluated different attention mechanisms applied over a state-of-the-art architecture for sequence labeling [18]. Argument mining is a rising area of Natural Language Processing (NLP) concerned with the automatic recognition and interpretation of argument components and their relations. Neural models are by now mature technologies to be exploited for automating the argument mining tasks, despite the issue of data sparseness. This could ease much of the manual effort involved in these tasks, taking into account heterogeneous types of texts and topics. They assessed the impact of different flavors of attention in the task of argument component detection over two datasets: essays and legal domain. They showed that attention not models the problem better but also supports interpretability. The results of this research have been published at FLAIRS 2019.

7.4.4. Mining and Reasoning on Legal Documents

Participants: Serena Villata, Cristian Cardellino, Milagro Teruel, Laura Alonso Alemany, Guido Governatori, Leendert Van Der Torre, Beishui Liao, Nir Oren.

Together with Cristian Cardellino (Univ. Cordoba), Santiago Marro (Univ. Cordoba), Milagro Teruel (Univ. Cordoba) and Laura Alonso Alemany (Univ. Cordoba), we have adapted the semi-supervised deep learning architecture known as Convolutional Ladder Networks, from the domain of computer vision, and explored how well it works for a semi-supervised Named Entity Recognition and Classification task with legal data. The idea of exploring a semi-supervised technique is to assess the impact of large amounts of unsupervised data (cheap to obtain) in specific tasks that have little annotated data, in order to develop robust models that are less prone to overfitting. In order to achieve this, first we checked the impact on a task that is easier to measure. We presented some preliminary results, however, the experiments carried out showed some interesting insights that foster further research in the topic. The results of this research have been published at FLAIRS 2019 [9].

Together with some colleagues from Data61 Queensland (Australia) and Antonino Rotolo (University of Bologna), Serena Villata proposed a framework for modelling legislative deliberation in the form of dialogues. Roughly, in legislative dialogues coalitions can dynamically change and propose rule-based theories associated with different utility functions, depending on the legislative theory the coalitions are trying to determine. The results of this research have been published at ICAIL 2019 [21].

Finally, together with Nir Oren (Univ. Aberdeen), Leendert van der Torre (Univ. Luxembourg) and Beishui Liao (Univ. Zhejiang), we defined, using hierarchical abstract normative systems (HANS), three kinds of prioritized normative reasoning approaches called Greedy, Reduction and Optimization. Then, after formulating an argumentation theory for a HANS, we showed that for a totally ordered HANS, Greedy and Reduction can be represented in argumentation by applying the weakest link and the last link principles, respectively, and Optimization can be represented by introducing additional defeats capturing the idea that for each argument that contains a norm not belonging to the maximal obeyable set then this argument should be rejected. The results of this research have been published on the Journal of Logic and Computation [3].

7.4.5. Natural Language Processing of Song Lyrics

Participants: Michael Fell, Elena Cabrio, Fabien Gandon, Alain Giboin.

We progressed our work in the WASABI ANR project in two directions. First, we tackled the problem of summarizing song lyrics. Given the peculiar structure of songs, applying generic text summarization methods to lyrics can lead to the generation of highly redundant and incoherent text. We thus proposed to enhance state-of-the-art text summarization approaches with a method inspired by audio thumbnailing. We showed how these summaries that take into account the audio nature of the lyrics outperform the generic methods according to both an automatic evaluation and human judgments. The work resulted in an RANLP publication [17]. Second, we investigated the task of detecting swear words and other potential harmful content in lyrics. The Parental Advisory Label (PAL) is a warning label that is placed on audio recordings in recognition of profanity or inappropriate references, with the intention of alerting parents of material potentially unsuitable for children.

Since 2015, digital providers such as iTunes, Spotify, Amazon Music and Deezer also follow PAL guidelines and tag such tracks as explicit.

Nowadays, such labelling is carried out mainly manually on voluntary basis, with the drawbacks of being time consuming and therefore costly, error prone and partly a subjective task. Therefore, we compared automated methods ranging from dictionary-based lookup to state-of-the-art deep neural networks to automatically detect explicit contents in English lyrics. We showed that more complex models perform only slightly better on this task, and relying on a qualitative analysis of the data, we discussed the inherent hardness and subjectivity of the task. The work was published at the RANLP conference [16]. We are currently modelling emotion in song lyrics, with the focus on the hierarchical and sequential structure of these texts, in which lines make up segments which make up the full lyric. And later parts may be perceived differently in light of the emotion previous parts have caused.

7.4.6. RDF Mining

Participants: Thu Huong Nguyen, Andrea Tettamanzi.

In collaboration with our former PhD student Tran Duc Minh, Claudia d'Amato of the University of Bari, and Nguyen Thanh Binh of the Danang University, we made a comparison of rule evaluation metrics for EDMAR, our evolutionary approach to discover multi-relational rules from ontological knowledge bases exploiting the services of an OWL reasoner [36].

In the framework of Nguyen Thu Huong's thesis, we have proposed a grammar-based evolutionary method to mine RDF datasets for OWL class disjointness axioms [31], [30].

7.4.7. Machine Learning for Operations Research

Participant: Andrea Tettamanzi.

Together with Alberto Ceselli and Saverio Basso of the University of Milan we used machine learning techniques to understand good decompositions of linear programming problems [1].

7.4.8. Image recognition with Semantic Data

Participants: Anna Bobasheva, Fabien Gandon, François Raygagne, Frédéric Precioso.

The objective of the MonaLIA 2.0 project is to exploit the crossover between the Deep Learning methods of image analysis and knowledge-based representation and reasoning and its application to the semantic indexing of annotated works and images in JocondeLab dataset. The goal is to identify automated or semi-automated tasks to improve the annotation and information retrieval. This project was an 11-month contract with Ministry of Culture plus 6-month internship.

- Training dataset preparation

  Developed SPARQL query to extract the subsets of images to train the multi-label Deep Learning classifiers for a given set of categories

  Developed Python scripts to filter and balance training images and Joconde specific data loader

  Identified categories that are not linked by Garnier Thesaurus but visually related and extended the Joconde metadata with the new RDF triples (e.g. category ”Rider” is linked to categories ”Horse” and ”Human being”)

  Researched effects of various image transformations on the object detection performance (resizing, cropping, padding, scaling)

  For the underrepresented categories (bicycle, airplane, cat, etc.) downloaded the images from the external sources such as Kaggles' “Painter by Number”, the Behance Artistic Media Set, and Cleveland Museum of Art. This has been done with the internship of François Raygagne.

- Building Deep Learning model

  Adapted the pre-trained VGG16 and Inception v3 PyTorch implementations for multi-label classification of the artwork images

  Tuned models hyperparameters

  Experimented with scaling the multi-labeled for 10, 20, 40 classes

  Experimented with binary classifiers for a single category

- Classification results consumption

  Studied the possible dependencies between knowledge graph metrics and classification performance (average precision of object detection)

  Extended the Joconde metadata with prediction scores produced by the classifiers

  Included the scores into category search queries to filter and order the results to produce more relevant results

Results were presented at atelier Culture - Inria, on december 2nd, Institut national d'histoire de l'art in Paris.

7.4.9. Hospitalization Prediction

Participants: Raphaël Gazzotti, Catherine Faron Zucker, Fabien Gandon.

HealthPredict is a project conducted in collaboration with the Département d'Enseignement de Recherche en Médecine Générale (DERMG) at Université Côte d'Azur and the SynchroNext company. It aims at providing a digital health solution for the early management of patients through consultation with their general practitioner and health care circuit. Concretely, it is a predictive Artificial Intelligence interface that allows us to cross the data of symptoms, diagnosis and medical treatments of the population in real time to predict the hospitalization of a patient. We propose and evaluate different ways to enrich the features extracted from electronic medical records with ontological resources before turning them into vectors used by Machine Learning algorithms to predict hospitalization. We reported and discussed the results of our first experiments on the database PRIMEGE PACA at EGC 2019 [38] and ESWC 2019 [19]. We propose a semi-supervised approach based on DBpedia to extract medical subjects from EMRs and evaluate the impact of augmenting the features used to represent EMRs with these subjects in the task of predicting hospitalization. Our results will be presented at SAC 2020 [61]. We designed an interface to assist in the decision-making process of general practitioners that allows them to identify in patients the first signs that lead to hospitalization and medical problems to be treated as a priority. It has been presented at [55].

7.4.10. Learning Analytics and Adaptive learning

Participants: Oscar Rodríguez Rocha, Catherine Faron Zucker.

We developed semantic queries to analyse the student activity data available in the Educlever knowledge graph and the SIDES knowledge graph, showing the added value of Semantic Web modelling enabling ontology-based reasoning. The results of our analysis of the SIDES knowledge graph have been presented at the 2019 French workshop on AI and Health [39].

The faculties of medicine, all grouped together under the auspices of the *Conférence des doyens*, are collectively proposing to upgrade the SIDES solution to an innovative solution called Intelligent Health Education System 3.0 (SIDES 3.0). As part of this community-based approach, the coordination of the project will be carried out by the *Université Numérique Thématique (UNT) en Santé et Sport*, the *GIP UNESS.fr*. This structure offers an ideal national positioning for support and coordination of training centers (UFR) and also offers long-term financial sustainability.

In particular, Inria through the Wimmics research team focuses on the recommendation of existing questions to the students according to their profile. For this, research activities are performed to classify the questions present in the platform by difficulty levels according to the Bloom's revised taxonomy, considering the information contained in text of the question. Also, research activities have focused to predict the probability of the outcomes of the students to questions considering previous answers stored in the SIDES graph.

With the ultimate goal of recommending resources adapted to the student's profile and context, we developed an approach to predict the success of students when answering training or test questions by learning a student model from the SIDES knowledge graph. To learn a user model from the SIDES knowledge graph, we combine state-of-the-art features with node embeddings. Our first results will be presented at SAC 2020.

The level of complexity and specificity of the learning objective associated with a question may be a key criterion to integrate in the recommendation process. For this purpose, we developed an approach to classify the questions of the SIDES platform according to the reference Bloom's taxonomy, by extracting the level of complexity and specificity of their learning objectives from their textual descriptions with semantic rules.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. PREMISSE Collaborative Project

Participants: Molka Dhouib, Catherine Faron Zucker, Andrea Tettamanzi.

Partner: SILEX France.

This collaborative project with the SILEX France company started in march 2017, funded by the ANRT (CIFRE PhD). SILEX France is developing a B2B platform where service providers and consumers upload their service offers or requests in free natural language; the platform is intended to recommend service providers to the applicant, which are likely to fit his/her service request. The aim of this project is to develop a solution to link together service providers and consumers.

8.1.2. HealthPredict Collaborative Project

Participants: Raphaël Gazzotti, Catherine Faron Zucker, Fabien Gandon.

Partner: Synchronext.

This collaborative project with the Synchronext company started in april 2017, funded by the ANRT (CIFRE PhD). Synchronext is a startup aiming at developing Semantic Web business solutions. The aim of this project is to design a digital health solution for the early management of patients through consultations with their general practitioner and health care circuit. The goal is to develop a predictive Artificial Intelligence interface that allows to cross the data of symptoms, diagnosis and medical treatments of the population in real time to predict the hospitalization of a patient.

8.1.3. Joint Lab EduMICS

Participants: Olivier Corby, Catherine Faron Zucker, Géraud Fokou Pelap, Fabien Gandon, Alain Giboin.

Partner: Educlever.

EduMICS (Educative Models Interactions Communities with Semantics) is a joint laboratory (LabCom) between the Wimmics team and the Educlever company that ended in early 2019. The aim of EduMICS was to develop research and technologies with the ultimate goal to adapt educational progressions and pedagogical resource recommendation to learner profiles.

8.1.4. Curiosity Collaborative Project

Participants: Catherine Faron Zucker, Oscar Rodríguez Rocha.

Partner: TeachOnmars.

This collaborative project with the TeachOnmars company started in October 2019. TeachOnMars is developping a platform for mobile learning. The aim of this project is to develop an approach for automatically indexing and semantically annotating heterogeneous pedagogical resources from different sources to build up a knowledge graph enabling to compute training paths, that correspond to the learner's needs and learning objectives.

8.2. Bilateral Grants with Industry

Accenture gifts (June 2017 - January 2022): Wimmics has received two gifts from Accenture. Together with additional funds from another project these gifts have been used to fund the Engineer position and then the PhD Grant (June 2017 - January 2022) of Nicholas Halliwell on a topic agreed with Accenture: "interpretable and explainable predictions"

9. Partnerships and Cooperations

9.1. Regional Initiatives

- Nhan Le Thanh is responsible of project Idex Jedi MIRE, Université Côte d'Azur (2017-2020)
- IADB UCA Project *Integration and Learning on Biomedical Data*[0], is a project funded by UCA JEDI Labex (Université Côte d'Azur). The goal of the project is to leverage medical prognosis and decision making in the clinical domain with big data analysis techniques, Natural Language Processing and Machine Learning. The partners are: I3S, Wimmics, CHU Nice, BCL (Bases, Corpus, Language) Laboratory.

[0] *Intégration et Apprentissage sur les Données Biomédicales*

9.2. National Initiatives

9.2.1. PIA GDN ANSWER

Participants: Fabien Gandon, Hai Huang, Vorakit Vorakitphan, Serena Villata, Elena Cabrio.

ANSWER stands for Advanced aNd Secured Web Experience and seaRch [0]. It is a GDN project (Grands Défis du Numérique) from the PIA program (Programme d'Investissements d'Avenir) on Big Data. The project is between four Inria research teams and the Qwant company.

The aim of the ANSWER project is to develop the new version of the Qwant [0] search engine by introducing radical innovations in terms of search criteria as well as indexed content and users' privacy.

The purpose is to strengthen everyone's confidence in the search engine and increase the effectiveness of Web search. Building trust in the search engine is based on innovations in (1) Security: computer security, privacy; (2) Completeness: completeness and heterogeneity of (re)sources; and (3) Neutrality: analysis, extraction, indexing, and classification of data.

Increasing the effectiveness of Web-based research relies on innovations related to (1) Relevance: variety and value of content taken into account, measurement of emotions carried by query results; (2) Interaction with the user: adaptation of the interfaces to the types of research; and (3) Performance: perceived relevance of results and response time.

The proposed innovations include:

- Design and develop models and tools for the detection of emotions in query results:
  - Ontology, thesaurus, linguistic resources
  - Metrics, indicators, classification of emotions
- Design and develop new crawling algorithms:
  - Dynamic crawling strategies
  - Crawlers and indexes for linked open data
- Ensure respect for privacy:
  - Detection of Internet tracking
  - Preventive display of tracing techniques
  - Certified security of automatic adaptation of ads to keywords entered by the user

9.2.2. DGA CONFIRMA

Participants: Elena Cabrio, Serena Villata.

The theme of this new project with DGA is counter argumentation against fake news. Its duration is 2018-2020.

9.2.3. Ministry of Culture: MonaLIA 2.0

Participants: Anna Bobasheva, François Raygagne, Fabien Gandon, Frédéric Precioso.

The objective of the MonaLIA 2 project is to exploit the crossover of the automatic learning methods particularly applied to image analysis and knowledge-based representation and reasoning, in particular for the semantic indexing of annotated works and images in JocondeLab. The goal is to identify automated or semi-automatable tasks to improve the annotation. This project follows the preliminary project MonaLIA 1 which established the state of the art in order to evaluate the potential and the combination of learning (notably deep learning) and the semantization of annotations on the case of JocondeLab. In the project MonaLIA 2 we now want to go beyond the preliminary study and to design and build a prototype and the methods assisting the creation, the improvement and the maintenance of the metadata of the image database in order to assist the actors of the cultural world in their daily tasks. The preliminary study identified several possible coupling

[0] https://project.inria.fr/answer/
[0] http://www.qwant.com

points between deep learning from non-necessarily structured data and reasoning from structured data. This project proposes to select the most promising of them to carry out a proof of concept combining these methods by focusing on the assistance to the annotation and curation tasks of the metadata of a real base to improve the contents, the course and exploitation thereafter.

9.2.4. ANR WASABI

Participants: Michel Buffa, Elena Cabrio, Catherine Faron Zucker.

The ANR project WASABI started in January 2017 with IRCAM, Deezer, Radio France and the SME Parisson, consists in building a 2 million songs knowledge base of commercial popular music (rock, pop, etc.) Its originality is the joint use of audio-based music information extraction algorithms, song lyrics analysis algorithms (natural language processing), and the use of the Semantic Web. Web Audio technologies will then explore these bases of musical knowledge by providing innovative applications for composers, musicologists, music schools and sound engineers, music broadcasters and journalists. This project is in its mid-execution and gave birth to many publications in international conferences as well as some mainstream coverage (i.e for "la fête de la Science"). Michel Buffa, national coordinator of this project, presented the project to "Journées Sciences et Musique" in October 2019 in Rennes, and animated a Master Class during the Sophia Summit 2019 event in November 2019. Participation in the ANR OpenMiage project aimed at offering online Bachelor and Master degrees.

Industrial transfer of some of the results of the WASABI project (partnership with AmpedStudio.com/Amp Track company) for integration of our software into theirs), SATT PACA.

Web site: http://wasabihome.i3s.unice.fr

9.2.5. ANR SIDES 3.0

Participants: Catherine Faron Zucker, Olivier Corby, Fabien Gandon, Alain Giboin, Andrea Tettamanzi.

Partners: Université Grenoble Alpes, Inria, Ecole Normale Supérieure de Lyon, Viseo, Theia.

SIDES 3.0 is an ANR project (2017-2020) which started in fall 2017. It is led by Université Grenoble Alpes (UGA) and its general objective is to introduce semantics within the existing SIDES educational platform [0] for medicine students, in order to provide them with added value educational services.

Web site: https://www.uness.fr/anr/projets/dune/sides3.0

9.2.6. ANR D2KAB

Participants: Olivier Corby, Catherine Faron Zucker, Franck Michel.

Partners: LIRMM, INRA, IRD, ACTA

D2KAB is an ANR project which started in June 2019, led by the LIRMM laboratory (UMR 5506). Its general objective is to to create a framework to turn agronomy and biodiversity data into knowledge - semantically described, interoperable, actionable, open– and investigate scientific methods and tools to exploit this knowledge for applications in science and agriculture.

Web site: http://www.d2kab.org

9.2.7. Smart Enseigno

Participant: Catherine Faron Zucker.

Partner: Educlever, Ludotic, Cabrilog, IFE

As a follow-up of the EduMICS project, the Smart Enseigno project started in September 2019, led by Educlever. It is funded by the Ministry of National Education (MEN), within the Programme des Investissements d'Avenir (PIA2), action Partenariat d'innovation Intelligence artificielle(PI-IA) [00]. This project aims at developing resources and intelligent services within the Educlever platform for secondary school mathematics education.

[0] http://side-sante.org/
[0] https://eduscol.education.fr/pid29713/appels-a-projets-numeriques-des-investissements-d-avenir.html
[0] https://primabord.eduscol.education.fr/P2IA

9.2.8. DBpedia.fr

Participants: Elmahdi Korfed, Fabien Gandon.

The DBpedia.fr project proposes the creation of a French chapter of the DBpedia database. This project was the first project of the Semanticpedia convention signed by the Ministry of Culture, the Wikimedia foundation and Inria.

Web site: http://dbpedia.fr

9.2.9. Convention between Inria and the Ministry of Culture

Participant: Fabien Gandon.

We supervise the research convention with the Ministry of Culture to foster research and development at the crossroad of culture and digital sciences. This convention signed between Inria and the Ministry of Culture provides a framework to support projects at the cross-road of the cultural domain and the digital sciences.

9.2.10. Qwant-Inria Joint Laboratory

Participant: Fabien Gandon.

We supervise the Qwant-Inria Joint Laboratory where joint teams are created and funded to contribute to the search engine research and development. The motto of the joint lab is Smart Search and Privacy with five research directions:

- Crawling, Indexing, Searching
- Execution platform, privacy by design, security, ethics
- Maps and navigation
- Augmented interaction, connected objects, chatbots, personnal assistants
- Education technologies (EdTech)

We released the final, but confidential, report of the Qwant-Culture short-term project. This project aimed at identifying possibilities of exploiting the Qwant search engine to improve the search for information in the digital cultural resources of the French Ministry of Culture. Some possibilities have been selected to be the subject of research actions in the context a long-term project.

9.2.11. GDRI Zoomathia

Participants: Catherine Faron Zucker, Franck Michel, Andrea Tettamanzi.

Wimmics is a partner of the International Research Group (GDRI) Zoomathia funded by two CNRS institutes: INEE and INSHS. This group aims at studying transmission of zoological knowledge from Antiquity to Middle-Age through material resources (bio residues, artefacts), iconography and texts.

As a continuation of the work initiated with the *Muséum National d'Histoire Naturelle* (MNHN) during the last three years, the TAXREF-LD linked data dataset, that we produced jointly with the MNHN, now appears in the Linked Open Data cloud [0] and is published on AgroPortal [0]. Relatedly, we have reflected on modelling principles for biodiversity Linked Data [63].

Web site: http://www.cepam.cnrs.fr/zoomathia/

[0] http://lod-cloud.net/
[0] http://agroportal.lirmm.fr/ontologies/TAXREF-LD/

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

- AI4EU : In January 2019, the AI4EU consortium was established to build the first European Artificial Intelligence On-Demand Platform and Ecosystem with the support of the European Commission under the H2020 programme. We participate to the design of an ontology of AI resources. We have set up a prototype of Web server with a SPARQL endpoint to demonstrate the ontology and RDF metadata. Web site: https://www.ai4eu.eu

9.3.2. Collaborations in European Programs, Except FP7 & H2020

MIREL Project

Program: RISE

Project acronym: MIREL

Project title: MIning and REasoning with Legal texts

Duration: January 2016 - December 2019

Coordinator: University of Luxembourg

Other partners: 16 members from 11 countries [0].

Abstract: project that defines a formal framework and develops tools for MIning and REasoning with Legal texts, with the aim of translating these legal texts into formal representations that can be used for querying norms, checking compliance, and supporting decision .

CREEP EIT Project

Program: KIC EIT Digital 2018

Project acronym: CREEP

Project title: Cyberbulling Effects Prevention

Duration: January 2018 - December 2019

Coordinator: Fondazione Bruno Kessler

Other partners: University of Trento, Fondazione Bruno Kessler, ExpertSystem, NeuroNation

Abstract: CREEP (Cyberbulling Effects Prevention) aims at identifying and preventing the possible negative impacts of cyberbullying on young people. It seeks to realize advanced technologies for the early detection of cyberbullying phenomena through the monitoring of social media and the communication of preventive advices and personalized recommendations tailored to teenagers' needs through a virtual coaching system (chatbot).

9.4. International Research Visitors

- Laura Alonso Alemany, Professor, Cordoba University, Argentina
- Luigi Asprino, PhD, Research Assistant, Institute of Cognitive Sciences and Technologies, Roma, Italy
- Cristian Cardelino, PhD student, Cordoba University, Argentina
- Alberto Ceselli, Professor, University of Milano, Italy
- Andrei Ciortea, Postdoctoral researcher, University St. Gallen, Switzerland
- Johanna Frau, PhD student, Cordoba University, Argentina
- Marco Guerini, Researcher, Fondazione Bruno Kessler, Trento, Italy
- Phan Hieu Ho, PhD student, Danang Polytech, Vietnam
- Dario Malchiodi, Associate Professor, University of Milano, Italy

[0] http://www.mirelproject.eu/members.html

- Enrico Mensa, PhD Student, University of Torino, Italy
- Than Tuan Nguyen, Ph. D. student, Université Hanoi, Vietnam
- Debora Nozza, PhD student, University of Milano, Italy
- Johan Pauwels, Research Assistant, Queen Mary University of London
- Mark Sandler, Professor, Queen Mary University of London
- Milagro Teruel, PhD student, Cordoba University, Argentina

9.4.1. Visits to International Teams

9.4.1.1. Research Stays Abroad

- Fabien Gandon visited Stanford, USA from July to August 2019. In the context of the project MIREL he worked on the problem of SHACL-based validation of ontologies.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events: Organisation

10.1.1.1. General Chair, Scientific Chair

Elena Cabrio was Conference Handbook Chair of ACL 2019 (Association of Computational Linguistics conference). Florence (Italy), July 2019.

Catherine Faron Zucker was co-chair of the AFIA scientific day on Education and Training on Artificial Intelligence (EFIA), Paris, 10/02/2019.

Fabien Gandon was general chair of ISWC the International Semantic Web Conference, October, 2019.

Serena Villata was Handbook Chair of the 2019 Conference on Empirical Methods in Natural Language Processing (EMNLP- 2019).

10.1.1.2. Member of the Organizing Committees

Michel Buffa was co-organizer of the W3C Workshop on Web Games, 27-28 June 2019; Redmond, WA, USA.

Fabien Gandon was co-organizer of the Joint Day Inria Ministry of Culture 02/12/2019.

10.1.2. Scientific Events: Selection

10.1.2.1. Chair of Conference Program Committees

Nhan Le Thanh:

Program chair of 13th International Conference on Computing and Communication Technologies (RIVF). 20-22 March 2019, Danang, Vietnam.

10.1.2.2. Member of the Conference Program Committees

Michel Buffa:

WebAudio conference 2019

W3C Workshop on Web Games, 27-28 June 2019; Redmond, WA, USA

Elena Cabrio:

Association for Computational Linguistics conference (ACL 2019), EMNLP2019, the Extended Semantic Web Conference (ESWC 2019), the International Semantic Web Conference, the AAAI Conference on Artificial Intelligence (AAAI-19).

Olivier Corby:

Digital Health, Ingénierie des Connaissances, ICCS, IJCAI, ISWC, KCAP, Quweda, SBBD, TheWebConf, WUM.

Jérôme Delobelle:

AAAI, IJCAI 2019 ⇒ Distinguished Program Committee member, Rencontres des Jeunes Chercheurs en Intelligence Artificielle (RJCIA), AAMAS.

Catherine Faron Zucker:

TheWebConf, IJCAI (Int. Joint Conference on Artificial Intelligence), ESWC (European Semantic Web Conference), ISWC (Int. Semantic Web Conference), Semantics, ICCS (Int. Conference on Conceptual Structures), IC (Ingénierie des Connaissances), EGC (Extraction et Gestion des Connaissances), EIAH (Environnements Informatiques pour l'Apprentissage Humain).

Fabien Gandon reviewed for: IJCAI, EGC, WebSci.

Oscar Rodríguez Rocha:

SAC 2020 - ACM Symposium on Applied Computing 2020 - The Semantic Web and Applications (SWA), AAAI 2020 - The 34th AAAI Conference on Artificial Intelligence, IJCAI, Semantics, IEEE-RIVF Internation Conference on Computing and Communication Technologies, KEOD International Conference on Knowledge Engineering and Ontology Development, KSE International Conference on Knowledge and Systems Engineering.

Andrea Tettamanzi:

AAAI-19, ACM 2020 (SWA Track), EGC 2020, EKAW 2020, PPSN 2020, TheWebConf 2020, and Web Intelligence 2020 conferences. He was Senior PC Member of IJCAI.

Serena Villata:

IJCAI, EMNLP, AAAI, AAMAS, JURIX, ICAIL.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

Catherine Faron Zucker:

Revue d'Intelligence Artificielle, Guest editor of the Semantic Web journal for a special issue devoted to extended versions of the best papers of EKAW 2018.

Serena Villata is among the authors of two editorial activities:

- Livio Robaldo, Serena Villata, Adam Wyner, Matthias Grabmair: Introduction for artificial intelligence and law: special issue "Natural Language Processing for Legal Texts". Artif. Intell. Law 27(2): 113-115 (2019) [4],
- Qingliang Chen, Paolo Torroni, Serena Villata: Principles and practice of multi-agent systems. Knowledge Eng. Review 34: e3 (2019) [2].

10.1.3.2. Reviewer - Reviewing Activities

Elena Cabrio:

Journal Argument and Computation.

Andrea Tettamanzi has served as a referee for the journals: Fuzzy Sets and Systems, Semantic Web Journal, Transactions on Evolutionary Computation.

Serena Villata:

Journal of Logic and Computation, Argument & Computation, Artificial Intelligence.

10.1.4. Invited Talks

Michel Buffa:

Programmable Audio Workshop, ”WebAudio applications developed during the WASABI ANR Project”, December 4, 2019 — GRAME-CNCM, Lyon (France)

Master Class ”Wasabi Project : Make Music Accessible To Everybody”, Sophia Summit, 19th November 2019, Sophia Antipolis, France.

Elena Cabrio:

An introduction to Computational Linguistics. University of Bologna (Italy). May 2019.

Olivier Corby:

Graph Data on the Web: extend the pivot, don't reinvent the wheel , W3C workshop on RDF and Property Graph, Berlin, March 5th.

SPARQL Template & Function, workshop at EDF, Orsay, May 21st.

Introduction au Web sémantique, Datathon workshop of ”archives nationales”, Paris, november 29th.

Jérôme Delobelle:

”Comment utiliser l'argumentation pour lutter contre les fausses informations?”, GraphiK team (Inria (Sophia Antipolis Méditerranée center), LIRMM (University of Montpellier and CNRS) and INRA), November 21st.

Catherine Faron Zucker:

Invited talk at the workshop of the MODAL project, Rennes, 2019/07/11: Injecting Domain Knowledge in Electronic Medical Records to Improve Hospitalization Prediction

Fabien Gandon:

Web Science 2019 keynote, The Web We Mix - benevolent AIs for a resilient web, Boston, USA, June,

RIVF 2019 keynote, Web of Data and Semantic Web: Linking Data and Their Schemas around the World, Da Nang Vietnam, March.

Andrea Tettamanzi:

Seminar, “Towards an Evolutionary Epistemology of Ontology Learning” at University of Danang, Vietnam, on March 19, 2019.

Conference on Unsupervised Learning at Amadeus, Sophia Antipolis, May 17, 2019.

Conference on Unsupervised Learning at Amadeus, Sophia Antipolis, October 25, 2019.

Serena Villata:

International Conference on Legal Data Mining, Machine Learning and Visualisation organized by HEC in March 2019 in Paris.

10.1.5. Leadership within the Scientific Community

Fabien Gandon is:

- member of IW3C2 steering committee for The Web Conference (WWW series) until May 2019.
- member of SWSA steering committee for the ISWC conference (as general chair of ISWC 2019).
- member of ESWC conference steering committee until October 2019.
- member of Web Science Trust Network.

10.1.6. Scientific Expertise

Michel Buffa:

Member of the W3C WebAudio working group

Academic Representative of Université Côte d'Azur to the W3C (AC Rep)

Elena Cabrio:

Reviewer of the proposals of the Vienna Science and Technology Fund (WWTF) in 2019.

Reviewer of the projects “soutien aux contrats doctoraux” of the Grand Est Région (France) in 2019.

Member of the evaluation committee assigning the AILC Master Thesis Award (the Italian association for Computational Linguistics) in 2019.

Catherine Faron Zucker:

scientific referent of the Inria Learning Lab,

member of the ANR scientific evaluation committe ”Artificial Intelligence” (CE23),

reviewer of project proposals for the MSH Paris-Saclay.

10.1.7. Research Administration

Michel Buffa:

Member of the scientific council of the GRAME laboratory (Lyon)

Director of the Miage de Nice Sophia-Antipolis, composed of Licence, Master 1 and four Master 2 degrees. About 350 students (http://miage.unice.fr)

Olivier Corby is member of the Scientific and Pedagogical committee of DS4H Graduate School ”Digital Systems for Humans” at Université Côte d’Azur. He is member of the scientific committee of Academy 1 RISE (Network, Information, Digital Society) at UCA. He is member of the PostDoc selection committee at Inria Sophia Antipolis.

Catherine Faron Zucker:

- General Treasurer of the French Society for Artificial Intelligence (AFIA).
- member of the steering committee of the AFIA college on Knowledge Engineering.
- member of the evaluation committee of Inria.
- member of the CPRH 27 commission at Université Côte d’Azur.
- coordinator of the Web option of the 5th year of Polytech Nice Sophia engineering school.
- pedagogical responsible of continuous training for the computer science department of Polytech Nice Sophia Antipolis.

Fabien Gandon is:

- Vice-head of science for Inria Sophia Antipolis - Méditerranée (Délégué Scientifique Adjoint, DSA)
- Advisory Committee representative of Inria at the World-Wide Web Consortium (W3C)
- Director of the joint research Laboratory Qwant-Inria
- Representative of Inria in the Web Science Trust Network
- Leader of the research convention with the French Ministry of Culture-Inria

Alain Giboin was member of the scientific committee of the IDEX Jedi Academy 5 ”Homme, Idées et Milieux”.

Serena Villata:

Since January 2019, Management Committee Member for France for the EU project COST Action CA17132 European network for argumentation and public policy analysis, nominated by the Ministére de l’Enseignement Supérieur, de la Recherche et de l’Innovation

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

DUT: Andrea Tettamanzi, Data Mining, 16 h ETD, L2, UCA, France.

Licence: Michel Buffa, JavaScript, 40h, L3 Miage, UNS, France.

Licence: Elena Cabrio, Introduction to the Web, 40 hours, (L2MASS), UNS, France.

Licence: Elena Cabrio, Internship supervision, 27 hours, (L3MIAGE), UNS, France.

Licence: Elena Cabrio, Web, 36 hours, (L3 MIAGE), UNS, France.

Licence: Elena Cabrio, Object Oriented Programming, 14 hours (L3 MIAGE), UNS, France.

Licence: Elena Cabrio, Software Engineering, 20 hours, (L3 MIAGE), UNS, France.

Licence: Andrea Tettamanzi, Advanced Web Programming (client side), 39h , L2, UNS, France.

Licence: Andrea Tettamanzi, Web, 30h, L3, UNS, France.

Master: Michel Buffa, Web technologies front and back end, 40h, M1, UNS, France.

Master: Michel Buffa, Server Side JavaScript and modern front-end frameworks, 60h, M2 Miage NTDP and MBDS, UNS, France.

Master: Michel Buffa, Programmable Web, 40h, M2, Polytech-Nice UNS, France.

Master: Elena Cabrio, Computational Linguistics, 30 hours, (Lettres), UNS, France.

Master: Elena Cabrio, Natural Language Processing for AI, 24 hours, (M1 INFO), UNS, France.

Master and Licence: Elena Cabrio, Responsible of the intership programme, 40 hours, (L3 and M2 MIAGE), UNS, France.

Master: Elena Cabrio, Project supervision, Polytech project “Applied Math”, 5 hours, UNS, France.

Master:Olivier Corby, Semantic Web, 20h, Polytech Nice, UNS, France.

Master: Catherine Faron Zucker, Web languages, 48h, M1, PNS UNS.

Master: Catherine Faron Zucker, Semantic Web technologies (EN), 48h, M2 Informatique, PNS, UNS.

Master: Catherine Faron Zucker, Knowledge Engineering (EN), 28h, M2 Informatique, PNS, UNS.

Master: Catherine Faron Zucker, Semantic Web technologies (EN), 30h, M1 Data Science, UNS.

Master: Catherine Faron Zucker, XML technologies, 16h, M2 IMAFA, PNS, UNS.

Master: Catherine Faron Zucker, Projects and Internship tutoring, 32h, M2, PNS, UNS.

Master: Fabien Gandon, Integrating Semantic Web technologies in Data Science developments, 56 h, M2, DSTI, France.

Master: Alain Giboin, Human-Computer-Interaction Design and Evaluation, 21h, M2, UNS, France.

Master: Alain Giboin, Adaptation of User Interfaces, 4h, M2, UNS, France.

Master: Alain Giboin, Task and Activity Analysis for HCI design and evaluation, 16h, M2 Sociology and Ergonomics of Digital Technologies, UNS, France.

Master: Alain Giboin, Digital Strategy (formerly: Economics and ICT) : Ergonomics, 16h, M2 Economics and ICT, ISEM, UNS, France.

Master: Oscar Rodríguez Rocha, Web of Data, 15h, M2, Polytech Nice, UNS, France.

Master: Oscar Rodríguez Rocha, Knowledge Engineering, 10h, M2, Polytech Nice, UNS, France.

Master: Oscar Rodríguez Rocha, Web Langages, 15h, M1, Polytech Nice, UNS, France.

Master: Andrea Tettamanzi, Logic for AI, 30 h ETD, M1, UNS, France.

Master: Andrea Tettamanzi, Web, 30 h ETD, M1, UNS, France.

Master: Andrea Tettamanzi, Agent-Based Modeling, 30 h ETD, M2, UNS, France.

E-learning

Mooc: Michel Buffa, ”JavaScript Intro” published first in Juin 2017 on the EDx platform (MIT/Harvard), still active and updated regularly.

Mooc: Michel Buffa, ”HTML5 Coding Essentials and Best Practices”

Mooc: Michel Buffa, ”HTML5 Apps and Games”, also on EDx, are still active and updated regularly.

More than 700.000 registered users since 2015 for these MOOCS.

Mooc: Fabien Gandon, Olivier Corby & Catherine Faron Zucker, Web of Data and Semantic Web (FR), 7 weeks, http://www.france-universite-numerique.fr/, Inria, France Université Numérique, Education for Adults, 3815 learners registered for 2019.

Mooc: Fabien Gandon, Olivier Corby & Catherine Faron Zucker, Introduction to a Web of Linked Data (EN), 4 weeks, http://www.france-universite-numerique.fr/, Inria, France Université Numérique, Education for Adults, 1226 learners registered for 2019.

Mooc: Fabien Gandon, Olivier Corby & Catherine Faron Zucker, Web of Data (EN), 4 weeks, https://www.coursera.org/, Coursera, Education for Adults, 1037 learners registered.

10.2.2. Supervision

PhD in progress: **Molka Dhouib**, *Modelling and supporting a B2B social network of service providers and consumers*, UCA, Catherine Faron Zucker, Andrea Tettamanzi.

PhD in progress: **Ahmed El Amine Djebri**, *Uncertainty in Linked Data*, UCA, Andrea Tettamanzi, Fabien Gandon.

PhD in progress: **Antonia Ettore**, *Artificial Intelligence for Education and Training: Knowledge Representation and Reasoning for the development of intelligent services in pedagogical environments*, UCA, Catherine Faron Zucker, Franck Michel.

PhD in progress: **Michael Fell**, *Natural Language Processing of Song Lyrics*, UCA, Co-supervision Elena Cabrio & Fabien Gandon.

PhD in progress: **Raphaël Gazzotti**, *Modelling Electronic Medical Records and Predicting Hospitalization*, UCA, Catherine Faron Zucker, Fabien Gandon.

PhD in progress: **Nicholas Halliwell**, *Explainable and Interpretable Prediction*, UCA, Fabien Gandon, Serena Villata.

PhD in progress: **Tobias Mayer**, *Argument Mining for Clinical Trials*, UNS, Johan Montagnat (CNRS, I3S), Serena Villata and Céline Poudat (UNS).

PhD in progress: **Thu Huong Nguyen**, *Mining the Semantic Web for OWL Axioms*, Andrea Tettamanzi, UNS.

PhD in progress: **Mahamadou Toure**, *Models and architectures for restricted and local mobile access to the Data Web* , UCA, Fabien Gandon, Moussa Lo (UGB, Senegal).

PhD in progress: **Vorakit Vorakitphan**, *Argumentation and Emotions Emotion Detection with Adaptive Sentiment Analysis*, Elena Cabrio, Serena Villata, UCA.

Internship

Master internship: **ElMahdi Ammari**, GUI builder for WebAudio plugins (WebComponents) developed as part of the WASABI project. Integration into the FAUST IDE.

Master internship: **Antonia Ettorre**, *Modelling and publishing machine-processable curated biodiversity data*, UCA, Franck Michel, Catherine Faron Zucker.

Bachelor internship: **Matthis Lequiniou**, *Applying and comparing state-of-the-art algorithms to predict student's success on the SIDES knowledge graph*, UCA, Catherine Faron Zucker, Oscar Rodríguez Rocha.

Master internship: **Zineb Rahhali**, Machine learning to associate songs with presets of instruments and audio effects encoded in WebAudio.

Master internship: **Yun Tian**, *LinkedDataViz - Visualisation de données sur les co-publications scientifiques à partir de l'application HAL RDF*, Olivier Corby & Marco Winckler (I3S).

Master internship: **Maroua Tikat**, Development of ontologies to describe the WASABI corpus

10.2.3. Juries

Michel Buffa:

Reviewer of Pasquale LISENA PhD : "Recommandation musicale basée sur la connaissance : modèles, algorithmes et recherche exploratoire", defended October 11th, 2019, EURECOM – Sophia Antipolis

Elena Cabrio:
Reviewer and member of the PhD committee of Marco Rovera, University of Turin (Italy), July 2019.
Member of the PhD committee of Yaroslav Nechaev, University of Trento (Italy), April 2019.

Catherine Faron Zucker:

- reviewer of Cassia Trojahn's HDR, entitled *Towards ontology matching maturity: contributions to complex, holistic and foundational ontology matching*, defended on December 12 at Université de Toulouse;
- reviewer of Justine Reynaud's PhD thesis, entitled *Découverte de définitions dans le web des données*, defended on December 10 at Université de Lorraine;
- reviewer of Alexis Lebis' PhD thesis, entitled *Capitaliser les processus d'analyse de traces d'apprentissage : modélisation ontologique & assistance à la réutilisation*, defended on May 22 at Sorbonne Universités;
- reviewer of Tanguy Raynaud's PhD thesis, entitled *Génération de Questions à Choix Multiples Thématiques à Partir de Bases de Connaissances*, defended on February 28 at Université Jean Monnet;
- reviewer of Ademar Crotti Junior's PhD thesis, entitled *A Jigsaw Puzzle Metaphor for Representing Linked Data Mappings*, defended on February 25 at University of Dublin, Ireland;
- external member of the monitoring committee of Stella Zevio's PhD thesis at Université Paris Nord;
- external member of the monitoring committee of Francesco Bariatti's PhD thesis at Université de Rennes;
- external member of the monitoring committee of Pauline Folz's PhD thesis at Université de Rennes.

Fabien Gandon:

- Reviewer HDR Fatiha Sais, entitled *Knowledge Graph Refinement: Link Detection, Link Invalidation, Key Discovery and Data Enrichment*" 20/06/2019
- Member jury HDR Clément Jonquet, Ontology Repository and Ontology-based Services, 26/05/2019

Andrea Tettamanzi was reviewer of the HDR thesis of Nathalie Hernandez, *La centralité des ontologies, du Web Sémantique des utilisateurs au Web Sémantique des objets*, Université de Toulouse 2, December 13, 2019.

10.3. Popularization

10.3.1. Education

Artificial Intelligence training course for high school teachers (Inria Sophia Antipolis) - "Qu'est-ce que l'IA ?" by Jérôme Delobelle.

10.3.2. Interventions

Science Festival ("Fête de la Science") 2019, presentation of the WASABI project by Michel Buffa during "Journées Science et Musique" organized by IRISA in Rennes, October 2019.

10.3.3. Internal action

Presentation of Artificial Intelligence to college students by Jérôme Delobelle during their week-long visit to Inria Sophia Antipolis.

11. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journal

[1] S. BASSO, A. CESELLI, A. G. B. TETTAMANZI.*Random sampling and machine learning to understand good decompositions*, in "Annals of Operations Research", 2020, vol. 284, n^o^ 2, p. 501-526 [*DOI :* 10.1007/S10479-018-3067-9], https://hal.inria.fr/hal-02319521

[2] Q. CHEN, P. TORRONI, S. VILLATA.*Principles and practice of multi-agent systems*, in "Knowledge Engineering Review", 2019, vol. 34 [*DOI :* 10.1017/S0269888918000243], https://hal.archives-ouvertes.fr/hal-02381163

[3] B. LIAO, N. OREN, L. VAN DER TORRE, S. VILLATA.*Prioritized norms in formal argumentation*, in "Journal of Logic and Computation", March 2019, vol. 29, n^o^ 2, p. 215-240 [*DOI :* 10.1093/LOGCOM/EXY009], https://hal.archives-ouvertes.fr/hal-02381116

[4] L. ROBALDO, S. VILLATA, A. WYNER, M. GRABMAIR.*Introduction for artificial intelligence and law: special issue "natural language processing for legal texts"*, in "Artificial Intelligence and Law", June 2019, vol. 27, n^o^ 2, p. 113-115 [*DOI :* 10.1007/S10506-019-09251-2], https://hal.archives-ouvertes.fr/hal-02381156

[5] G. ROCHER, J.-Y. TIGLI, S. LAVIROTTE, N. LE THANH.*Effectiveness assessment of Cyber-Physical Systems*, in "International Journal of Approximate Reasoning", 2020, vol. 118, p. 112-132 [*DOI :* 10.1016/J.IJAR.2019.12.002], https://hal.archives-ouvertes.fr/hal-02441654

[6] A. VENERANDI, G. FUSCO, A. G. B. TETTAMANZI, D. EMSELLEM.*A Machine Learning Approach to Study the Relationship between Features of the Urban Environment and Street Value*, in "Urban Science", September 2019, vol. 3, n^o^ 3, 100 [*DOI :* 10.3390/URBANSCI3030100], https://hal.inria.fr/hal-02319539

International Conferences with Proceedings

[7] P. ARSLAN, M. CORAZZA, E. CABRIO, S. VILLATA.*Overwhelmed by Negative Emotions? Maybe You Are Being Cyber-bullied!*, in "SAC 2019 - The 34th ACM/SIGAPP Symposium On Applied Computing", Limassol, Cyprus, April 2019 [*DOI :* 10.1145/3297280.3297573], https://hal.archives-ouvertes.fr/hal-02020829

[8] S. BIENZ, A. CIORTEA, S. MAYER, F. GANDON, O. CORBY.*Escaping the Streetlight Effect: Semantic Hypermedia Search Enhances Autonomous Behavior in the Web of Things*, in "IoT 2019 - 9th International Conference on the Internet of Things", Bilbao, Spain, October 2019 [*DOI :* 10.1145/1122445.1122456], https://hal.inria.fr/hal-02289497

[9] C. Cardellino, L. Alonso Alemany, M. Teruel, S. Villata, S. Marro.*Convolutional Ladder Networks for Legal NERC and the Impact of Unsupervised Data in Better Generalizations*, in "FLAIRS 2019 - 32th International Florida Artificial Intelligence Research Society Conference", Sarasota, United States, May 2019, https://hal.archives-ouvertes.fr/hal-02381093

[10] A. Ciortea, S. Mayer, F. Gandon, O. Boissier, A. Ricci, A. Zimmermann.*A Decade in Hindsight: The Missing Bridge Between Multi-Agent Systems and the World Wide Web*, in "AAMAS 2019 - 18th International Conference on Autonomous Agents and Multiagent Systems", Montréal, Canada, 2019, 5, https://hal-emse.ccsd.cnrs.fr/emse-02070625

[11] M. Corazza, S. Menini, E. Cabrio, S. Tonelli, S. Villata.*Cross-Platform Evaluation for Italian Hate Speech Detection*, in "CLiC-it 2019 - 6th Annual Conference of the Italian Association for Computational Linguistics", Bari, Italy, November 2019, https://hal.archives-ouvertes.fr/hal-02381152

[12] A. H. C. Correia, F. Lecue.*Human-in-the-Loop Feature Selection*, in "AAAI 2019 Conference - 33th Association for the Advancement of Artificial Intelligence", Honolulu, United States, January 2019, https://hal.inria.fr/hal-01934916

[13] J. Delobelle, S. Villata.*Interpretability of Gradual Semantics in Abstract Argumentation*, in "ECSQARU 2019 - 15th European Conference on Symbolic and Quantitative Approaches to Reasoning with Uncertainty", Belgrade, Serbia, September 2019, https://hal.archives-ouvertes.fr/hal-02277678

[14] A. E. A. Djebri, A. G. B. Tettamanzi, F. Gandon.*Linking and Negotiating Uncertainty Theories Over Linked Data*, in "WWW 2019 - LDOW/LDDL Workshop of the World Wide Web Conference", San Francisco, United States, 2019 [*DOI :* 10.1145/3308560.3317074], https://hal.archives-ouvertes.fr/hal-02064075

[15] A. E. A. Djebri, A. G. B. Tettamanzi, F. Gandon.*Publishing Uncertainty on the Semantic Web: Blurring the LOD Bubbles*, in "ICCS 2019 - 24th International Conference on Conceptual Structures", Marburg, Germany, June 2019, p. 42-56 [*DOI :* 10.1007/978-3-030-23182-8_4], https://hal.inria.fr/hal-02167174

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[17] M. Fell, E. Cabrio, F. Gandon, A. Giboin.*Song Lyrics Summarization Inspired by Audio Thumbnailing*, in "RANLP 2019 - Recent Advances in Natural Language Processing", Varna, Bulgaria, September 2019, https://hal.archives-ouvertes.fr/hal-02281138

[18] J. Frau, M. Teruel, L. Alonso Alemany, S. Villata.*Different Flavors of Attention Networks for Argument Mining*, in "FLAIRS 2019 - 32th International Florida Artificial Intelligence Research Society Conference", Sarasota, United States, May 2019, https://hal.archives-ouvertes.fr/hal-02381078

[19] R. Gazzotti, C. Faron Zucker, F. Gandon, V. Lacroix-Hugues, D. Darmon.*Injecting Domain Knowledge in Electronic Medical Records to Improve Hospitalization Prediction*, in "ESWC 2019 - 16th Extended Semantic Web Conference", Portorož, Slovenia, Lecture Notes in Computer Science, May 2019, vol. 11503, p. 116–130 [*DOI :* 10.1007/978-3-030-21348-0_8], https://hal.archives-ouvertes.fr/hal-02064421

[20] R. GAZZOTTI, C. FARON ZUCKER, F. GANDON, V. LACROIX-HUGUES, D. DARMON.*Injection of Automatically Selected DBpedia Subjects in Electronic Medical Records to boost Hospitalization Prediction*, in "SAC2020 - The 35th ACM/SIGAPP Symposium On Applied Computing", Brno, Czech Republic, March 2020 [*DOI :* 10.1145/3341105.3373932], https://hal.archives-ouvertes.fr/hal-02389918

[21] G. GOVERNATORI, A. ROTOLO, R. RIVERET, S. VILLATA.*Modelling Dialogues for Optimal Legislation*, in "ICAIL 2019 - 17th International Conference on Artificial Intelligence and Law", Montreal, Canada, ACM Press, June 2019, p. 229-233 [*DOI :* 10.1145/3322640.3326731], https://hal.archives-ouvertes.fr/hal-02381105

[22] S. HADDADAN, E. CABRIO, S. VILLATA.*DISPUTool – A tool for the Argumentative Analysis of Political Debates*, in "IJCAI 19 - 28th International Joint Conference on Artificial Intelligence", Macao, Macau SAR China, International Joint Conferences on Artificial Intelligence Organization, August 2019, p. 6524-6526 [*DOI :* 10.24963/IJCAI.2019/944], https://hal.inria.fr/hal-02381055

[23] S. HADDADAN, E. CABRIO, S. VILLATA.*Yes, we can! Mining Arguments in 50 Years of US Presidential Campaign Debates*, in "ACL 2019 - 57th Annual Meeting of the Association for Computational Linguistics", Florence, Italy, July 2019, 7, https://hal.inria.fr/hal-02194887

[24] *Best Paper*
H. HUANG, F. GANDON.*Learning URI Selection Criteria to Improve the Crawling of Linked Open Data*, in "ESWC2019 - 16th Extended Semantic Web Conference", Portoroz, Slovenia, June 2019, https://hal.inria.fr/hal-02073854.

[25] P. MARTIN, O. CORBY, C. FARON ZUCKER.*Ontology Design Rules Based On Comparability Via Particular Relations*, in "SEMANTiCS 2019 - European conference on Semantic Technologies and AI", Karlsruhe, Germany, September 2019, https://hal.inria.fr/hal-02279726

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Project-Team ZENITH

Scientific Data Management

IN COLLABORATION WITH: Laboratoire d'informatique, de robotique et de microélectronique de Montpellier (LIRMM)

IN PARTNERSHIP WITH:
CNRS

Université de Montpellier

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Data and Knowledge Representation and Processing

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2. Overall Objectives

2.1. Overall Objectives

Data-intensive science such as agronomy, astronomy, biology and environmental science must deal with overwhelming amounts of experimental data, as produced through empirical observation and simulation. Similarly, digital humanities are faced for decades with the problem of exploiting vast amounts of digitized cultural and historical data, such as broadcasted radio or TV content. Such data must be processed (cleaned, transformed, analyzed) in order to draw new conclusions, prove scientific theories and eventually produce knowledge. However, constant progress in scientific observational instruments (e.g. satellites, sensors, large hadron collider), simulation tools (that foster in silico experimentation) or digitization of new content by archivists create a huge data overload. For example, climate modeling data has hundreds of exabytes.

Scientific data is very complex, in particular because of the heterogeneous methods, the uncertainty of the captured data, the inherently multiscale nature (spatial, temporal) of many sciences and the growing use of imaging (e.g. molecular imaging), resulting in data with hundreds of dimensions (attibutes, features, etc.). Modern science research is also highly collaborative, involving scientists from different disciplines (e.g. biologists, soil scientists, and geologists working on an environmental project), in some cases from different organizations in different countries. Each discipline or organization tends to produce and manage its own data, in specific formats, with its own processes. Thus, integrating such distributed data gets difficult as the amounts of heterogeneous data grow. Finally, a major difficulty is to interpret scientific data. Unlike web data, e.g. web page keywords or user recommendations, which regular users can understand, making sense out of scientific data requires high expertise in the scientific domain. And interpretation errors can have highly negative consequences, e.g. deploying an oil driller under water at a wrong position.

Despite the variety of scientific data, we can identify common features: big data; manipulated through workflows; typically complex, e.g. multidimensional; with uncertainty in the data values, e.g., to reflect data capture or observation; important metadata about experiments and their provenance; and mostly append-only (with rare updates).

The three main challenges of scientific data management can be summarized by: (1) scale (big data, big applications); (2) complexity (uncertain, high-dimensional data), (3) heterogeneity (in particular, data semantics heterogeneity). These challenges are also those of data science, with the goal of making sense out of data by combining data management, machine learning, statistics and other disciplines. The overall goal of Zenith is to address these challenges, by proposing innovative solutions with significant advantages in terms of scalability, functionality, ease of use, and performance. To produce generic results, we strive to develop architectures, models and algorithms that can be implemented as components or services in specific computing environments, e.g. the cloud. We design and validate our solutions by working closely with our scientific partners in Montpellier such as CIRAD, INRA and IRD, which provide the scientific expertise to interpret the data. To further validate our solutions and extend the scope of our results, we also foster industrial collaborations, even in non scientific applications, provided that they exhibit similar challenges.

Our approach is to capitalize on the principles of distributed and parallel data management. In particular, we exploit: high-level languages as the basis for data independence and automatic optimization; declarative languages to manipulate data and workflows; and highly distributed and parallel environments such as cluster and cloud for scalability and performance. We also exploit machine learning, probabilities and statistics for high-dimensional data processing, data analytics and data search.

3. Research Program

3.1. Distributed Data Management

Data management is concerned with the storage, organization, retrieval and manipulation of data of all kinds, from small and simple to very large and complex. It has become a major domain of computer science, with a large international research community and a strong industry. Continuous technology transfer from research to industry has led to the development of powerful DBMS, now at the heart of any information system, and of advanced data management capabilities in many kinds of software products (search engines, application servers, document systems, etc.).

To deal with the massive scale of scientific data, we exploit large-scale distributed systems, with the objective of making distribution transparent to the users and applications. Thus, we capitalize on the principles of large-scale distributed systems such as clusters, peer-to-peer (P2P) and cloud.

Data management in distributed systems has been traditionally achieved by distributed database systems which enable users to transparently access and update several databases in a network using a high-level query language (e.g. SQL). Transparency is achieved through a global schema which hides the local databases' heterogeneity. In its simplest form, a distributed database system supports a global schema and implements distributed database techniques (query processing, transaction management, consistency management, etc.). This approach has proved to be effective for applications that can benefit from centralized control and full-fledge database capabilities, e.g. information systems. However, it cannot scale up to more than tens of databases.

Parallel database systems extend the distributed database approach to improve performance (transaction throughput or query response time) by exploiting database partitioning using a multiprocessor or cluster system. Although data integration systems and parallel database systems can scale up to hundreds of data sources or database partitions, they still rely on a centralized global schema and strong assumptions about the network.

In contrast, peer-to-peer (P2P) systems adopt a completely decentralized approach to data sharing. By distributing data storage and processing across autonomous peers in the network, they can scale without the need for powerful servers. P2P systems typically have millions of users sharing petabytes of data over the Internet. Although very useful, these systems are quite simple (e.g. file sharing), support limited functions (e.g. keyword search) and use simple techniques (e.g. resource location by flooding) which have performance problems. A P2P solution is well-suited to support the collaborative nature of scientific applications as it provides scalability, dynamicity, autonomy and decentralized control. Peers can be the participants or organizations involved in collaboration and may share data and applications while keeping full control over their (local) data sources. But for very-large scale scientific data analysis, we believe cloud computing (see next section), is the right approach as it can provide virtually infinite computing, storage and networking resources. However, current cloud architectures are proprietary, ad-hoc, and may deprive users of the control of their own data. Thus, we postulate that a hybrid P2P/cloud architecture is more appropriate for scientific data management, by combining the best of both approaches. In particular, it will enable the clean integration of the users' own computational resources with different clouds.

3.2. Big Data

Big data (like its relative, data science) has become a buzz word, with different meanings depending on your perspective, e.g. 100 terabytes is big for a transaction processing system, but small for a web search engine. It is also a moving target, as shown by two landmarks in DBMS products: the Teradata database machine in the 1980's and the Oracle Exadata database machine in 2010.

Although big data has been around for a long time, it is now more important than ever. We can see overwhelming amounts of data generated by all kinds of devices, networks and programs, e.g. sensors, mobile devices, connected objects (IoT), social networks, computer simulations, satellites, radiotelescopes, etc. Storage capacity has doubled every 3 years since 1980 with prices steadily going down (e.g. 1 Gigabyte of Hard Disk Drive for: 1M$ in 1982, 1K$ in 1995, 0.02$ in 2015), making it affordable to keep more data around. And massive data can produce high-value information and knowledge, which is critical for data analysis, decision support, forecasting, business intelligence, research, (data-intensive) science, etc.

The problem of big data has three main dimensions, quoted as the three big V's:

- Volume: refers to massive amounts of data, making it hard to store, manage, and analyze (big analytics);
- Velocity: refers to continuous data streams being produced, making it hard to perform online processing and analysis;
- Variety: refers to different data formats, different semantics, uncertain data, multiscale data, etc., making it hard to integrate and analyze.

There are also other V's such as: validity (is the data correct and accurate?); veracity (are the results meaningful?); volatility (how long do you need to store this data?).

Many different big data management solutions have been designed, primarily for the cloud, as cloud and big data are synergistic. They typically trade consistency for scalability, simplicity and flexibility, hence the new term Data-Intensive Scalable Computing (DISC). Examples of DISC systems include data processing frameworks (e.g. Hadoop MapReduce, Apache Spark, Pregel), file systems (e.g. Google GFS, HDFS), NoSQL systems (Google BigTable, Hbase, MongoDB), NewSQL systems (Google F1, CockroachDB, LeanXcale). In Zenith, we exploit or extend DISC technologies to fit our needs for scientific workflow management and scalable data analysis.

3.3. Data Integration

Scientists can rely on web tools to quickly share their data and/or knowledge. Therefore, when performing a given study, a scientist would typically need to access and integrate data from many data sources (including public databases). Data integration can be either physical or logical. In the former, the source data are integrated and materialized in a data warehouse. In logical integration, the integrated data are not materialized, but accessed indirectly through a global (or mediated) schema using a data integration system. These two approaches have different trade-offs, e.g. efficient analytics but only on historical data for data warehousing versus real-time access to data sources for data integration systems (e.g. web price comparators).

In both cases, to understand a data source content, metadata (data that describe the data) is crucial. Metadata can be initially provided by the data publisher to describe the data structure (e.g. schema), data semantics based on ontologies (that provide a formal representation of the domain knowledge) and other useful information about data provenance (publisher, tools, methods, etc.). Scientific metadata is very heterogeneous, in particular because of the autonomy of the underlying data sources, which leads to a large variety of models and formats. Thus, it is necessary to identify semantic correspondences between the metadata of the related data sources. This requires the matching of the heterogeneous metadata, by discovering semantic correspondences between ontologies, and the annotation of data sources using ontologies. In Zenith, we rely on semantic web techniques (e.g. RDF and SparkQL) to perform these tasks and deal with high numbers of data sources.

Scientific workflow management systems (SWfMS) are also useful for data integration. They allow scientists to describe and execute complex scientific activities, by automating data derivation processes, and supporting various functions such as provenance management, queries, reuse, etc. Some workflow activities may access or produce huge amounts of distributed data. This requires using distributed and parallel execution environments. However, existing workflow management systems have limited support for data parallelism. In Zenith, we use an algebraic approach to describe data-intensive workflows and exploit parallelism.

3.4. Data Analytics

Data analytics refers to a set of techniques to draw conclusions through data examination. It involves data mining, statistics, and data management, and is applied to categorical and continuous data. In the Zenith team, we are interested in both of these data types. Categorical data designates a set of data that can be described as “check boxes”. It can be names, products, items, towns, etc. A common illustration is the market basket data, where each item bought by a client is recorded and the set of items is the basket. The typical data mining problems with this kind of data are:

- **Frequent itemsets and association rules**. In this case, the data is usually a table with a high number of rows and the data mining algorithm extracts correlations between column values. A typical example of frequent itemset from a sensor network in a smart building would say that “in 20% rooms, the door is closed, the room is empty, and lights are on.”
- **Frequent sequential pattern extraction.** This problem is very similar to frequent itemset discovery but considering the order between. In the smart building example, a frequent sequence could say that “in 40% of rooms, lights are on at time i, the room is empty at time $i + j$ and the door is closed at time $i + j + k$”.
- **Clustering**. The goal of clustering is to group together similar data while ensuring that dissimilar data will not be in the same cluster. In our example of smart buildings, we could find clusters of rooms, where offices will be in one category and copy machine rooms in another because of their differences (hours of people presence, number of times lights are turned on/off, etc.).

Continuous data are numeric records that can have an infinite number of values between any two values. A temperature value or a timestamp are examples of such data. They are involved in a widely used type of data known as time series: a series of values, ordered by time, and giving a measure, e.g. coming from a sensor. There is a large number of problems that can apply to this kind of data, including:

- **Indexing and retrieval.** The goal, here, is usually to find, given a query q and a time series dataset D, the records of D that are most similar to q. This may involve any transformation of D by means of an index or an alternative representation for faster execution.
- **Pattern and outlier detection.** The discovery of recurrent patterns or atypical sub-windows in a time series has applications in finance, industrial manufacture or seismology, to name a few. It calls for techniques that avoid pairwise comparisons of all the sub-windows, which would lead to prohibitive response times.
- **Clustering**. The goal is the same as categorical data clustering: group similar time series and separate dissimilar ones.

One main problem in data analytics is to deal with data streams. Existing methods have been designed for very large data sets where complex algorithms from artificial intelligence were not efficient because of data size. However, we now must deal with data streams, sequences of data events arriving at high rate, where traditional data analytics techniques cannot complete in real-time, given the infinite data size. In order to extract knowledge from data streams, the data mining community has investigated approximation methods that could yield good result quality.

3.5. High dimensional data processing and search

High dimensionality is inherent in applications involving images, audio and text as well as in many scientific applications involving raster data or high-throughput data. Because of the *dimensionality curse*, technologies for processing and analyzing such data cannot rely on traditional relational DBMS or data mining methods. It rather requires to employ machine learning methods such as dimensionality reduction, representation learning or random projection. The activity of Zenith in this domain focuses on methods that permit data processing and search at scale, in particular in the presence of strong uncertainty and/or ambiguity. Actually, while small datasets are often characterized by a careful collection process, massive amounts of data often come with outliers and spurrious items, because it appears impossible to guarantee faultless collection at massive bandwidth. Another source of noise is often the sensor itself, that may be of low quality but of high sampling rate, or even the actual content, e.g. in cultural heritage applications when historical content appears seriously damaged by time. To attack these difficult problems, we focus on the following research topics:

- **Uncertainty estimation**. Items in massive datasets may either be uncertain, e.g. for automatically annotated data as in image analysis, or be more or less severely corrupted by noise, e.g. in noisy audio recordings or in the presence of faulty sensors. In both cases, the concept of *uncertainty* is central for the end-user to exploit the content. In this context, we use probability theory to quantify uncertainty and propose machine learning algorithms that may operate robustly, or at least assess the quality of their output. This vast topic of research is guided by large-scale applications (both data search and data denoising), and our research is oriented towards computationally effective methods.
- **Deep neural networks**. A major breakthrough in machine learning performance has been the advent of deep neural networks, which are characterized by high numbers (millions) of parameters and scalable learning procedures. We are striving towards original architectures and methods that are theoretically grounded and offer state-of-the-art performance for data search and processing. The specific challenges we investigate are: very high dimensionality for static data and very long-term dependency for temporal data, both in the case of possibly strong uncertainty or ambiguity (e.g. hundreds of thousands of classes).
- **Community service**. Research in machine learning is guided by applications. In Zenith, two main communities are targeted: botany, and digital humanities. In both cases, our observation is that significant breakthroughs may be achieved by connecting these communities to machine learning

researchers. This may be achieved through wording application-specific problems in classical machine learning parlance. Thus, the team is actively involved in the organization of international evaluation campaigns that allow machine learning researchers to propose new methods while solving important application problems.

4. Application Domains

4.1. Data-intensive Scientific Applications

The application domains covered by Zenith are very wide and diverse, as they concern data-intensive scientific applications, i.e., most scientific applications. Since the interaction with scientists is crucial to identify and tackle data management problems, we are dealing primarily with application domains for which Montpellier has an excellent track record, i.e., agronomy, environmental science, life science, with scientific partners like INRA, IRD and CIRAD. However, we are also addressing other scientific domains (e.g. astronomy, oil extraction, music processing) through our international collaborations.

Let us briefly illustrate some representative examples of scientific applications on which we have been working on.

- **Management of astronomical catalogs**. An example of data-intensive scientific applications is the management of astronomical catalogs generated by the Dark Energy Survey (DES) project on which we are collaborating with researchers from Brazil. In this project, huge tables with billions of tuples and hundreds of attributes (corresponding to dimensions, mainly double precision real numbers) store the collected sky data. Data are appended to the catalog database as new observations are performed and the resulting database size has hundres of TB. Scientists around the globe can query the database with queries that may contain a considerable number of attributes. The volume of data that this application holds poses important challenges for data management. In particular, efficient solutions are needed to partition and distribute the data in several servers. An efficient partitioning scheme should try to minimize the number of fragments accessed in the execution of a query, thus reducing the overhead associated to handle the distributed execution.
- **Personal health data analysis and privacy** Today, it is possible to acquire data on many domains related to personal data. For instance, one can collect data on her daily activities, habits or health. It is also possible to measure performance in sports. This can be done thanks to sensors, communicating devices or even connected glasses. Such data, once acquired, can lead to valuable knowledge for these domains. For people having a specific disease, it might be important to know if they belong to a specific category that needs particular care. For an individual, it can be interesting to find a category that corresponds to her performances in a specific sport and then adapt her training with an adequate program. Meanwhile, for privacy reasons, people will be reluctant to share their personal data and make them public. Therefore, it is important to provide them with solutions that can extract such knowledge from everybody's data, while guaranteeing that their private data won't be disclosed to anyone.
- **Botanical data sharing**. Botanical data is highly decentralized and heterogeneous. Each actor has its own expertise domain, hosts its own data, and describes them in a specific format. Furthermore, botanical data is complex. A single plant's observation might include many structured and unstructured tags, several images of different organs, some empirical measurements and a few other contextual data (time, location, author, etc.). A noticeable consequence is that simply identifying plant species is often a very difficult task; even for the botanists themselves (the so-called taxonomic gap). Botanical data sharing should thus speed up the integration of raw observation data, while providing users an easy and efficient access to integrated data. This requires to deal with social-based data integration and sharing, massive data analysis and scalable content-based information retrieval. We address this application in the context of the French initiative Pl@ntNet, with CIRAD and IRD.
- **Biological data integration and analysis**.

Biology and its applications, from medicine to agronomy and ecology, are now producing massive data, which is revolutionizing the way life scientists work. For instance, using plant phenotyping platforms such as PhenoDyn and PhenoArch at INRA Montpellier, quantitative genetic methods allow to identify genes involved in phenotypic variation in response to environmental conditions. These methods produce large amounts of data at different time intervals (minutes to months), at different sites and at different scales ranging from small tissue samples to the entire plant until whole plant population. Analyzing such big data creates new challenges for data management and data integration.

- **Audio heritage preservation**.

  Since the end of the 19^{th} century, France has commissioned ethnologists to record the world's immaterial audio heritage. This results in datasets of dozens of thousands of audio recordings from all countries and more than 1200 ethnies. Today, this data is gathered under the name of 'Archives du CNRS — Musée de l'Homme' and is handled by the CREM (Centre de Recherche en Ethno-Musicologie). Profesional scientists in digital humanities are accessing this data daily for their investigations, and several important challenges arise to ease their work. The KAMoulox project, lead by A. Liutkus, targets at offering online processing tools for the scientists to automatically restore this old material on demand.

These application examples illustrate the diversity of requirements and issues which we are addressing with our scientific application partners. To further validate our solutions and extend the scope of our results, we also want to foster industrial collaborations, even in non scientific applications, provided that they exhibit similar challenges.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

- Antoine Liutkus and Fabian Stoter won the second place at the Global Pytorch Summer Hackaton 2019 organized by FaceBook with the open-unmix software.
- Antoine Liutkus obtained the *Outstanding Reviewer Award* from IEEE.
- Vitor Silva obtained the *best PhD thesis award* from SBBD.

5.1.2. Software

The Pl@ntNet mobile application reached its ten million downloads.

6. New Software and Platforms

6.1. Pl@ntNet

KEYWORDS: Plant identification - Deep learning - Citizen science

FUNCTIONAL DESCRIPTION: Pl@ntNet is a participatory platform and information system dedicated to the production of botanical data through deep learning-based plant identification. It includes 3 main front-ends, an Android app (the most advanced and the most used one), an iOs app (being currently re-developed) and a web version. The main feature of the application is to return the ranked list of the most likely species providing an image or an image set of an individual plant. In addition, Pl@ntNet's search engine returns the images of the dataset that are the most similar to the queried observation allowing interactive validation by the users. The back-office running on the server side of the platform is based on Snoop visual search engine (a software developed by ZENITH) and on NewSQL technologies for the data management. The application is distributed in more than 180 countries (10M downloads) and allows identifying about 20K plant species at present time.

- Participants: Antoine Affouard, Jean-Christophe Lombardo, Pierre Bonnet, Hervé Goëau, Mathias Chouet and Julien Champ
- Contact: Alexis Joly
- Publication: Pl@ntNet app in the era of deep learning

6.2. ThePlantGame

KEYWORD: Crowd-sourcing

FUNCTIONAL DESCRIPTION: ThePlantGame is a participatory game whose purpose is the production of big taxonomic data to improve our knowledge of biodiversity. One major contribution is the active training of the users based on innovative sub-task creation and assignment processes that are adaptive to the increasing skills of the user. Thousands of players are registered and produce on average about tens new validated plant observations per day. The accuracy of the produced taxonnomic tags is very high (about 95%), which is quite impressive considering the fact that a majority of users are beginners when they start playing.

- Participants: Maximilien Servajean and Alexis Joly
- Contact: Alexis Joly
- Publication: Crowdsourcing Thousands of Specialized Labels: A Bayesian Active Training Approach

6.3. Chiaroscuro

KEYWORDS: Privacy - P2P - Data mining

FUNCTIONAL DESCRIPTION: Chiaroscuro is a complete solution for clustering personal data with strong privacy guarantees. The execution sequence produced by Chiaroscuro is massively distributed on personal devices, coping with arbitrary connections and disconnections. Chiaroscuro builds on our novel data structure, called Diptych, which allows the participating devices to collaborate privately by combining encryption with differential privacy. Our solution yields a high clustering quality while minimizing the impact of the differentially private perturbation.

- Participants: Tristan Allard, Georges Hebrail, Florent Masseglia and Esther Pacitti
- Contact: Florent Masseglia
- Publication: Chiaroscuro: Transparency and Privacy for Massive Personal Time-Series Clustering

6.4. DfAnalyzer

Dataflow Analysis

KEYWORDS: Data management - Monitoring - Runtime Analysis

FUNCTIONAL DESCRIPTION: DfAnalyzer is a tool for monitoring, debugging, steering, and analysis of dataflows while being generated by scientific applications. It works by capturing strategic domain data, registering provenance and execution data to enable queries at runtime. DfAnalyzer provides lightweight dataflow monitoring components to be invoked by high performance applications. It can be plugged in scripts, or Spark applications, in the same way users already plug visualization library components.

- Participants: Vitor Sousa Silva, Daniel De Oliveira, Marta Mattoso and Patrick Valduriez
- Partners: COPPE/UFRJ - Uff
- Contact: Patrick Valduriez
- Publication: DfAnalyzer: Runtime Dataflow Analysis of Scientific Applications using Provenance
- URL: https://github.com/vssousa/dfanalyzer-spark

6.5. CloudMdsQL Compiler

KEYWORDS: Optimizing compiler - NoSQL - Data integration

FUNCTIONAL DESCRIPTION: The CloudMdsQL (Cloud Multi-datastore Query Language) polystore transforms queries expressed in a common SQL-like query language into an optimized query execution plan to be executed over multiple cloud data stores (SQL, NoSQL, HDFS, etc.) through a query engine. The compiler/optimizer is implemented in C++ and uses the Boost.Spirit framework for parsing context-free grammars. CloudMdsQL has been validated on relational, document and graph data stores in the context of the CoherentPaaS European project.

- Participants: Boyan Kolev, Oleksandra Levchenko and Patrick Valduriez
- Contact: Patrick Valduriez
- Publication: CloudMdsQL: Querying Heterogeneous Cloud Data Stores with a Common Language

6.6. Savime

Simulation And Visualization IN-Memory

KEYWORDS: Data management. - Distributed Data Management

FUNCTIONAL DESCRIPTION: SAVIME is a multi-dimensional array DBMS for scientific applications. It supports a novel data model called TARS (Typed ARray Schema), which extends the basic array data model with typed arrays. In TARS, the support of application dependent data characteristics is provided through the definition of TAR objects, ready to be manipulated by TAR operators. This approach provides much flexibility for capturing internal data layouts through mapping functions, which makes data ingestion independent of how simulation data has been produced, thus minimizing ingestion time.

- Participants: Hermano Lustosa, Fabio Porto and Patrick Valduriez
- Partner: LNCC - Laboratório Nacional de Computação Científica
- Contact: Patrick Valduriez
- Publication: TARS: An Array Model with Rich Semantics for Multidimensional Data

6.7. OpenAlea

KEYWORDS: Bioinformatics - Biology

FUNCTIONAL DESCRIPTION: OpenAlea is an open source project primarily aimed at the plant research community. It is a distributed collaborative effort to develop Python libraries and tools that address the needs of current and future works in Plant Architecture modeling. It includes modules to analyze, visualize and model the functioning and growth of plant architecture. It was formally developed in the Inria VirtualPlants team.

RELEASE FUNCTIONAL DESCRIPTION: OpenAlea 2.0 adds to OpenAlea 1.0 a high-level formalism dedicated to the modeling of morphogenesis that makes it possible to use several modeling paradigms (Blackboard, L-systems, Agents, Branching processes, Cellular Automata) expressed with different languages (Python, L-Py, R, Visual Programming, ...) to analyse and simulate shapes and their development.

- Participants: Christian Fournier, Christophe Godin, Christophe Pradal, Frédéric Boudon, Patrick Valduriez, Esther Pacitti and Yann Guédon
- Partners: CIRAD - INRA
- Contact: Christophe Pradal
- Publications: OpenAlea: Scientific Workflows Combining Data Analysis and Simulation - OpenAlea: A visual programming and component-based software platform for plant modeling

6.8. Triton Server

End-to-end Graph Mapper

KEYWORD: Web Application

FUNCTIONAL DESCRIPTION: A server for managing graph data and applications for mobile social networks. The server is built on top of the OrientDB graph database system and a distributed middleware. It provides an End-to-end Graph Mapper (EGM) for modeling the whole application as (i) a set of graphs representing the business data, the in-memory data structure maintained by the application and the user interface (tree of graphical components), and (ii) a set of standardized mapping operators that maps these graphs with each other.

- Participants: Didier Parigot, Patrick Valduriez and Benjamin Billet
- Contact: Didier Parigot
- Publication: End-to-end Graph Mapper

6.9. museval

KEYWORDS: Source Separation - Metric

SCIENTIFIC DESCRIPTION: museval is a Python package aimed at evaluating audio source separation algorithm on the musdb corpus.

It as a scientific tool of high impact, but of limited transfer importance, since it is only (but widely) used by the community to evaluate performance in scientific publications.

FUNCTIONAL DESCRIPTION: The BSSEval metrics, as implemented in the [MATLAB toolboxes](http://bass-db.gforge.inria.fr/bss_eval/) and their re-implementation in [mir_eval](http://craffel.github.io/mir_eval/#module-mir_eval.separation) are widely used in the audio separation literature. One particularity of BSSEval is to compute the metrics after optimally matching the estimates to the true sources through linear distortion filters. This allows the criteria to be robust to some linear mismatches. Apart from the optional evaluation for all possible permutations of the sources, this matching is the reason for most of the computation cost of BSSEval, especially considering it is done for each evaluation window when the metrics are computed on a framewise basis.

For this package, we enabled the option of having _time invariant_ distortion filters, instead of necessarily taking them as varying over time as done in the previous versions of BSS eval. First, enabling this option _significantly reduces_ the computational cost for evaluation because matching needs to be done only once for the whole signal. Second, it introduces much more dynamics in the evaluation, because time-varying matching filters turn out to over-estimate performance. Third, this makes matching more robust, because true sources are not silent throughout the whole recording, while they often were for short windows.

RELEASE FUNCTIONAL DESCRIPTION: This version makes museval compatible with the latest MUSDB package version

- Participant: Antoine Liutkus
- Contact: Antoine Liutkus
- Publication: The 2018 Signal Separation Evaluation Campaign

6.10. Imitates

Indexing and mining Massive Time Series

KEYWORDS: Time Series - Indexing - Nearest Neighbors

FUNCTIONAL DESCRIPTION: Time series indexing is at the center of many scientific works or business needs. The number and size of the series may well explode depending on the concerned domain. These data are still very difficult to handle and, often, a necessary step to handling them is in their indexing. Imitates is a Spark Library that implements two algorithms developed by Zenith. Both algorithms allow indexing massive amounts of time series (billions of series, several terabytes of data).

- Partners: New York University - Université Paris-Descartes
- Contact: Florent Masseglia
- Publication: ParCorr: efficient parallel methods to identify similar time series pairs across sliding windows

6.11. VersionClimber

KEYWORDS: Software engineering - Deployment - Versionning

FUNCTIONAL DESCRIPTION: VersionClimber is an automated system to help update the package and data infrastructure of a software application based on priorities that the user has indicated (e.g. I care more about having a recent version of this package than that one). The system does a systematic and heuristically efficient exploration (using bounded upward compatibility) of a version search space in a sandbox environment (Virtual Env or conda env), finally delivering a lexicographically maximum configuration based on the user-specified priority order. It works for Linux and Mac OS on the cloud.

- Participants: Christophe Pradal, Dennis Shasha, Sarah Cohen-Boulakia and Patrick Valduriez
- Partners: CIRAD - New York University
- Contact: Christophe Pradal
- Publication: VersionClimber: version upgrades without tears
- URL: https://versionclimber.readthedocs.io/

6.12. UMX

open-unmix

KEYWORDS: Source Separation - Audio

SCIENTIFIC DESCRIPTION: Implements state of the art audio/music source separation with DNNs.

This software is intended to serve as a reference in the domain. It has notably been the object of several scientific communications: 1. An Overview of Lead and Accompaniment Separation in Music https://hal-lirmm.ccsd.cnrs.fr/lirmm-01766781/ 2. Music separation with DNNs: making it work (ISMIR 2018 Tutorial) https://sigsep.github.io/ismir2018_tutorial/index.html#/cover

FUNCTIONAL DESCRIPTION: This software implements audio source separation with deep learning, using pytorch and tensorflow frameworks.

It comprises the code for both training and testing the separation networks, in a flexible manner.

Pre and post-processing around the actual deep neural nets include sophisticated specific multichannel filtering operations.

- Authors: Antoine Liutkus, Fabian Robert Stoter and Emmanuel Vincent
- Contact: Antoine Liutkus
- Publication: An Overview of Lead and Accompaniment Separation in Music

7. New Results

7.1. Scientific Workflows

7.1.1. User Steering in Dynamic Workflows

Participants: Renan Souza, Patrick Valduriez.

In long-lasting scientific workflow executions in HPC machines, computational scientists (users) often need to fine-tune several workflow parameters. These tunings are done through user steering actions that may significantly improve performance or improve the overall results. However, in executions that last for weeks, users can lose track of what has been adapted if the tunings are not properly registered. In [18], we address the problem of tracking online parameter fine-tuning in dynamic workflows steered by users. We propose a lightweight solution to capture and manage provenance of the steering actions online with negligible overhead. The resulting provenance database relates tuning data with data for domain, dataflow provenance, execution, and performance, and is available for analysis at runtime. We show how users may get a detailed view of execution, providing insights to determine when and how to tune. We discuss the applicability of our solution in different domains and validate it with a real workflow in Oil and Gas extraction. In this experiment, the user could determine which tuned parameters influence simulation accuracy and performance. The observed overhead for keeping track of user steering actions at runtime is negligible.

7.1.2. ProvLake: Efficient Runtime Capture of Multiworkflow Data

Participants: Renan Souza, Patrick Valduriez.

Computational Science and Engineering (CSE) projects are typically developed by multidisciplinary teams. Despite being part of the same project, each team manages its own workflows, using specific execution environments and data processing tools. Analyzing the data processed by all workflows globally is critical in a CSE project. However, this is hard because the data generated by these workflows are not integrated. In addition, since these workflows may take a long time to execute, data analysis needs to be done at runtime to reduce cost and time of the CSE project. A typical solution in scientific data analysis is to capture and relate workflow runtime data in a provenance database, thus allowing for runtime data analysis. However, such data capture competes with the running workflows, adding significant overhead to their execution. To solve this problem, we introduce a system called ProvLake [39]. While capturing the data, ProvLake logically integrates and ingests them into a provenance database ready for runtime analysis. We validate ProvLake in a real use case in Oil and Gas extraction with four workflows that process 5 TB datasets for a deep learning classifier. Compared with Komadu, the closest competing solution, our approach has much smaller overhead.

7.1.3. Adaptive Caching of Scientific Workflows in the Cloud

Participants: Gaetan Heidsieck, Christophe Pradal, Esther Pacitti, Patrick Valduriez.

We consider the efficient execution of data-intensive scientific workflows in the cloud. Since it is common for workflow users to reuse other workflows or data generated by other workflows, a promising approach for efficient workflow execution is to cache intermediate data and exploit it to avoid task re-execution. In [27], we propose an adaptive caching solution for data-intensive workflows in the cloud. Our solution is based on a new scientific workflow management architecture that automatically manages the storage and reuse of intermediate data and adapts to the variations in task execution times and output data size. We evaluated our solution by implementing it in the OpenAlea system and performing extensive experiments on real data with a data-intensive application in plant phenotyping. The results show that adaptive caching can yield major performance gains.

7.2. Query Processing

7.2.1. Top-k Query Processing Over Encrypted Data in the Cloud

Participants: Sakina Mahboubi, Reza Akbarinia, Patrick Valduriez.

Cloud computing provides users and companies with powerful capabilities to store and process their data in third-party data centers. However, the privacy of the outsourced data is not guaranteed by the cloud providers. One solution for protecting the user data against security attacks is to encrypt the data before being sent to the cloud servers. Then, the main problem is to evaluate user queries over the encrypted data.

In [12], we propose a system, called SD-TOPK (Secure Distributed TOPK), that encrypts and stores user data in a cloud across a set of nodes, and is able to evaluate top-k queries over the encrypted data. SD-TOPK comes with a novel top-k query processing algorithm that finds a set of encrypted data that is proven to contain the top-k data items. This is done without having to decrypt the data in the nodes where they are stored. In addition, we propose a powerful filtering algorithm that removes the false positives as much as possible without data decryption. We implemented and evaluated the performance of our system over synthetic and real databases. The results show excellent performance for SD-TOPK compared to TA-based approaches.

7.2.2. Parallel Query Rewriting in Key-Value Stores under Single-Key Constraints

Participant: Reza Akbarinia.

Semantic constraints bring important knowledge about the structure and the domain of data. They allow users to better exploit their data thanks to the possibility of formulating high-level queries, which use a vocabulary richer than that of the single sources. However, the constraint-based rewriting of a query may lead to a huge set of new queries, which has a consequent impact on the query answering time.

In [37], we propose a novel technique for parallelizing both the generation and the evaluation of the rewriting set of a query serving as the basis for distributed query evaluation under constraints. Our solution relies on a schema for encoding the possible rewritings of a query on an integer interval. This allows us to generate equi-size partitions of rewritings, and thus to balance the load of the parallel working units that are in charge of generating and evaluating the queries. The experimental evaluation of our technique shows a significant reduction of query rewriting and execution time by means of parallelization.

7.3. Data Analytics

7.3.1. SAVIME: Simulation Data Analysis and Visualization

Participant: Patrick Valduriez.

Limitations in current DBMSs prevent their wide adoption in scientific applications. In order to make scientific applications benefit from DBMS support, enabling declarative data analysis and visualization over scientific data, we present an in-memory array DBMS system called SAVIME. In [34], we describe the system SAVIME, along with its data model. Our preliminary evaluation show how SAVIME, by using a simple storage definition language (SDL) can outperform the state-of-the-art array database system, SciDB, during the process of data ingestion. We also show that it is possible to use SAVIME as a storage alternative for a numerical solver without affecting its scalability.

7.3.2. Massively Distributed Indexing of Time Series

Participants: Djamel Edine Yagoubi, Reza Akbarinia, Boyan Kolev, Oleksandra Levchenko, Florent Masseglia, Patrick Valduriez, Dennis Shasha.

Indexing is crucial for many data mining tasks that rely on efficient and effective similarity query processing. Consequently, indexing large volumes of time series, along with high performance similarity query processing, have became topics of high interest. For many applications across diverse domains though, the amount of data to be processed might be intractable for a single machine, making existing centralized indexing solutions inefficient.

In [20], we propose a parallel solution to construct the state of the art iSAX-based index over billions of time series by making the most of the parallel environment by carefully distributing the work load. Our solution takes advantage of frameworks such as MapReduce or Spark. We provide dedicated strategies and algorithms for a deep combination of parallelism and indexing techniques. We also propose a parallel query processing algorithm that, given a query, exploits the available processing nodes to answer the query in parallel using the constructed parallel index. We implemented our index construction and query processing algorithms, and evaluated their performance over large volumes of data (up to 4 billion time series of length 256, for a total volume of 6 TB). Our experiments demonstrate high performance of our algorithm with an indexing time of less than 2 hours for more than 1 billion time series, while the state of the art centralized algorithm needs more than 5 days. They also illustrate that our approach is able to process 10M queries in less than 140 seconds, while the state of the art centralized algorithm need almost 2300 seconds.

We have implemented our solutions in the Imitates software. The demonstration of Imitates [32] is available at http://imitates.gforge.inria.fr/. The demo visitors are able to choose query time series, see how each algorithm approximates nearest neighbors and compare times in a parallel environment.

7.3.3. Online Correlation Discovery in Sliding Windows of Time Series

Participants: Djamel Edine Yagoubi, Reza Akbarinia, Boyan Kolev, Oleksandra Levchenko, Florent Masseglia, Patrick Valduriez, Dennis Shasha.

In some important applications (such as finance, retail, etc.), we need to find correlated time series in a time window, and then continuously slide this window. Doing this efficiently in parallel could help gather important insights from the data in real time. In [30], we address the problem of continuously finding highly correlated pairs of time series over the most recent time window. Our solution, called ParCorr, uses the sketch principle for representing the time series. We implemented ParCorr on top of UPM-CEP, a Complex Event Processing streaming engine developed by our partner Universitat Politecnica de Madrid. Our solution improves the parallel processing of UPM-CEP, allowing higher throughput using less resources. An interesting aspect of our solution is the discovery of time series that are correlated to a certain subset of time series. The discovered correlations can be used to select features for training a regression model for prediction.

7.3.4. Time Series Clustering via Dirichlet Mixture Models

Participants: Khadidja Meguelati, Florent Masseglia.

Dirichlet Process Mixture (DPM) is a model used for clustering with the advantage of discovering the number of clusters automatically and offering nice properties like, *e.g.*, the potential convergence to the actual clusters in the data. These advantages come at the price of prohibitive response times, which impairs its adoption and makes centralized DPM approaches inefficient. In [35], we propose DC-DPM (Distributed Computing DPM), a parallel clustering solution that gracefully scales to millions of data points while remaining DPM compliant, which is the challenge of distributing this process. In [36], we propose HD4C (High Dimensional Data Distributed Dirichlet Clustering), a parallel clustering solution that addresses the curse of dimensionality by distributed computing and performs clustering of high dimensional data such as time series (as a function of time), hyperspectral data (as a function of wavelength) etc. For both methods, our experiments on synthetic and real world data show high performance.

7.4. Machine Learning for Biodiversity Informatics

7.4.1. Phenological Stage Annotation with Deep Convolutional Neural Networks

Participants: Titouan Lorieul, Herve Goeau, Alexis Joly.

Herbarium based phenological research offers the potential to provide novel insights into plant diversity and ecosystem processes under future climate change. The goal of this study [11], conducted in collaboration with US and French ecologists, is to automate the scoring of reproductive phenological stages within a huge amount of digitized herbaria and provide significant resources for the ecological and organismal scientific communities. Specifically, we address three questions: 1) Can fertility, i.e., the presence of reproductive structures, be automatically detected from digitized specimens using deep learning? 2) Are the detection models generalizable to different herbarium data sets? and 3) Is it possible to automatically record stages (i.e., phenophases) within longer phenological events on herbarium specimens? This is the first time that such an analysis has been conducted at this scale, on such a large number of herbarium specimens and species. The results obtained for 7782 species of plants representing angiosperms, gymnosperms, and ferns suggest that it is possible to consider large-scale phenological annotation across broad phylogenetic groups.

7.4.2. Deep Species Distribution Modelling

Participants: Benjamin Deneu, Christophe Botella, Alexis Joly.

Species distribution models (SDM) are widely used for ecological research and conservation purposes. Given a set of species occurrences and environmental data (such as climatic rasters, soil occupation, altitude, etc.), the aim is to infer the spatial distribution of the species over a given territory. In a previous work, we showed that using deep convolutional networks significantly improved predictive performance compared to conventional punctual approaches. We have deepened this methodology with two main contributions. The first one is to extend the model to explicitly take into account species co-occurrences [22]. This is achieved through a new multimodal architecture that allows the joint learning of biotic and abiotic patterns in a common representation space. The second contribution is to experiment deep SDMs at the scale of several tens of thousands of species and tens of millions of occurrences. These contributions were made possible thanks to the use of supercomputer supercomputer Jean Zay (more than 1000 GPUs) of the GENCI national infrastructure.

7.4.3. Evaluation of Species Identification and Prediction Algorithms

Participants: Alexis Joly, Herve Goeau, Christophe Botella, Benjamin Deneu, Fabian Robert Stoter.

We run a new edition of the LifeCLEF evaluation campaign [29] with the involvement of 16 research teams worldwide. The main outcomes of the 2019-th edition are:

- **GeoLifeCLEF.** The main result of the second edition of this challenge [24] is that deep convolutional models outperform the most efficient machine learning models used in ecology (such as random forests or boosted trees). In particular, they are able to transfer knowledge from animals distribution to plant distribution, which had never been shown before.
- **PlantCLEF.** The 2019-th edition of the plant identification challenge [26] was designed to evaluate automated identification on the flora of data deficient regions, tropical ones in particular. It is based on a dataset of 10K species mainly focused on the Guiana shield and the Northern Amazon rainforest, an area known to have one of the greatest diversity of plants and animals in the world. The results reveal that the identification performance in this context is considerably lower than the one obtained on temperate plants of Europe and North America. The performance of convolutional neural networks fall due to the very low number of training images for most species and the higher degree of noise that is occurring in such data.
- **Bird sounds identification.** The 2019-the edition of the BirdCLEF challenge [41] focuses on the difficult task of recognizing all birds vocalizing in omni-directional soundscape recordings. Therefore, the dataset of the previous year has been extended with more than 350 hours of manually annotated soundscapes that were recorded using 30 field recorders in Ithaca (NY, USA). The main outcome is that the recognition performance can be significantly improved thanks to sophisticated data augmentation methods adapted to the problem.

In addition to organizing these challenges, we published a synthesis of the LifeCLEF evaluation campaign since its inception in 2011. This synthesis [44] is part of a larger book published on the occasion of the 20th anniversary of the CLEF international research forum. It highlights the rapid progress that automatic identification has made over the past decade, and allows us to take a step back on the future challenges of this discipline.

7.4.4. Optimal Checkpointing for Heterogeneous Chains: How to Train Deep Neural Networks with Limited Memory

Participants: Alena Shilova, Alexis Joly.

In many deep learning tasks for biodiversity, limited GPU memory is a performance limiting factor. The use of larger image sizes, in particular, is often not possible because the back-propagation algorithm requires storing all network activation maps in memory during for the backward stage. A larger image size could improve the performance of many tasks such as the analysis of digitized herbarium beds, range modeling or early detection of crop weeds in precision agriculture.

In this work [47], done in collaboration with the REAL-OPT team, we introduce a new activation checkpointing method which allows to significantly decrease memory usage when training Deep Neural Networks with the back-propagation algorithm. Similarly to checkpointing techniques coming from the literature on Automatic Differentiation, it consists in dynamically selecting the forward activations that are saved during the training phase, and then automatically recomputing missing activations from those previously recorded. We propose an original computation model that combines two types of activation savings: either only storing the layer inputs, or recording the complete history of operations that produced the outputs (this uses more memory, but requires fewer recomputations in the backward phase), and we provide an algorithm to compute the optimal computation sequence for this model, when restricted to memory persistent sequences. We provide a PyTorch implementation that processes the entire chain, dealing with any sequential DNN whose internal layers may be arbitrarily complex and automatically executing it according to the optimal checkpointing strategy computed given a memory limit. Through extensive experiments, we show that our implementation consistently outperforms existing checkpointing approaches for a large class of networks, image sizes and batch sizes.

7.5. Machine Learning for Audio Heritage Data

Audio data is typically exploited through large repositories. For instance, music right holders face the challenge of exploiting back catalogues of significant sizes while ethnologists and ethnomusicologists need to browse daily through archives of heritage audio recordings that have been gathered across decades. The originality of our research on this aspect is to bring together our expertise in large volumes and probabilistic music signal processing to build tools and frameworks that are useful whenever audio data is to be processed in large batches. In particular, we leverage on the most recent advances in probabilistic and deep learning applied to signal processing from both academia (e.g. Telecom Paris, PANAMA & Multispeech Inria project-teams, Kyoto University) and industry (e.g. Mitsubishi, Sony), with a focus towards large scale community services.

7.5.1. Setting the State of the Art in Music Demixing

Participants: Fabian-Robert Söter, Antoine Liutkus.

We have been very active in the topic of music demixing, with a prominent role in defining the state of the art in this domain. This has been achieved through several means.

- In the previous years, we have been organizing the Signal Separation Evaluation Challenge (SiSEC), an international event in the signal processing community that is held since 2007. Its objective is to bring together researchers to evaluate their algorithms on music separation/demixing on the same data and with the same metrics. From 2016 to 2019, A. Liutkus was the lead chair of SiSEC.
- We have developed the *open-unmix* [19] software, which is a reference implementation for music source separation. For the first time, it makes it possible for any researcher to use and improve a state-of-the art implementation (MIT-licensed) in the domain. In terms of performance, open-unmix mathes the best results we observed over the years as the organizers of SiSEC. The open-unmix software won the second place at the Global Pytorch Summer Hackaton 2019 organized by FaceBook.

The *pro* private version of this software is currently under active development for transfer to industry.

- In [6], we present the field to the non-specialist researcher, in a wide-audience scientific magazine. We are also core contributors of the audio section for the position paper on the use of AI for the creation industry [48].

7.5.2. Generative Modelling for Audio

Participants: Antoine Liutkus, Fabian-Robert Söter, Mathieu Fontaine.

Discriminative training for audio signal processing is inherently limited in the sense that it boils down to assuming that the target signals are present in the input, and can be recovered through some kind of filtering, even if this involves sophisticated deep models. We move forward to a new paradigm for signal processing, in which the observed signals and time series are not assumed to comprise the totality of the target, but rather some arbitrarily degraded version of it. The objective then can be understood as *generating new content given this input*. For instance, bandwidth extension may be thought of as audio super-resolution.

Our research on generative modelling concerns both methodological/theoretical aspects and applied research. On the former, we introduce the Sliced Wasserstein Flow in our ICML paper [33], which enables the optimal transport of particles from two probability spaces in a principled way. On the latter, we study the combination of heavy-tailed probabilistic models with generative audio models for source separation in [31], [25].

Our strategy is to go beyond our current expertise on music demixing to address the new and very active topics of audio style transfer and enhancement, with large scale applications for the exploitation and repurposing of large audio corpora.

7.5.3. Robust Probabilistic Models for Time-series

Participants: Mathieu Fontaine, Antoine Liutkus, Fabian-Robert Söter.

Processing large amounts of data for denoising or analysis comes with the need to devise models that are robust to outliers and permit efficient inference. For this purpose, we advocate the use of non-Gaussian models for this purpose, which are less sensitive to data-uncertainty. Our contributions on this topic can be split in two parts. First, we develop new filtering methods that go beyond least-squares estimation. In collaboration with researchers from Telecom Paris, we introduce several methods that generalize least-squares Wiener filtering to the case of α-stable processes [2]. This work is currently also under review as a journal paper. Second, as mentioned in the previous section, we have been working on generative models for audio, with the particular twist that the deep models we consider are trained probabilistically under α-stable assumptions. This has the remarkable effect of significantly augmenting robustness [31], [25].

8. Bilateral Contracts and Grants with Industry

8.1. SAFRAN (2018-2019)

Participants: Reza Akbarinia, Florent Masseglia.

SAFRAN and Inria are involved in the DESIR frame-agreement (Florent Masseglia is the scientific contact on "Data Analytics and System Monitoring" topic). In this context, SAFRAN dedicates 80K€ for a joint study of one year on time series indexing. The specific time series to be exploited are those of engine benchmarking with novel characteristics for the team (multiscale and multidimensional).

8.2. INA (2019-2022)

Participants: Quentin Leroy, Alexis Joly.

The PhD of Quentin Leroy is funded in the context of an industrial contract (CIFRE) with INA, the French company in charge of managing the French TV archives and audio-visual heritage. The goal of the PhD is to develop new methods and algorithms for the interactive learning of new classes in INA archives.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. Institut de Convergence Agriculture numérique #DigitAg, (2017-2023), 275Keuro.

Participants: Alexis Joly, Florent Masseglia, Esther Pacitti, Christophe Pradal, Patrick Valduriez.

#DigitAg brings together in a partnership of seventeen actors (public research and teaching organizations, transfer actors and companies) with the objective of accelerating and supporting the development of agriculture companies in France and in southern countries based on new tools, services and uses. Based in Montpellier with an office in Toulouse and Rennes and led by Irstea, #DigitAg's ambition is to become a world reference for digital agriculture. In this project, Zenith is involved in the analysis of big data from agronomy, in particular, plant phenotyping and biodiversity data sharing.

9.1.2. ANR WeedElec (2018-2021), 106 Keuro.

Participants: Julien Champ, Hervé Goëau, Alexis Joly.

The WeedElec project offers an alternative to global chemical weed control. It combines an aerial means of weed detection by drone coupled to an ECOROBOTIX delta arm robot equipped with a high voltage electrical weeding tool. WeedElec's objective is to remove the major related scientific obstacles, in particular the weed detection/identification, using hyperspectral and colour imaging, and associated chemometric and deep learning techniques.

9.1.3. Others

9.1.3.1. Pl@ntNet InriaSOFT consortium, 80 Keuro / year

Participants: Alexis Joly, Jean-Christophe Lombardo, Julien Champ, Hervé Goëau.

This contract between four research organisms (Inria, INRA, IRD and CIRAD) aims at sustaining the Pl@ntNet platform in the long term. It has been signed in November 2019 in the context of the InriaSOFT national program of Inria. Each partner subscribes a subscription of 20K euros per year to cover engineering costs for maintenance and technological developments. In return, each partner has one vote in the steering committee and the technical committee. He can also use the platform in his own projects and benefit from a certain number of service days within the platform. The consortium is not fixed and is not intended to be extended to other members in the coming years.

9.1.3.2. Ministry of Culture, 130 Keuro

Participants: Alexis Joly, Jean-Christophe Lombardo.

Two contracts have been signed with the ministry of culture to adapt, extend and transfer the content-based image retrieval engine of Pl@ntNet ("Snoop") toward two major actors of the French cultural domain: the French National Library (BNF) and the French National institute of audio-visual (INA).

9.1.3.3. INRA/Inria PhD program, 100 Keuro

Participant: Alexis Joly.

This contract between INRA and Inria allows funding a 3-years PhD student (Christophe Botella). The addressed challenge is the large-scale analysis of Pl@ntNet data with the objective to model species distribution (a big data approach to species distribution modeling). The PhD student is supervised by Alexis Joly with François Munoz (ecologist, IRD) and Pascal Monestiez (statistician, INRA).

9.2. European Initiatives

9.2.1. FP7 & H2020 Projects

9.2.1.1. CloudDBAppliance

Participants: Reza Akbarinia, Boyan Kolev, Florent Masseglia, Esther Pacitti, Patrick Valduriez.

Project title: CloudDBAppliance

Instrument: H2020
Duration: 2016 - 2019
Total funding: 5 Meuros (Zenith: 500Keuros)
Coordinator: Bull/Atos, France
Partners: Inria Zenith, U. Madrid, INESC and the companies LeanXcale, QuartetFS, Nordea, BTO, H3G, IKEA, CloudBiz, and Singular Logic.
Inria contact: Florent Masseglia, Patrick Valduriez

The project aims at producing a European Cloud Database Appliance for providing a Database as a Service able to match the predictable performance, robustness and trustworthiness of on premise architectures such as those based on mainframes. In this project, Zenith is in charge of designing and implementing the components for analytics and parallel query processing.

9.2.1.2. Cos4Cloud

Participants: Alexis Joly, Jean-Christophe Lombardo, Antoine Affouard.

Project title: Cos4Cloud
Instrument: H2020
Duration: 2019 - 2022
Total funding: 5 Meuros (Zenith: 400Keuros)
Coordinator: CSIC (Spain)
Partners: The Open University, CREAF, Bineo, EarthWatch, SLU, NKUA, CERT, Bineo, ECSA.
Inria contact: Alexis Joly

Cos4Cloud will integrate citizen science in the European Open Science Cloud (EOSC) through the co-design of innovative services to solve challenges faced by citizen observatories, while bringing Citizen Science (CS) projects as a service for the scientific community and the society and providing new data sources. In this project, Zenith is in charge of developing innovative web services related to automated species identification, location-based species prediction and training data aggregation services.

9.3. International Initiatives

The team has two PhD students funded by an Algerian initiative ("Bourses d'excellence Algériennes "):

- Khadidja Meguelati, since 2016, "Massively Distributed Time Series Clustering via Dirichlet Mixture Models"
- Lamia Djebour, since 2019, "Parallel Time Series Indexing and Retrieval with GPU architectures"

9.3.1. Inria International Labs

In the context of LIRIMA, P. Valduriez gave a one week course in big data at IMSP, Bénin, in march, and an online seminar on Blockchain on 13 dec at Inria Rennes.

9.3.2. Inria Associate Teams Not Involved in an Inria International Labs

9.3.2.1. SciDISC

Title: Scientific data analysis using Data-Intensive Scalable Computing

International Partner (Institution - Laboratory - Researcher):

Universidade Federal do Rio de Janeiro (Brazil) - Computer Laboratory - Marta Mattoso

Start year: 2017

See also: https://team.inria.fr/zenith/scidisc/

Data-intensive science requires the integration of two fairly different paradigms: high-performance computing (HPC) and data-intensive scalable computing (DISC). Spurred by the growing need to analyze big scientific data, the convergence between HPC and DISC has been a recent topic of interest [[Coutinho 2014, Valduriez 2015]. This project will address the grand challenge of scientific data analysis using DISC (SciDISC), by developing architectures and methods to combine simulation and data analysis. The expected results of the project are: new data analysis methods for SciDISC systems; the integration of these methods as software libraries in popular DISC systems, such as Apache Spark; and extensive validation on real scientific applications, by working with our scientific partners such as INRA and IRD in France and Petrobras and the National Research Institute (INCT) on e-medicine (MACC) in Brazil.

9.3.3. Inria International Partners

9.3.3.1. Informal International Partners

We have regular scientific relationships with research laboratories in

- North America: Univ. of Waterloo (Tamer Özsu), UCSB Santa Barbara (Divy Agrawal and Amr El Abbadi), Northwestern Univ. (Chicago), university of Florida (Pamela Soltis, Cheryl Porter, Gil Nelson), Harvard (Charles Davis), UCSB (Susan Mazer).
- Asia: National Univ. of Singapore (Beng Chin Ooi, Stéphane Bressan), Wonkwang University, Korea (Kwangjin Park), Kyoto University (Japan), Tokyo University (Hiroyoshi Iwata)
- Europe: Univ. of Madrid (Ricardo Jiménez-Periz), UPC Barcelona (Josep Lluis Larriba Pey), HES-SO (Henning Müller), University of Catania (Concetto Spampinatto), Cork School of Music (Ireland), RWTH (Aachen, Germany), Chemnitz technical university (Stefan Kahl), Berlin Museum für Naturkunde (Mario Lasseck), Stefanos Vrochidis (Greece, ITI), UK center for hydrology and ecology (Tom August)
- Africa: Univ. of Tunis (Sadok Ben-Yahia), IMSP, Bénin (Jules Deliga)
- Australia: Australian National University (Peter Christen)
- Central America: Technologico de Costa-Rica (Erick Mata, former director of the US initiative Encyclopedia of Life)

9.3.4. Participation in Other International Programs

9.3.4.1. Inria International Chairs

Dennis Shasha (NYU)

Title: Data Science in a Dynamic World

International Partner: New York University (NYU), USA

Duration: 2015 - 2019

Start year: 2015

Many fundamental problems in natural science from astronomy to microbiology require data from heterogeneous sources, hence giving rise to a new “data science”. The basic workflow is to collect that data, form some kind of similarity metric between objects based on each data source, and then weight those different similarity metrics for some data analysis task. The goal is to gain actionable insight such as the cause of some symptoms, the function of some protein, or the likely source of some epidemic. Most often this is conceived of as "do-it-once" exercise. However, as data acquisition techniques improve, data may evolve continuously. When that happens the question is whether new revised insights can be obtained in a close to real time manner. Whether this is possible depends on the qualities of the new data, the weighting of the data sources, and the machine learning algorithms used. This project addresses data science in a dynamic world, aiming to find fast and minimalist methods to update insights as new data appears. This will result in new data management algorithms that will be implemented in tools and validated in the context of real data, in particular biology data.

9.3.5. Visits of International Scientists

- Renan Souza (COPPE/UFRJ and IBM,Brazil): “Providing Online Data Analytical Support for Humans in the Loop of Computational Science and Engineering Applications” on Jan 15.
- Youcef Djenouri (Norwegian University of Science and Technology, Trondheim): “Urban traffic outlier detection” on Feb 14.
- Dennis Shasha (NYU) “Bounce Blockchain: a secure, energy-efficient permission less blockchain” on May 27.
- Alvaro Coutinho (COPPE/UFRJ, Brazil): “Some Reflections on Predictive Science in Geophysical Applications” on Nov 20.
- Marta Mattoso (COPPE/UFRJ, Brazil): “Adding Provenance Data to Experiments: From Computational Science to Deep Learning” on Nov 20.
- Eduardo Ogasawara, (CEFET-RJ, Brazil): “Event Detection in Time Series” on Nov 20.
- Heraldo Borges (CEFET-RJ, Brazil): “Discovering Patterns in Restricted Space-Time Datasets” on Nov 20.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events: Organisation

10.1.1.1. General Chair, Scientific Chair

- Florent Masseglia: co-organizer of the first edition of the ADITCA workshop, at CLOSER 2019: http://closer.scitevents.org/ADITCA.aspx?y=2019
- Florent Masseglia:

  of the second edition of the ADITCA workshop, at DATA 2019: http://www.dataconference.org/ADITCA.aspx

10.1.1.2. Member of the Organizing Committees

- A. Joly: organizing committee of the international conference CLEF 2019 and the chair of the LifeCLEF track, Lugano, sept. 2019 (http://clef2019.clef-initiative.eu/)

10.1.2. Scientific Events: Selection

10.1.2.1. Member of the Conference Program Committees

- Artificial Intelligence & Knowledge Engineering (AIKE), 2019: F. Masseglia

- European Conference on Machine Learning and Principles and Practice of Knowledge Discovery in Databases (PKDD), 2019: F. Masseglia
- Int. Conf. on Data Science, Technology and Applications (DATA), 2019: F. Masseglia
- Int. Conf. on Information Management and Big Data (SIMBig), 2019: F. Masseglia
- IEEE Int. Conf. on Data Mining (ICDM), 2019: F. Masseglia
- ACM Symposium on Applied Computing (ACM SAC), Data Mining Track (DM), 2019: F. Masseglia
- ACM Symposium on Applied Computing (ACM SAC), Data Stream Track (DS), 2019: F. Masseglia
- Extraction et Gestion des Connaissances (EGC), 2019: F. Masseglia
- Int. Conf. on Extending DataBase Technologies (EDBT), 2019: E. Pacitti
- Int. Conf. on Multimedia Retrieval (ICMR), 2019: A. Joly
- Int. Conf. on Acoustics, Speech, and Signal Processing (ICASSP), 2019: A. Joly, A. Liutkus
- Int. Conf. on Computer Vision (CVPR), 2019: A. Joly
- Int. Conf. and Labs of the Evaluation Forum (CLEF), 2019: A. Joly
- European. Conf. on Information Retrieval (ECIR), 2019: A. Joly
- EAI Int. Conf. on e-Infrastructure and e-Services for Developing Countries (AFRICOMM 2019): P. Valduriez.
- Bases de Données Avancées (BDA), 2019: E. Pacitti, R. Akbarinia
- IEEE/ACM Int. Symposium in Cluster, Cloud, and Grid Computing (CCGrid) 2019: Esther Pacitti

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- VLDB Journal: P. Valduriez.
- Transactions on Large Scale Data and Knowledge Centered Systems: R. Akbarinia.
- Distributed and Parallel Databases: E. Pacitti, P. Valduriez.
- Book series “Data Centric Systems and Applications” (Springer): P. Valduriez.
- Plant Methods: C. Pradal.

10.1.3.2. Reviewer - Reviewing Activities

- EVISE Future Generation Computer Systems Journal (FGCS): F. Masseglia
- Information Systems (IS): T. Mondal, F. Masseglia
- Distributed and Parallel Databases (DAPD): E. Pacitti, P. Valduriez
- IEEE Transactions on Knowledge and Data Engineering (TKDE): R. Akbarinia, F. Masseglia
- IEEE Transactions on Industrial Informatics: R. Akbarinia
- Knowledge and Information Systems (KAIS): R. Akbarinia
- Plant methods: A. Joly
- Machine Learning: A. Joly
- Pattern Recognition Letters: A. Joly
- Transactions on Image Processing: A. Joly
- ACM Trans. on Database Systems: E. Pacitti
- Knowledge and Information Systems (KAIS): F. Masseglia
- IEEE Transaction on Signal Processing (TSP): A. Liutkus
- IEEE Transactions on Audio Speech and Language Processing (TASLP): A. Liutkus

- IEEE Signal Processing Magazine: A. Liutkus
- IEEE Signal Processing Letters: A. Liutkus
- Frontiers in Plant Science: C. Pradal
- Neural Information Processing Systems (NeurIPS): A. Liutkus
- Int. Conf. on Machine Learning (ICML): A. Liutkus
- Int. Conf. on Acoustics, Speech and Signal Processing (ICASSP): A. Liutkus

10.1.4. Invited Talks

- E.Pacitti: Inaugural lecture, “Data Processing: an evolutionary and multidisciplinary perspective”, CEFET/RJ, Rio de Janeiro on 12 August 2019.
- A. Joly: "AI for plant phenology" on 17 January at a workshop of the University of Florida (keynote); "AI for plant biodiversity monitoring" on 7 November at HPC-AI-BigData Convergence days (Conv’ 2019); "An end-to-end deep learning approach to biodiversity monitoring", on 12 December at British Ecological Society conference (BES 2019);
- A. Liutkus: tutorial on "music source separation" at Int. Symposium on Music Information Retrieval (ISMIR 2018).
- F. Masseglia: “Données, humanités et démarche scientifique”. Panel at the Inria Science Days (Journées Scientifiques Inria), on June 6, Lyon; “Analyse de données scientifiques”. IRD, on June 27, Montpellier. “Analyse de données à grande échelle”. TILECS Workshop. on July 4, Grenoble.
- P. Valduriez: "The Case for Hybrid Transaction Analytical Processing" on 25 April at IBM Research Brazil, Rio de Janeiro, Brazil; "Blockchain 2.0: opportunities and risks" on 14 Nov at Online Franco-African LIRIMA Seminar, Inria, Rennes; "Data-intensive Science" on 6 Nov. at HPC- AI-BigData Convergence Days (Conv’2019), EDF Lab Paris-Saclay; tutorial "NewSQl: principles, systems and trends" on 12 Dec at IEEE Bigdata 2019; participation in panel "Big Data Heterogeneity Challenges" on 11 Dec at IEEE Bigdata 2019; "Scalable transaction and polystore data management in LeanXcale" on 6 Dec at UC Berkeley and on 13 Dec at UCLA and UC Irvine.
- C. Pradal: "Multiscale plant modelling and Phenotyping" on 8 october at Tottori University and on 16 october at Nagoya University, Japan; workshop on plant modelling on 28 october at Tokyo University, Japan.

10.1.5. Leadership within the Scientific Community

- A. Joly: Scientific manager of the LifeCLEF research forum.
- A. Liutkus: elected member of the IEEE Technical Committee on Audio and Acoustic Signal Processing.
- P. Valduriez: President of the Steering Committee of the BDA conference.

10.1.6. Scientific Expertise

- F. Masseglia: expert for the HCERES evaluation of the DAVID Lab (UVSQ). January 2019.
- R. Akbarinia: expert for the French National Research Agency (ANR).
- A: Joly: scientific advisory board of the ANR program "AI for biodiversity", expert for the National HPC grand equipment (GENCI) "grand challenge" program, reviewer for STIC AmSud international program.
- E. Pacitti: reviewer for STIC AmSud international program.
- P. Valduriez: reviewer for STIC AmSud international program.
- P. Valduriez: reviewer for NSERC (Canada).
- C. Pradal: member of CSS EGBIP (Commissions Scientifiques Spécialisées) INRA.

10.1.7. Research Administration

- A. Joly: Technical director of the InriaSOFT consortium Pl@ntNet and representative of Inria in the steering committee.
- F. Masseglia: "Chargé de mission pour la médiation scientifique Inria" and head of Inria's national network of colleagues involved in science popularization.
- E. Pacitti: head of Polytech' Montpellier's Direction of Foreign Relationships.
- P. Valduriez: scientific manager for the Latin America zone at Inria's Direction of Foreign Relationships (DPEI).

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Most permanent members of Zenith teach at the Licence and Master degree levels at UM2.

Esther Pacitti:

IG3: Database design, physical organization, 54h, level L3, Polytech'Montpellier, UM2

IG4: Networks, 42h, level M1, Polytech' Montpellier, 50 students, UM2

IG4: Distributed Databases, Big Data, 80h , level M1, Polytech' Montpellier, 50 students UM2

IG5: Iot- Information Management, 27h, level M2, Polytech' Montpellier, 15 students, UM2

Industry internship supervision and committees, level M2, Polytech' Montpellier, 40h

Patrick Valduriez:

Professional: Distributed Information Systems, Big Data Architectures, 75h, level M2, Capgemini Institut

Alexis Joly:

University of Montpellier: Machine Learning, 15h, level M2

Polytech' Montpellier: Content-Based Image Retrieval, 4.5h, level M1

AgroParisTech: Convolutional Neural Networks in Ecology and Agronomy, 2h, level M1

InnObs technical school: Innovations in the observation of seasonal biological events and associated data management, 6h, professionals.

Antoine Liutkus

University Paul Valery (Montpellier): multidimensional data analysis, 15h, level M1

Polytech' Montpellier: Audio Machine Learning, 1.5h, level M1

10.2.2. Supervision

PhD & HDR:

HDR: Reza Akbarinia, Parallel Techniques for Big Data Analytics, Univ. Montpellier, 24 May.

PhD: Renan Souza, Massively Distributed Clustering, UFRJ, Brazil, 17 Dec. Advisors: Marta Mattoso (UFRJ), Patrick Valduriez.

PhD: Mathieu Fontaine, Alpha-stable models for signal processing, IAEM, Nancy, 18 July. Advisors: Roland Badeau (Telecom Paris), Antoine Liutkus.

PhD: Christophe Botella, Large-scale Species Distribution Modelling based on Citizen Science data, Montpellier, 8 October. started Oct 2016, Univ. Montpellier. Advisors: Alexis Joly, François Munoz (univ. of Grenoble), Pascal Monestiez (INRA).

PhD in progress: Gaetan Heidsieck, Distributed Management of Scientific Workflows for High-Throughput Plant Phenotyping, started Oct 2017, Univ. Montpellier. Advisors: Esther Pacitti, Christophe Pradal, François Tardieu (INRA).

PhD in progress: Heraldo Borges, Discovering Tight Space-Time Sequences, started Oct 2018, Univ. Montpellier. Advisors: Esther Pacitti, Eduardo Ogaswara.

PhD in progress: Titouan Lorieul, Pro-active Crowdsourcing, started Oct 2016, Univ. Montpellier. Advisor: Alexis Joly.

PhD in progress: Khadidja Meguelati, Massively Distributed Clustering, started Oct 2016, Univ. Montpellier. Advisors: Nadine Hilgert (INRA), Florent Masseglia.

PhD in progress: Lamia Djebour, Parallel Time Series Indexing and Retrieval with GPU architectures, started Oct 2019, Univ. Montpellier. Advisors: Reza Akbarinia, Florent Masseglia.

PhD in progress: Quentin Leroy, Active learning of unknown classes, started Oct 2019, Univ. Montpellier, Industrial contract with INA, Advisors: Alexis Joly

10.2.3. Juries

Members of the team participated to the following PhD or HDR committees:

- R. Akbarinia: Chao Zhang (Univ. Clermont Auvergne, reviewer)
- A. Joly: Christophe Botella (Univ. of Montpellier, advisor)
- F. Masseglia: Rebecca Pontes Salles (Master thesis of 2.5 years, CEFET, Rio de Janeiro), Ricardo Sperandio (Univ. Rennes, reviewer), Thibault Desprez (Univ. Bordeaux, reviewer).
- E. Pacitti: Daniel de Oliveira Junior (Univ. Federal Fluminense, Brazil)
- E. Pacitti: Heraldo Borges Phd qualification (CEFET, Brazil)
- P. Valduriez: Alexandru Costan (HDR, ENS Rennes, reviewer), Patricio Cerda (Univ. Paris Saclay, reviewer), Renan Souza (UFRJ, Rio de Janeiro, advisor)
- E. Pacitti: Selection Committe for professor position (University of Montpellier)

10.3. Popularization

10.3.1. Internal or external Inria responsibilities

F. Masseglia is “Chargé de mission auprès de la DGD-S Inria pour la médiation scientifique” (50% of his time) and heads Inria’s national network of colleagues involved in science popularization.

10.3.2. Articles and contents

- F. Masseglia is co-author of [21], [40] on the feedback of Class’Code after 3 years of project and on a vision about future work for computational thinking education and computer science popularisation.
- A. Joly has given several interviews to different media giving rise to web articles about Pl@ntNet (see e.g. Google news with keyword Pl@ntNet).

10.3.3. Education

Computer science is, for the first time in France, an official discipline teached in high school (Lycée) with the common course about "Sciences Numériques et Technologie". As written by Inira’s CEO Bruno Sportisse: *"For over a decade, the institute has carried out actions that have paved the way with the firm conviction that "training in and through digital technology" is strategic: I am thinking here, in particular, of the Class’Code project."*

F. Masseglia is the initiator, with Serge Abiteboul, of the program called "1 scientifique — 1 classe : Chiche !" with the goal of reaching *all* the students of a specific level. This massive plan should concern all scientists at Inria and our partners in France.

F. Masseglia was ambassador of Inria for the Science Celebration Day (Fête de la science):

- https://www.youtube.com/watch?v=13957C9FxVg
- https://www.youtube.com/watch?v=ypnQe91Pztc

F. Masseglia gave a one day training on the Thymio robot for education in the media library networkprofessionals. February 1. Montpellier. 18 attendees.

F. Masseglia gave a one day training to teachers of French National Education on computational thinking. March 12. Montpellier. 20 attendees.

F. Masseglia gave a one day training to teachers in pediatric hospitals (CHU Arnaud de Villeneuve). February 2. Montpellier. 10 attendees.

F. Masseglia gave two days of training to computer science, robotics and computational thinking to reference teachers ("conseillers pédagogiques"). April 15 & 16. Montpellier. 20 attendees.

F. Masseglia gave two days of training to the media library network professionals on Poppy Ergo Jr. June 28 & September 6. Montpellier. 11 attendees.

F. Masseglia is a member of the scientific committee of a conference cycle on "Science and Society" organised with MSHSud.

P. Valduriez gave an invited talk on "Succeed in your Ph.D. Thesis: good practices and return of experience" at the Ph.D. meeting at LIRIS, Lyon, on Dec 11.

A. Joly was a member of the scientific advisory board of the AI Family Challenge organized by the NGO Iridescent that "supports girls, children, and their families to identify problems in their communities and find technology based solutions".

He organized an educational outing at the Montpellier Botanical Garden as part of the summer school organized each year by Polytech Montpellier (June 11). He participated in the organization and animation of the "wild salad" training organized by the association "Les écologistes de l'Euzière" 13-15 March.

10.3.4. Interventions

F. Masseglia participated in the LIRMM events on science popularisation ("Fête de la science" on Feb 19, "accueil de stagiaires" on Oct 11), Montpellier.

A. Joly participated in: the animation of the Inria stand at the SIDO exhibition (April 10-11, Lyon); the Pl@ntNet launch ceremony in Costa Rica in the presence of the Minister of Research and decision-makers (April 20).

E. Pacitti participated in Polytech'Montpellier International Summer School (Flow) on the subject of Data Science - Plant Phenotyping.

A. Joly participated in the day "Ramène ta science" co-organized by TelaBotanica and "Sciences Avenir" associations at the Halle Tropisme in Montpellier (as part of the Labbota initiative). He co-facilitated a participatory workshop and a debate with citizens on the theme of participatory science.

10.3.5. Creation of media or tools for science outreach

In the context of the Floris'tic project, A. Joly participates regularly to popularization, educational and citizen science actions in France (with schools, cities, parks, associations, etc.). The softwares developed within the project (Pl@ntNet, Smart'Flore and ThePlantGame) are used in a growing number of formal educational programs and informal educational actions of individual teachers. For instance, Smart'Flore is used by the French National Education in a program for reducing early school leaving. Pl@ntNet app is used in the Reunion island in an educational action called Vegetal riddle organized by the Center for cooperation at school. It is also used in a large-scale program in Czech republic and Slovakia (with a total of 100 classrooms involved in the program). An impact study of the Pl@ntNet application did show that 6% of the respondents use it for educational purposes in the context of their professional activity.

F. Masseglia participated in the work group on "Jeu des 7 familles de l'informatique". This card game provides support for education to computer science from the history point of view.

A. Joly actively participates to the design and development of all Pl@ntNet dissemination tools in particular Pl@ntNet web site that contains contents for the press, articles for the general public, tutorials of Pl@ntNet tools, guidelines for users of the API, etc.

11. Bibliography

Publications of the year

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[2] M. FONTAINE.*Alpha-stable processes for signal processing*, Université de Lorraine, June 2019, https://tel.archives-ouvertes.fr/tel-02188304

[3] C. PRADAL.*Dataflow architecture for modular and generic plant simulation systems*, Université de Montpellier, July 2019, https://tel.archives-ouvertes.fr/tel-02193606

[4] R. SOUZA.*Supporting User Steering In Large-Scale Workflows With Provenance Data*, UFRJ, Rio de Janeiro, December 2019, https://hal-lirmm.ccsd.cnrs.fr/tel-02418022

Articles in International Peer-Reviewed Journal

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