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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

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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 [52]. 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.

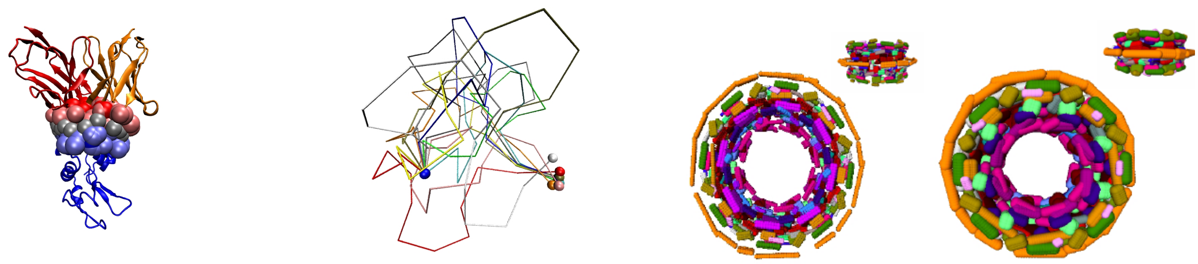
Modeling in Computational Structural Biology. Acquiring structural data is not always possible: NMR is restricted to relatively small molecules; membrane proteins do not crystallize, etc. As a matter of fact, the order of magnitude of the number of genomes sequenced is of the order of one thousand, which 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 [50], [38] and later Connolly [33], 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) [40], 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 [52]. Yet, in spite of almost three decades of investigations, the basic principles guiding the formation of interfaces and accounting for its stability are unknown [55]. Current investigations follow two routes. From the experimental perspective [37], 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 [49]. From the modeling perspective, the main issue consists of guessing the hot residues from sequence and/or structural informations [44].

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 [31], 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 [53], [39]. 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 [45]. 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 [32]. At the atomic level and in spite of recent observations on the local structure of the neighborhood of a given atom [54], 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 [36].

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 [48]. 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

[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.

[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.

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 [30]. 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 [29], the largest assembly known to date in the eukaryotic cell, and consisting of 456 protein *instances* of 30 *types*.

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 [28], 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 [28]. 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.

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

At the side-chain level, the question of improving rotamer libraries is still of interest [34]. 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) [51]. 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 [47], to Morse theory [42] and to analysis of meta-stable states of time series [43] have been proposed.

3.5. Algorithmic foundations

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

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 [46].

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. Origin of Public Memory B Cell Clones in Fish After Antiviral Vaccination

Participants: F. Cazals, S. Marillet.

In collaboration with S. Magadan, L. Jouneau, S. Marillet, P. Boudinot (INRA, Virologie et Immunologie Moléculaires, Université Paris-Saclay, Jouy-en-Josas, France); M. Puelma Touzel, T. Mora, A. Walczak (Laboratoire de Physique Théorique, CNRS, Sorbonne Université, and Ecole Normale Supérieure (PSL), Paris, France); W. Chaara, A. Six (Sorbonne Université, INSERM, UMR S 959, Immunology-Immunopathology - Immunotherapy (I3), Paris, France); E. Quillet (INRA, Génétique Animale et Biologie Intégrative, Université Paris-Saclay, Jouy-en-Josas, France); O. Sunyer (Department of Pathobiology, School of Veterinary Medicine, University of Pennsylvania, Philadelphia, PA, United States); S. Fillatreau (INEM, INSERM U1151/CNRS UMR8253, Institut Necker-Enfants Malades, Faculté de Médecine Paris Descartes, Paris, France; Faculté de Médecine, Université Paris Descartes, Sorbonne Paris Cité, Paris, France; Assistance Publique des Hopitaux de Paris (AP-HP), Hopital Necker Enfants Malades, Paris, France).

Vaccination induces *publi*c antibody clonotypes common to all individuals of a species, that may mediate universal protection against pathogens. Only few studies tried to trace back the origin of these public B-cell clones. Here [16] we used Illumina sequencing and computational modeling to unveil the mechanisms shaping the structure of the fish memory antibody response against an attenuated Viral Hemorrhagic Septicemia rhabdovirus. After vaccination, a persistent memory response with a public VH5JH5 IgM component was composed of dominant antibodies shared among all individuals. The rearrangement model showed that these public junctions occurred with high probability indicating that they were already favored before vaccination due to the recombination process, as shown in mammals. In addition, these clonotypes were in the naive repertoire associated with larger similarity classes, composed of junctions differing only at one or two positions by amino acids with comparable properties. The model showed that this property was due to selective processes exerted between the recombination and the naive repertoire. Finally, our results showed that public clonotypes greatly expanded after vaccination displayed several VDJ junctions differing only by one or two amino acids with similar properties, highlighting a convergent response. The fish public memory antibody response to a virus is therefore shaped at three levels: by recombination biases, by selection acting on the formation of the pre-vaccination repertoire, and by convergent selection of functionally similar clonotypes during the response. We also show that naive repertoires of IgM and IgT have different structures and sharing between individuals, due to selection biases. In sum, our comparative approach identifies three conserved features of the antibody repertoire associated with public memory responses. These features were already present in the last common ancestors of fish and mammals, while other characteristics may represent species-specific solutions.

5.2. Modeling macro-molecular assemblies

Keywords: macro-molecular assembly, reconstruction by data integration, proteomics, mass spectrometry, modeling with uncertainties, connectivity inference.

5.2.1. Complexity Dichotomies for the Minimum F-Overlay Problem – Application for low resolution models of macro-molecular assemblies

Participant: D. Mazauric.

In collaboration with N. Cohen (CNRS, Laboratoire de Recherche en Informatique) and F. Havet (CNRS, Inria/I3S project-team Coati) and I. Sau (CNRS, Laboratoire d'Informatique de Robotique et de Microélectronique de Montpellier) and R. Watrigant (University Lyon I, Laboratoire de l'Informatique du Parallélisme).

In this article [14], we analyze a generalization of the minimum connectivity inference problem (MCI). MCI models the computation of low-resolution structures of macro-molecular assemblies, based on data obtained by native mass spectrometry. The generalization studied in this article, allows us to consider more refined constraints for the characterization of low resolution models of large assemblies. We model this problem by using hypergraphs: for a (possibly infinite) fixed family of graphs F, we say that a graph $G overlays F$ on a hypergraph H if $V(H)$ is equal to $V(G)$ and the subgraph of G induced by every hyperedge of H contains some member of F as a spanning subgraph. While it is easy to see that the complete graph on $|V(H)|$ overlays F on a hypergraph H whenever the problem admits a solution, the Minimum F-Overlay problem asks for such a graph with at most k edges, for some given $k \in \mathbb{N}$. This problem allows to generalize some natural problems which may arise in practice. For instance, if the family F contains all connected graphs, then Minimum F-Overlay corresponds to the MCI problem. Our main contribution is a strong dichotomy result regarding the polynomial vs. NP-complete status with respect to the considered family F. Roughly speaking, we show that the easy cases one can think of (e.g. when edgeless graphs of the right sizes are in F, or if F contains only cliques) are the only families giving rise to a polynomial problem: all others are NP-complete. We then investigate the parameterized complexity of the problem and give similar sufficient conditions on F that give rise to $W[1]$-hard, $W[2]$-hard or FPT problems when the parameter is the size of the solution.

5.3. Modeling the flexibility of macro-molecules

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

5.3.1. 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. We correct these limitations with the so-called combined RMSD [26], 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 RMSD 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 a choice to perform positive and negative discrimination of degree of freedom, with applications to the design of move sets and collective coordinates. Combined RMSD are available within the Structural Bioinformatics Library (http: //sbl.inria.fr).

5.3.2. Multiscale analysis of structurally conserved motifs

Participants: F. Cazals, R. Tetley.

This work [25] develops a generic framework to perform a multiscale structural analysis of two structures (homologous proteins, conformations) undergoing conformational changes. Practically, given a seed structural alignment, we identify structural motifs with a hierarchical structure, characterized by three unique properties. First, the hierarchical structure sheds light on the trade-off between size and flexibility. Second, motifs can be combined to perform an overall comparison of the input structures in terms of combined RMSD, an improvement over the classical least RMSD. Third, motifs can be used to seed iterative aligners, and to design hybrid sequence-structure profile HMM characterizing protein families. From the methods standpoint, our framework is reminiscent from the bootstrap and combines concepts from rigidity analysis (distance difference matrices), graph theory, computational geometry (space filling diagrams), and topology (topological persistence). On challenging cases (class II fusion proteins, flexible molecules) we illustrate the ability of our tools to localize conformational changes, shedding light of commonalities of structures which would otherwise appear as radically different. Our tools are available within the Structural Bioinformatics Library (http://sbl.inria.fr). We anticipate that they will be of interest to perform structural comparisons at large, and for remote homology detection.

5.3.3. Hybrid sequence-structure based HMM models leverage the identification of homologous proteins: the example of class II fusion proteins

Participants: F. Cazals, R. Tetley.

In collaboration with P. Guardado-Calvo, J. Fedry, and F. Rey (Inst. Pasteur Paris, France).

In [27], we present a sequence-structure based method characterizing a set of functionally related proteins exhibiting low sequence identity and loose structural conservation. Given a (small) set of structures, our method consists of three main steps. First, pairwise structural alignments are combined with multi-scale geometric analysis to produce structural motifs i.e. regions structurally more conserved than the whole structures. Second, the sub-sequences of the motifs are used to build profile hidden Markov models (HMM) biased towards the structurally conserved regions. Third, these HMM are used to retrieve from UniProtKB proteins harboring signatures compatible with the function studied, in a bootstrap fashion. We apply these hybrid HMM to investigate two questions related to class II fusion proteins, an especially challenging class since known structures exhibit low sequence identity (less than 15%) and loose structural similarity (of the order of 15A in lRMSD). In a first step, we compare the performances of our hybrid HMM against those of sequence based HMM. Using various learning sets, we show that both classes of HMM retrieve unique species. The number of unique species reported by both classes of methods are comparable, stressing the novelty brought by our hybrid models. In a second step, we use our models to identify 17 plausible HAP2-GSC1 candidate sequences in 10 different drosophila melanogaster species. These models are not identified by the PFAM family HAP2-GCS1 (PF10699), stressing the ability of our structural motifs to capture signals more subtle than whole Pfam domains. In a more general setting, our method should be of interest for all cases functional families with low sequence identity and loose structural conservation. Our software tools are available from the FunChaT package of the Structural Bioinormatics Library (http://sbl.inria.fr).

5.3.4. Hamiltonian Monte Carlo with boundary reflections, and application to polytope volume calculations

Participants: F. Cazals, A. Chevallier.

In collaboration with S. Pion (Auctus, Inria Bordeaux).

This paper [23] studies HMC with reflections on the boundary of a domain, providing an enhanced alternative to Hit-and-run (HAR) to sample a target distribution in a bounded domain. We make three contributions. First, we provide a convergence bound, paving the way to more precise mixing time analysis. Second, we present a robust implementation based on multi-precision arithmetic – a mandatory ingredient to guarantee exact predicates and robust constructions. Third, we use our HMC random walk to perform polytope volume calculations, using it as an alternative to HAR within the volume algorithm by Cousins and Vempala. The tests, conducted up to dimension 50, show that the HMC RW outperforms HAR.

5.3.5. 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. 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. As such, we propose in [22] 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 distribution. 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.

5.4. Algorithmic foundations

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

Making a stride towards a better understanding of the biophysical questions discussed in the previous sections requires various methodological developments discussed below.

5.4.1. A Sequential non-parametric multivariate two-sample test

Participant: F. Cazals.

In collaboration with A. Lhéritier (Amadeus, France).

Given samples from two distributions, a nonparametric two-sample test aims at determining whether the two distributions are equal or not, based on a test statistic. Classically, this statistic is computed on the whole dataset, or is computed on a subset of the dataset by a function trained on its complement. We consider methods in a third tier [15], so as to deal with large (possibly infinite) datasets, and to automatically determine the most relevant scales to work at, making two contributions. First, we develop a generic sequential nonparametric testing framework, in which the sample size need not be fixed in advance. This makes our test a truly sequential nonparametric multivariate two-sample test. Under information theoretic conditions qualifying the difference between the tested distributions, consistency of the two-sample test is established. Second, we instantiate our framework using nearest neighbor regressors, and show how the power of the resulting two-sample test can be improved using Bayesian mixtures and switch distributions. This combination of techniques yields automatic scale selection, and experiments performed on challenging datasets show that our sequential tests exhibit comparable performances to those of state-of-the-art nonsequential tests.

5.4.2. Comparing two clusterings using matchings between clusters of clusters

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

In collaboration with R. Watrigant (University Lyon I, Laboratoire de l'Informatique du Parallélisme, France).

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. 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 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).

5.4.3. 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 (Inria/I3S project-team Coati) and A. Chaintreau (Columbia University in the city of New York) and G. Ducoffe (National Institute for Research and Development in Informatics and Research Institute of the University of Bucharest).

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 [35], [41]. In this paper we disprove this. Specifically, we prove that for any $k \geq 4$, the maximum time of convergence is an $\Omega(|V|^{\Theta(\log |V|)})$.

See [19] for details.

5.4.4. *Sequential metric dimension*

Participant: D. Mazauric.

In collaboration with J. Bensmail (I3S, Inria/I3S project-team Coati) and F. Mc Inerney (Inria/I3S project-team Coati) and N. Nisse (Inria, Inria/I3S project-team Coati) and S. Pérennes (CNRS, Inria/I3S project-team Coati).

In the localization game, introduced by Seager in 2013, an invisible and immobile target is hidden at some vertex of a graph G. At every step, one vertex v of G can be probed which results in the knowledge of the distance between v and the secret location of the target. The objective of the game is to minimize the number of steps needed to locate the target whatever be its location.

We address the generalization of this game where $k \geq 1$ vertices can be probed at every step. Our game also generalizes the notion of the *metric dimension* of a graph. Precisely, given a graph G and two integers $k, \ell \geq 1$, the *localization* problem asks whether there exists a strategy to locate a target hidden in G in at most ℓ steps and probing at most k vertices per step. We first show that, in general, this problem is NP-complete for every fixed $k \geq 1$ (resp., $\ell \geq 1$). We then focus on the class of trees. On the negative side, we prove that the localization problem is NP-complete in trees when k and ℓ are part of the input. On the positive side, we design a $(+1)$-approximation for the problem in n-node trees, *i.e.*, an algorithm that computes in time $O(n \log n)$ (independent of k) a strategy to locate the target in at most one more step than an optimal strategy. This algorithm can be used to solve the localization problem in trees in polynomial time if k is fixed.

We also consider some of these questions in the context where, upon probing the vertices, the relative distances to the target are retrieved. This variant of the problem generalizes the notion of the *centroidal dimension* of a graph.

See [17], [18], [21] for details.

6. Partnerships and Cooperations

6.1. International Research Visitors

6.1.1. *Visits of International Scientists*

6.1.1.1. 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 Xuchun Zhang, École Polytechnique de l'Université Nice Sophia Antipolis, filière Mathématiques Appliquées et Modélisation, year 4 (Master 1). Supervision: Jean-Baptiste Caillau (Inria project-team McTao), Enzo Giusti (startup Oui!Greens), Dorian Mazauric, and Joanna Moulierac (Inria/I3S project-team Coati). *Problèmes d'affectations d'annonces dans un réseau anti gaspillage !*
- Project of Ruiqing Chang and Xuchun Zhang, École Polytechnique de l'Université Nice Sophia Antipolis, Filière Mathématiques Appliquées et Modélisation, year 4 (Master 1). Supervision: Jean-Baptiste Caillau (Inria project-team McTao), Enzo Giusti (startup Oui!Greens), Dorian Mazauric, and Joanna Moulierac (Inria/I3S project-team Coati). *Problèmes d'affectations d'annonces dans un réseau anti gaspillage !*

- Internship of Nguyen Thi Viet Ha, Master 2 Fundamental Computer Science, École Normale Supérieure de Lyon. Supervision: Frédéric Havet (Inria/I3S project-team Coati), Dorian Mazauric, and Rémi Watrigant (École Normale Supérieure de Lyon and Université Claude Bernard Lyon 1). *Graph Algorithms for low resolution model of large protein assemblies.*
- Internship of Timothée O'Donnell, Master 2 University Paris Saclay, Master bioinformatique. *Structural modeling of FMRP dimers in solution*. Supervision: F. Cazals.

7. Dissemination

7.1. Promoting Scientific Activities

7.1.1. Scientific Events Organisation

7.1.1.1. Member of the Organizing Committees

– Frédéric Cazals was member of the advisory board of:

- *Algorithms in Structural Bio-informatics*. The 2018/2019 edition (January 2019, CIRM, Marseille) focuses on RNA bioinformatics. See https://algosb2019.sciencesconf.org/.

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 Geometry Processing
- Symposium on Solid and Physical Modeling
- Intelligent Systems for Molecular Biology (ISMB) / Protein Interactions & Molecular Networks
- IEEE International Conference on BioInformatics and BioEngineering

7.1.3. Journal

7.1.3.1. Reviewer - Reviewing Activities

– Frédéric Cazals reviewed for the following journals:

- Journal of computational geometry
- PLOS Computational Biology

– Dorian Mazauric reviewed for the following journal and conference:

- Theoretical Computer Science
- 16th Workshop on Approximation and Online Algorithms (WAOA 2018)

7.1.4. Invited Talks

– Frédéric Cazals gave the following invited talks:

- *Energy landscapes: sampling, analysis, comparison*, RNA Kinetics days, Ecole polytechnique, October 2018.
- *Randomized algorithms for volume/density of states calculations in high-dimensional spaces*: Energy landscapes, Kalamata, Greece, September 2018;
- *Randomized algorithms for volume/density of states calculations in high-dimensional spaces*: Advances in Computational Statistical Physics, CIRM, France, September 2018.
- *Understanding scoring/energy landscapes: a tale of local minima and density of states*, Meet-U: when proteins meet each other, January 2018, Paris.

7.1.5. 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-.... 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/).

7.1.6. 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:

- 2016-2019. Member of the *Comité de Centre*, Inria Sophia Antipolis - Méditerranée.
- 2018-.... 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, 36 h TD, niveau M1, École Polytechnique de l'Université Nice Sophia Antipolis, filière Sciences Informatiques, France.

7.2.2. Supervision

- **PhD:** Romain Tetley, *Mixed sequence-structure based analysis of proteins, with applications to functional annotations*, defended on the 21/11/2018. Université Côte d'Azur.
- **PhD in progress, 4th year:** Augustin Chevallier, *Random walks for estimating the volume of convex bodies and densities of states in high dimensional spaces*, defense scheduled in February 2019. Université Côte d'Azur.
- **PhD in progress, 2nd year:** Denys Bulavka, *Modeling macro-molecular motions*. Université Côte d'Azur. Under the supervision of Frédéric Cazals.
- **PhD in progress, 2nd 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, 1st 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, 1st 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:

- Hugo Schweke, Paris-Saclay University, December 2018. Rapporteur on the PhD thesis *Développement d'une méthode* in silico *pour caractériser le potentiel d'interaction des surfaces protéiques dans un environnement encombré*. Advisors: Marie-Hélène Mucchielli-Giorgi and Anne Lopes.
- Julien Ogor, ENSTA Bretagne, May 2018. Rapporteur on the PhD thesis *Design of algorithms for the automatic characterization of marine dune morphology and dynamics*. Advisor: B. Zerr.
- Rodrigo Dorantes-Gilardi, University of Lyon, April 2018. Rapporteur on the PhD thesis *Bio-Mathematical aspects of the plasticity of proteins*. Advisors: L. Vuillon and C. Lesieur.

– Dorian Mazauric:

- Romain Tetley, Université Côte d'Azur, Novembre 2018. PhD thesis *Mixed sequence-structure based analysis of proteins, with applications to functional annotations*. Advisor: Frédéric Cazals.

7.3. Popularization

This part mainly concerns Dorian Mazauric.

7.3.1. Internal or external Inria responsibilities

- Member of Mastic Commission (Médiation et Animation scientifiques Inria Sophia Antipolis - Méditerranée).
- Coordinator of the popularization project GALEJADE (Graphes et ALgorithmes : Ensemble de Jeux À Destination des Écoliers (mais pas que)) founded by Inria, Fondation Blaise Pascal, and Université Côte d'Azur. See https://galejade.inria.fr.
- Coordinator of the internships for undergraduates of middle school (niveau collège, troisième) at Inria Sophia Antipolis - Méditerranée (12 interns during one week).

7.3.2. Articles and contents

Frédéric Cazals published the following opinion article:

- *Recherche et développement : les entreprises françaises n'ont pas de vision*, Le Monde, April 2018. See https://www.lemonde.fr/sciences/article/2018/04/20/r-d-les-entreprises-francaises-n-ont-pas-de-vision_5288104_1650684.html.

Dorian Mazauric published online contents and posters. See https://galejade.inria.fr.

7.3.3. Education

- Trainings for 100 future teachers at ÉSPÉ (École SupÉrieure du Professorat et de l'Éducation) of Académie de Nice.
- Two trainings for 60 teachers of Cycle 3 (Le Cannet).
- Trainings for 20 teachers at numeric culture week-end organised by Class'Code MED.

7.3.4. Interventions

- National events:
  - Fête de la Science : Village des Sciences de Vinon-sur-Verdon, Juan-les-Pins, Villeneuve-Loubet et Mouans Sartoux : *La magie des graphes et du binaire, Algorithmes grandeur nature et jeux combinatoires*.
  - Semaine des maths : Conferences and activities at Centre International de Valbonne. With Christophe Godin. *Réfléchir pour Calculer ou Calculer pour Réfléchir.*
  - Conferences and activities at salon Code & Play 2018. *Graphes et algorithmes ? Jeux grandeur nature : algorithme de plus court chemin, algorithme de tri avec des cerceaux et des lattes en plastique – La magie des graphes et du binaire : tours de magie.*
- In educational institutions:
  - Two trainings for 60 teachers of Cycle 3 (Le Cannet).
  - Trainings for 100 future teachers at ÉSPÉ (École SupÉrieure du Professorat et de l'Éducation) of Académie de Nice.
  - High school: Conferences at Centre International de Valbonne. *Pas besoin de réfléchir, les ordinateurs calculent tellement vite ? Théorie des graphes et algorithmique.*
  - Middle school: Conferences at collège Alphonse Daudet of Nice and conferences at collège Jules Verne of Cagnes-sur-Mer. *La magie des graphes et du binaire.*

  - Primary: Conferences at École élémentaire of Tourrettes-sur-Loup. With Florence Barbara.
- Welcoming of schoolchildren or the general public in an Inria center:
  - MathC2+ internship: Activity for 40 students (high school). With Maria Guramare. *Algorithmes grandeur nature pour le calcul du plus court chemin et pour trier.*
  - Open days of Inria Sophia Antipolis - Méditerranée: *La magie des graphes, des algorithmes et du binaire*.
  - Presentation for twelve interns of middle school (niveau collège, troisième) by Frédéric Cazals.

7.3.5. Creation of media or tools for science outreach

- Creation of the website of the popularization project GALEJADE (Graphes et ALgorithmes : Ensemble de Jeux À Destination des Écoliers (mais pas que)) founded by Inria, Fondation Blaise Pascal, and Université Côte d'Azur. See https://galejade.inria.fr.
- Development of wooden objects for the dissemination of the scientific culture: wooden plateau for graph algorithms and convex hull, chocolate bar game made by 3D printers, kakemonos... See https://galejade.inria.fr/francais-pret-de-materiel/.

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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

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Project-Team ACUMES

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

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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 [115], or to the dynamics of turbulent flows for which large scale / small scale vortical structures interfere [143].

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 [84] for an existence result and [68], [83] 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 [74], [103] for some applications in traffic flow modelling, and [94], [99], [101] 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 [68], [83].

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 [75], [86] for the derivation of Lighthill-Whitham-Richards [126], [142] traffic flow model from Follow-the-Leader and [95] for results on crowd motion models (see also [117]). 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 [87], and extensively used since then to prove convergence of approximate solutions and deduce existence results, see for example [96] 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 [57], [98]. We refer, for example, to the notion of solution for non-hyperbolic systems [105], 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 [98].

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 [79]), and proved to be successful for studying emerging self-organised flow patterns [78]. The theoretical measure framework proves to be also relevant in addressing micro-macro limiting procedures of mean field type [106], 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* [151], [152]. Indeed, as observed in [135], 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 [125]). 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 [64], [65], [88], [124], 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 [138], 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 [82] 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, [53]) 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

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

where $u = u(t, \mathbf{x}) \in \mathbb{R}^N$, $N \geq 1$ 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 [50], sedimentation [59], supply chains [109], conveyor belts [110], biological applications like structured populations dynamics [134], or more general problems like gradient constrained equations [51]. Also, non-local in time terms arise in conservation laws with memory, starting from [81]. 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 [60], [67], [71], [107], [146]. 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 [60], [107] 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 [52] for scalar equations in one space dimension ($N = d = 1$), in [72] for scalar equations in several space dimensions ($N = 1$, $d \geq 1$) and in [46], [73], [77] for multi-dimensional systems of conservation laws. Besides, specific finite volume numerical methods have been developed recently in [46], [107] and [123].

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 [66]. In aerodynamics, inflow conditions like velocity modulus and direction, are subject to fluctuations [113], [133]. For some engineering problems, the geometry of the boundary can also be uncertain, due to structural deformation, mechanical wear or disregard of some details [90]. 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 [144], [150], 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 [145], [148], 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 [131]. 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 [113], [122], [127], [154] or an entropy closure method [85], or by discretizing the probability space and extending the numerical schemes to the stochastic components [45]. 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 [139], [150], [153].

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 [58]. Besides, we plan to extend previous works on sensitivity analysis [90], [128] 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 [61] (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 [150]. 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 [141] 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 [56], [108] for the backward time integration of the adjoint variables. The sensitivity equation method (SEM) offers a promising alternative [89], [118], 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 [90].
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) [143] , Detached-Eddy Simulation (DES) [147] or Organized-Eddy Simulation (OES) [62], 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 [120] 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

n 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 [91] [92]. 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 [93] 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 [136] 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 [156].

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 [100]. 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 [47] 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 [155]. However, the lack of efficient and flexible numerical models, 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 an industrial context. In particular, the prediction of actuated flows requires the use of advanced turbulence closures, like Detached Eddy Simulation or Large Eddy Simulation [104]. They are intrinsically three-dimensional and unsteady, yielding a huge computational effort for each analysis, which makes their use tedious for optimization purpose. 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.
- *Hierarchical optimization of control devices.* The optimization of dozen of actuators, in terms of locations, frequencies, amplitudes, will be practically tractable only if a hierarchical approach is adopted, which mixes fine (DES) and coarse (URANS) simulations, and possibly experiments. We intend to develop such an optimization strategy on the basis of Gaussian Process models (*multi-fidelity kriging*).

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 [114]. Further improvements require more advanced models, keeping into better account interactions at the microscopic scale, and adapted control techniques, see [63] 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 [76], [102], 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 [119].
- *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 [116] 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 [69], [70]), 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 [84], [103] or via the Hamilton-Jacobi approach [69], [70] 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 [80].

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 [158]. 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% [158].

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 [149], [132]. 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 [111], dorsal closure [49], actin organization [48]). 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 [97] it is shown that Madin-Darby Canine Kidney (MDCK) cells extend cryptic lamellipodia to drive the migration, several rows behind the wound edge. In [137] 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 [94], [99], [101].

- **Game strategies for thermoelastography.** Thermoelastography is an innovative non-invasive control technology, which has numerous advantages over other techniques, notably in medical imaging [130]. 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 [112], [121], we have demonstrated that Nash game approaches are efficient to tackle ill-posedness. We intend to extend the results obtained for Laplace equations in [112], 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. [140], 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. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

Tunisian Women Mathematicians' Association (TWMA) awarded B. Yahyaoui (Acumes PhD) with the Best 2017 PhD Thesis in Applied Mathematics (October 2018).

6. New Software and Platforms

6.1. MGDA

Multiple Gradient Descent Algorithm
KEYWORDS: Descent direction - Multiple gradients - Multi-objective differentiable optimization

SCIENTIFIC DESCRIPTION: The software provides a vector d whose scalar product with each of the given gradients (or directional derivative) is positive provided a solution exists. 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.

https://hal.inria.fr/hal-01139994 https://hal.inria.fr/hal-01414741
FUNCTIONAL DESCRIPTION: 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
- URL: http://mgda.inria.fr

6.2. 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

6.3. 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

7. New Results

7.1. Macroscopic traffic flow models on networks

Participants: Guillaume Costeseque, Nikodem Dymski, Paola Goatin, Nicolas Laurent-Brouty, Shuxia Tang, Yunzhi Wu, Alexandre Bayen [UC Berkeley, CA, USA], Alexander Keimer [UC Berkeley, CA, USA], Antonella Ferrara [U Pavia, Italy], Giulia Piacentini [U Pavia, Italy].

The relaxation limit for ARZ model. The Aw-Rascle-Zhang model [55], [157] can now be considered as a classical traffic flow model. In [27], we detail the mathematical behavior of the Aw-Rascle-Zhang model with relaxation [54]. In a Lagrangian setting, we use the Wave-Front-Tracking method with splitting technique to construct a sequence of approximate solutions. We prove that this sequence admits a limit. We then show that the limit is a weak entropy solution of the relaxed system associated to a given initial datum with bounded variation. Finally, we prove that this limit converges to a weak solution of the scalar conservation law when the relaxation parameter goes to zero.

Bounded acceleration. In [29], we propose a new mathematical model accounting for the boundedness of traffic acceleration at a macroscopic scale. 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 use Wave Front Tracking techniques to construct approximate solutions to the Initial Value Problem. We present some numerical examples including the case of successive traffic signals on an arterial road and we compare the solution to our model with the solution given by the classical LWR equation in order to evaluate the impact of bounded acceleration.

Second order models with moving bottlenecks. In [25], we study the Aw-Rascle-Zhang (ARZ) model with non-conservative local point constraint on the density flux introduced in [Garavello, M., and Goatin, P. The Aw-Rascle traffic model with locally constrained flow. Journal of Mathematical Analysis and Applications 378, 2 (2011), 634-648], its motivation being, for instance, the modeling of traffic across a toll gate. We prove the existence of weak solutions under assumptions that result to be more general than those required in [Garavello, M., and Villa, S. The Cauchy problem for the Aw-Rascle-Zhang traffic model with locally constrained flow. Journal of Hyperbolic Differential Equations 14, 03 (2017), 393-414]. More precisely, we do not require that the waves of the first characteristic family have strictly negative speeds of propagation. The result is achieved by showing the convergence of a sequence of approximate solutions constructed via the wave-front tracking algorithm. The case of solutions attaining values at the vacuum is considered. We also present an explicit numerical example to describe some qualitative features of the solutions.

Traffic control by autonomous vehicles. We consider the possibility of properly controlling a moving bottleneck to improve the traffic flow. The traffic is represented by means of a macroscopic model able to take into account the interactions with the bottleneck. This latter interacts with the surrounding flow modifying the traffic density and the flow speed profiles. An optimal control problem is stated by using the speed of the moving bottleneck as control variable. Specifically, in [30] the MPC (Model Predictive Control) approach is used to get a fuel consumption reduction when the traffic is congested due to the presence of a fixed bottleneck on the highway. In addition we have demonstrated that no increase of the travel time is caused by the control application. The concept illustrated in this paper suggests a future innovative traffic control approach. Indeed the prospective of exploiting special vehicles with manipulable speed to control the traffic flow is particularly attractive given the expected increasing penetration rate of autonomous vehicles in traffic networks in future years.

Well-posedness of conservation laws on networks with finite buffers. In collaboration with A. Bayen and A. Keimer (UC Berkeley), we introduce a model capable of dealing with conservation laws on networks and the coupled boundary conditions at the junctions. To that end we introduce a buffer of fixed arbitrary size and time dependent split ratios at the junctions which represent how traffic should be routed. One of the most important and interesting property of the presented model is its capability of showing spill-back phenomena over junctions. Having defined the dynamics on the level of conservation laws we lift them up to Hamilton Jacobi equations. The corresponding formulation in terms of H-J allows us to attack the problem that boundary datum of in and out-going junctions is a function of the queue size and vice versa. We do this by defining a fixed-point problem in a proper Banach space setting and prove the existence of a solution. Thus, the problem is solved on the level of Hamilton-Jacobi equations and due to the existent theory we also obtain a solution on the level of conservation laws with boundary datum in the sense of Bardos-Leroux-Nédélec.

Altogether, the system of conservation laws – locally coupled via the boundary conditions is studied for analytical questions of well-posedness, uniqueness and existence.

Finally we detail how to use this framework on a non-trivial road network, with several intersections and finite-length links.

Minimum time boundary controls. In collaboration with A. Bayen and A. Keimer (UC Berkeley), we are investigating the minimum time control problem for traffic flow. More precisely, we seek for the inflow upstream boundary condition that drives congested traffic to free flow condition on a stretch of road in minimum time.

Big Data analysis and modeling of road Traffic. Yunzhi Wu's internship, funded by Inria under the program "Transverse Actions", was co-supervised by Acumes (P. Goatin and G. Costeseque) and Zenith (F. Masseglia and R. Akbarinia). In this project, we processed the traffic data collected by loop detectors in the Mediterranean region during 3 months in 2015 (provided by DIRMED). We aimed at finding out the characteristics of traffic data and provide a new way of traffic prediction and estimation. The method of Motif Discovery was used for abnormality detection and pattern discovery. A modified method was also used for congestion prediction. Then we use the Co-Clustering method to group the data by day and loop. The clustering results were used to do a grouped calibration of fundamental diagram.

7.2. Non-local conservation laws

Participants: Felisia Angela Chiarello, Paola Goatin, Elena Rossi, Florent Berthelin [COFFEE, Inria].

F.A. Chiarello's PhD thesis focuses on non-local conservation laws. In [22], 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 [21], 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 is submitted [40].

In the setting of Florent Berthelin's secondement, we studied the regularity properties of solutions of a non-local traffic model involving a convolution product. Unlike other studies, the considered kernel is discontinuous on $\mathbb{R}$. We proved Sobolev estimates and the convergence of approximate solutions solving a viscous and regularized non-local equation. It leads to weak, $C([0,T],L^2(\mathbb{R}))$, and smooth, $W^{2,2N}([0,T]\times\mathbb{R})$, solutions for the non-local traffic model [16].

7.3. Well-posedness results for Initial Boundary Value Problems

Participants: Paola Goatin, Elena Rossi.

We focused on the IBVP for a general scalar balance law in one space dimension and proved its well-posedness and the stability of its solutions with respect to variations in the flux and in the source terms. For both results, the initial and boundary data are required to be bounded functions with bounded total variations. The existence of solutions is obtained from the convergence of a Lax-Friedrichs type algorithm, while the stability follows from an application of Kruzkov's doubling of variables method [33].

Exploiting the same techniques, we focused also on a non local version of the scalar IBVP for a conservation law. The flux is indeed assumed to depend non locally on the unknown, and the non local operator is "aware of boundaries". For this non local problem, existence and uniqueness of solutions are provided. In particular, the uniqueness follows from the Lipschitz continuous dependence on initial and boundary data, which is proved exploiting the results on the local IBVP [43].

7.4. Isogeometric analysis

Participants: Régis Duvigneau, Stefano Pezzano, Maxime Stauffert, Asma Azaouzi [ENIT], Maher Moakher [ENIT].

High-order isogeometric solvers are developed, based on CAD representations for both the geometry and the solution space, for applications targeted by the team, in particular hyperbolic or convection-dominated problems. Specifically, we investigate a Discontinuous Galerkin method for hyperbolic systems such as compressible Euler, or Navier-Stokes equations, based on an isogeometric formulation[24]: the partial differential equations governing the flow are solved on rational parametric elements, that preserve exactly the geometry of boundaries defined by Non-Uniform Rational B-Splines (NURBS) thanks to Bézier extraction techniques, while the same rational approximation space is adopted for the solution.

This topic has been studied in the context of A. Azaouzi's PhD work defended in December 2018, in co-supervision with M. Moakher at ENIT. Current works concern local refinement strategies by splitting algorithms, the arbitrary Lagrangian-Eulerian formulation in the isogeometric context (PhD work of S. Pezzano) and high-order shape sensitivity analysis (Post-doc of M. Stauffert, PRE "GeoSim").

7.5. Sensitivity equation method for hyperbolic systems

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

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 one-dimensional compressible Euler equations. Different approaches are tested to integrate the additional source term: a Roe solver, a Godunov method and a moving cells approach[18].

This study is achieved in collaboration with C. Chalons from University of Versailles, in the context of C. Fiorini's PhD work, defended in July 2018.

7.6. Classification algorithms in Bayesian optimization

Participants: Régis Duvigneau, Matthieu Sacher [Ecole Navale], Frédéric Hauville [Ecole Navale], Olivier Le Maître [CNRS-LIMSI].

A Gaussian-Process based optimization algorithm is proposed to efficiently determine the global optimum for expensive simulations, when some evaluations may fail, due to unrealistic configurations, solver crash, degenerated mesh, etc. The approach is based on coupling the classical Bayesian optimization method with a classification algorithm, to iteratively identify the regions where the probability of failure is high[35].

The method is applied to the optimization of foils and sails in the context of racing yachts[34], in particular for the America's Cup in collaboration with Groupama team. This work was part of M. Sacher's PhD work at Ecole Navale, defended in September 2018.

7.7. Solving with games the coupled problems of conductivity or obstacle identification and data recovery

Participants: Abderrahmane Habbal, Rabeb Chamekh [PhD, LAMSIN, Univ. Tunis Al Manar], Marwa Ouni [PhD, LAMSIN, Univ. Tunis Al Manar], Moez Kallel [LAMSIN, Univ. Tunis Al Manar], Nejib Zemzemi [Inria Bordeaux, EPI CARMEN].

We extend in two directions our previous successful attempts [112], [121] to tackle ill posed inverse problems as Nash games.

In a first direction, a Nash game algorithm is used for the solution of coupled conductivity identification and data completion in cardiac electrophysiology. In [19], we consider the identification problem of the conductivity coefficient for an elliptic operator using an incomplete over-specified measurements on the surface. We define three players with three corresponding criteria. The two first players use Dirichlet and Neumann strategies to solve the completion problem, while the third one uses the conductivity coefficient as strategy, and uses a cost which basically relies on an established identifiability theorem. The implemented algorithm is used for the electrocardiography ECG imaging inverse problem, dealing with inhomogeneities in the torso domain. The inverse problem of ECG consists in finding the electric potential distribution on the heart's surface given the one on the torso, so that it is a data completion problem. Furthermore, in our approach, the conductivity coefficients are known only by an approximate values. we conduct numerical experiments on a 2D torso case including noisy measurements. Results illustrate the ability of our computational approach to tackle the difficult problem of joint identification and data completion.

The second direction deals with Nash strategies for the inverse inclusion Cauchy-Stokes problem. We introduce in [44] a new algorithm to solve the problem of detecting unknown cavities immersed in a stationary viscous fluid, using partial boundary measurements. The considered fluid obeys a steady Stokes regime, the cavities are inclusions and 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 inclusion Cauchy-Stokes problem is ill-posed for both the cavities and missing data reconstructions, and designing stable and efficient algorithms is not straightforward. We reformulate the problem as a three-player Nash game. Thanks to an identifiability result derived for the Cauchy-Stokes inclusion 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 inclusion detection. We used a level-set approach to get rid of the tricky control dependence of functional spaces, and we provided the third player with the level-set function as strategy, with a cost functional of Kohn-Vogelius type. We propose an original algorithm, which we implemented using Freefem++. We present 2D numerical experiments for three different test-cases.The obtained results corroborate the efficiency of our 3-player Nash game approach to solve parameter or shape identification for Cauchy problems.

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

Participants: Mickael Binois [Univ. Chicago], Victor Picheny [INRA, Toulouse], Abderrahmane Habbal.

Game theory finds nowadays a broad range of applications in engineering and machine learning. However, in a derivative-free, expensive black-box context, very few algorithmic solutions are available to find game equilibria. In [31], we propose a novel Gaussian-process based approach for solving games in this context. We follow a classical Bayesian optimization framework, with sequential sampling decisions based on acquisition functions. Two strategies are proposed, based either on the probability of achieving equilibrium or on the Stepwise Uncertainty Reduction paradigm. Practical and numerical aspects are discussed in order to enhance the scalability and reduce computation time. Our approach is evaluated on several synthetic game problems with varying number of players and decision space dimensions. We show that equilibria can be found reliably for a fraction of the cost (in terms of black-box evaluations) compared to classical, derivative-based algorithms.

Another ongoing scope of research in multi-objective Bayesian optimization is to extend its applicability to a large number of objectives : the so-called many-objective optimization. Regarding the harsh many-objective optimization problems, the recovering of the set of optimal compromise solution generally requires lots of observations while being less interpretable, since this set tends to grow larger with the number of objectives. We thus propose to focus on a choice of a specific solution originating from game theory, the Kalai-Smorodinsky solution, that possesses attractive properties. In particular, it ensures equal marginal gains over all objectives. We further make it insensitive to a monotonic transformation of the objectives by considering the objectives in the copula space. A novel tailored algorithm is proposed to search for the solution, in the form of a Bayesian optimization algorithm: sequential sampling decisions are made based on acquisition functions that derive from an instrumental GP prior. Our approach is tested on three problems with respectively four, six and ten objectives.

The Nash and Kalai-Smorodinsky methods are available in the R package `GPGame` available on CRAN at https://cran.r-project.org/package=GPGame.

7.9. Stochastic multiple gradient descent algorithm

Participants: Jean-Antoine Désidéri, Fabrice Poirion [ONERA Châtillon, Aeroelasticity and Structural Dynamics Dept.], Quentin Mercier [ONERA Châtillon, Aeroelasticity and Structural Dynamics Dept.].

We have proposed a new method for multi-objective optimization problems in which the objective functions are expressed as expectations of random functions. The present method is based on an extension of the classical stochastic gradient algorithm and a deterministic multi-objective algorithm, the Multiple Gradient Descent Algorithm (MGDA). In MGDA a descent direction common to all specified objective functions is identified through a result of convex geometry. The use of this common descent vector and the Pareto stationarity definition into the stochastic gradient algorithm makes the algorithm able to solve multi-objective problems. The mean square and almost sure convergence of this new algorithm are proven considering the classical stochastic gradient algorithm hypothesis. The algorithm efficiency is illustrated on a set of benchmarks with diverse complexity and assessed in comparison with two classical algorithms (NSGA-II, DMS) coupled with a Monte Carlo expectation estimator [129]

7.10. Non-convex multiobjective optimization under uncertainty

Participants: Jean-Antoine Désidéri, Fabrice Poirion [ONERA Châtillon, Aeroelasticity and Structural Dynamics Dept.], Quentin Mercier [ONERA Châtillon, Aeroelasticity and Structural Dynamics Dept.].

A novel algorithm for solving multi-objective 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 parallelized. 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 [129].

8. Partnerships and Cooperations

8.1. European Initiatives

8.1.1. FK32

Title: Multi-agent Fokker-Planck Nash games

Programm: Bayerisch-Französische Hochschulzentrum / Centre de Coopération Univ. Franco-Bavarois (BFHZ-CCUFB)

Duration: January - December 2018

PIs: A. Borzi (Univ. Wuerzburg) and A. Habbal

The purpose of this project is the formulation and application of a new mathematical framework for modeling avoidance and/or meeting in multi-agents' motion in the framework of differential games with stochastic processes and related Fokker-Planck equations.

8.1.2. FP7 & H2020 Projects

8.1.2.1. TramOpt

Title: A Traffic Management Optimization platform for enhanced road network efficiency

Programm: H2020

Duration: Mai 2017 - Octobre 2018

Coordinator: Inria

Inria contact: Paola Goatin

Building on the advances of the ERC TRAM3 project, the TRAMOPT PoC project aims are twofold:

- developing a robust prototype to allow real-life testing and deployment of a novel traffic control Decision Support System (DSS) based on a software platform for road traffic management including variable speed limits, ramp-metering and re-routing policies. This DSS is intended for public and private traffic managers to increase freeway network performances (e.g. congestion and pollution reduction);
- assessing the exploitation perspectives through a dedicated market study evaluating the added value of TRAMOPT over existing solutions and identifying the best business approach to foster uptake and commercialization of our technology.

8.2. International Initiatives

8.2.1. NAMReD

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.

8.2.2. Inria International Labs

Inria Chile

Associate Team involved in the International Lab:

8.2.2.1. NOLOCO

Title: Efficient numerical schemes for non-local transport phenomena

International Partner (Institution - Laboratory - Researcher):

Universidad del Bio-Bio (Chile) - Department of Mathematics - 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.

8.2.3. Inria International Partners

8.2.3.1. 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.

8.2.3.2. Informal International Partners

University of Brescia, Information Engineering (R.M. Colombo: http://rinaldo.unibs.it/)

University of Mannheim, Scientific Computing Research Group (SCICOM) (S. Göttlich: http://lpwima.math.uni-mannheim.de/de/team/prof-dr-simone-goettlich/)

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

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

Technical University of Kaiserslautern - Department of mathematics (B. Simeon https://www.mathematik.uni-kl.de/en/das/people/head/simeon/)

8.3. International Research Visitors

8.3.1. Visits of International Scientists

- M.D. Rosini (January 2018, Lublin University): co-direction of N. Dymski's PhD thesis.
- R.M. Colombo (July 2018, Brescia University): well-posedness of Initial Boundary Value Problems.
- L.M. Villada (September 2018, University of Bio-Bio): finite volume schemes for non-local systems of conservation laws.

8.3.2. Visits to International Teams

8.3.2.1. Research Stays Abroad

- N. Laurent-Brouty visited UC Berkeley (A. Bayen) for 1 month in April-May 2018.
- E. Rossi visited Mannheim University (S. Göttlich) for 1.5 months in September-October 2018.

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 *"HYP2018 - Conference on Hyperbolic Problems: Theory, Numerics, and Applications"*, Penn State (USA), June 2018.
- P. Goatin was member of the scientific committee of *"PED2018 - Conference on Pedestrian and Evacuation Dynamics"*, Lund (Sweden), August 2018.

9.1.1.2. Member of the Organizing Committees

- P. Goatin and M.L. Delle Monache (Inria Grenoble) organized the mini-symposium *"Modélisation et gestion du trafic routier"*, CANUM 2018 - 44e Congrès National d'Analyse Numérique, Cap d'Agde (France), May 2018.
- P. Goatin and J. Pettré (Inria Rennes) organized the workshop *"Modélisation du piéton et de la foule en mouvement"*, Saclay (France), November 2018.
- P. Goatin was member of the organizing committee of the workshop *"Mathematical modeling with measures: where applications, probability and determinism meet"*, Lorentz Center, Leiden (The Netherlands), December 2018.
- R. Duvigneau and A. Habbal are members of the OC for the FGS French-German-Swiss Conference on Optimization, Nice, September 2019.

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

- A. Habbal was PC member of the African Conference on Research in Computer Science and Applied Mathematics (CARI 2018), Stellenbosch, South Africa
- P. Goatin was member of the International Program Committee of *"CTS2018 - 15th IFAC Symposium on Control in Transportation Systems"*, Savona (Italy), June 2018.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- P. Goatin is Managing Editor of *Networks and Heterogeneous Media*.

9.1.3.2. Reviewer - Reviewing Activities

- J.-A. Désidéri has made reviews for *Mathematical Problems in Engineering* (Hindawi Publishing Corporation) and *Numerical Algorithms* (Springer),
- R. Duvigneau is a reviewer for the following international journals : Computers & Fluids, International Journal for Numerical Methods in Fluids, Computer Methods for Applied Mechanical Engineering, Computer Aided Geometric Design, Applied Mathematics & Mechanics, Engineering Optimization.
- P. Goatin reviewed for the following international journals: SIAM Journal of Applied Mathematics; Networks and Heterogeneous Media; European Journal of Applied Mathematics; Journal of Advanced Transportation; IEEE Transactions on Intelligent Transportation Systems; Discrete and Continuous Dynamical Systems A.
- A. Habbal is reviewer for the following international journals: Journal of Structural and Multidisciplinary Optimization ; Journal of Math. Model. Nat. Phenom. ; Int. Journal of Mathematical Modeling and Numerical Optimization; Journal of Differential Equations; American Mathematical Society Reviews; European Journal of Operation Research (EJOR); Journal of Optimization Theory and Algorithms (JOTA).

9.1.4. Invited Talks

- F.A. Chiarello: Interactive workshop on hyperbolic equations, University of Ferrara (Italy), September 2018.
  Invited talk: *"Non-local multi-class traffic flow models"*.

- J.-A. Désidéri: Prioritized Multiobjective Optimization Using Nash Games - Towards Adaptive Optimization, ONERA, Toulouse, December 20, 2018.
- P. Goatin: ECMI 2018 - 20th European Conference on Mathematics for Industry, Budapest (Hungary), June 2018.
  Plenary talk: *"Traffic management by macroscopic models"*.
- P. Goatin: 14th Franco-Romanian Conference on Applied Mathematics, Bordeaux (France), August 2018.
  Plenary talk: *"Traffic management by macroscopic models"*.
- P. Goatin: Rencontres Normandes sur les aspects théoriques et numériques des EDP, Rouen (France), November 2018.
  Invited talk: *"Conservation laws with local constraints arising in traffic modeling"*.
- P. Goatin: LIA COPDESC Workshop "Analysis, control and inverse problems for PDEs", Napoli (Italy), November 2018.
  Plenary talk: *"Traffic control by autonomous vehicles"*.
- P. Goatin: CDC 2018 - 57th IEEE Conference on Decision and Control, Miami, FL (USA), December 2018. Workshop "Traffic Flow Control via PDE Techniques".
  Invited talk: *"Macroscopic modeling of traffic control by autonomous vehicles"*.
- A. Habbal: XI NPU-UTC Sino-French Seminar on Mechanics and Design of Advanced Material and Structures Symposium, Xi'An, China, April 2018.
  Plenary talk: *Games to solve Joint Data Completion and Obstacle Detection in Stokes Problems*.
- A. Habbal: Univ. Wurzburg Chair of Mathematics (Scientific Computing) Mathematical Colloquium, Wurzburg, May 2018.
  Plenary talk: *Games to solve Joint Data Completion and Obstacle Detection in Stokes Problems*.
- A. Habbal: Conference on Inverse Problems, Control and Shape Optimization (PICOF) Beirut, Lebanon, June 18-20 2018.
  Invited talk: *Detection of inclusions while recovering boundary data in Stokes Flows using Nash strategies*.
- A. Habbal: University Mohamed V, Rabat, June 2018.
  Plenary talk: *Avoidance mechanisms arising as Nash equilibria in Fokker-Planck constrained games*.
- E. Rossi: IFIP TC 7 Conference on System Modelling and Optimization, Essen (Germany), July 2018. Workshop "Modeling and optimization of networked systems".
  Invited talk: *"Crowd dynamics in domains with boundaries"*.

9.1.5. Scientific Expertise

- P. Goatin was proposals reviewer for FONDECYT program of CONICYT (National Committee of Science and Technology Research, Chile), 2018.

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 member of BCP ("Bureau du Comité des Projets") at Inria Sophia Antipolis Méditerranée (until August 2018).
- P. Goatin was member of the admission committee for Inria 2018 competitive selection of senior researchers (DR2).
- R. Duvigneau is member of CSD ("Comité Suivi Doctoral) at Inria Sophia Antipolis Méditerranée.
- R. Duvigneau is responsible for the Immersive Space Committee at Inria Sophia Antipolis Méditerranée.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master: Advanced Optimization, 40.5 hrs, M2, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (J.-A. Désidéri, R. Duvigneau).

Master: Conservation laws and finite volume scheme, 30 hrs, M2, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (P. Goatin).

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

Licence: Summer Project in Mathematical Modeling, 36 hrs, L3, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (A. Habbal).

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

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

Master: Modeling strategies for e-Formula races, 10 hrs, M1 Students Project, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (A. Habbal).

Master: Multi-agents Systems, 10 hrs, M1 Students Project, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (A. Habbal).

Master: Modeling and simulation of electric mobility, 10 hrs, M1 Students Project, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (A. Habbal).

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

Graduate autumn school “Theoretical and numerical aspects of PDEs”, Rouen (France), November 2018. Lecture: *“Macroscopic traffic flow models on networks”* (P. Goatin).

9.2.2. Supervision

PhD in progress: Rabeb Chamekh, *Game strategies for thermo-elasticity*, Jan 2015, Supervisors: A. Habbal, Moez Kallel (LAMSIN, ENIT, Tunis)

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 in progress: Kelthoum Chahour, *Modeling and optimal design of coronary angioplastic stents*, Nov 2015, Supervisors: A. Habbal, Rajae Aboulaich (LERMA, EMI, Rabat)

PhD defended in June 2018: C. Durantin, *Métamodélisation et optimisation de dispositifs photoniques* (Meta-modelling and Optimization for nanophotonic devices), University of Nice - Sophia Antipolis, June 2018. Supervisors: J.-A. Désidéri and A. Glière (CEA LETI).

PhD defended in October 2018: Q. Mercier, *Algorithme de descente pour la résolution de problèmes d'optimisation multiobjectif sous incertitudes* (Descent Algorithm for the solution of multi-objective optimization problems under uncertainties), University of Nice - Sophia Antipolis, October 2018. Supervisors: J.-A. Désidéri and F. Poirion (ONERA Châtillon).

PhD defended in December 2018: A. Azaouzi, *isogeometric analysis methods for hyperbolic systems*, ENIT (Tunisia) / University of Nice - Sophia Antipolis, Oct. 2018. Supervisors: R. Duvigneau and M. Moakher (ENIT).

PhD defended in November 2018 : Sosina Mengistu-Gashaw (EURECOM), *Mobility and connectivity modelling of 2-wheels traffic for ITS applications* , March 2015. Supervisors: P. Goatin and J. Härri (EURECOM).

PhD defended in September 2018: M. Sacher, *advanced methods for numerical optimization of yacht performance*, Ecole Navale , Oct. 2014. Supervisors: R. Duvigneau, O. Le Maitre (LIMSI), F. Hauville and J.-A. Astolfi (Ecole Navale).

PhD defended in July 2018: C. Fiorini, *Sensitivity equation method for hyperbolic systems*, Univ. Versailles, Oct. 2014. Supervisors: R. Duvigneau, C. Chalons (Univ. Versailles).

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

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

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

PhD in progress : 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).

9.2.3. Juries

- R. Duvigneau was member of the committee of P. Ploe's PhD thesis *"Surrogate based optimization of hydrofoil shapes using RANS simulations"*, Ecole Centrale de Nantes, June 26th, 2018.
- R. Duvigneau was member of the committee of F. Mastrippolito's PhD thesis *"Optimisation de forme numérique de problèmes multiphysiques et multiéchelles : application aux échangeurs de chaleur"*, Ecole Centrale de Lyon, December 14th, 2018.
- P. Goatin was referee of M. Pfirsching's PhD thesis *"A multi-scale model for material flow problems based on a non-local conservation law: simulation and optimization"*, Universität Mannheim, April 11th, 2018.
- J.-A. Désidéri was referee of T. Achard's PhD. Thesis *Techniques de calcul du gradient aéro-structure haute-fidélité pour l'optimisation de voilures flexibles* (Techniques for computing the high-fidelity aero-structural gradient for the optimization of flexible wings), CNAM, Paris, December 2017.
- J.-A. Désidéri was a member of the jury of J. Mas Colomer's Phd. Thesis *Similitude Aéroélastique d'un Démonstrateur en Vol via l'Optimisation Multidisciplinaire* (Aeroelastic similarity of a Flight Demonstrator via Multidisciplinary Optimization), University of Toulouse, December 2018.

9.3. Popularization

9.3.1. Articles and contents

- Press article: *Dossier. Cette mathématicienne met le trafic en équation pour réduire les embouteillages*, Nice Matin, August 2018 (P. Goatin).
- TV interview for the program "Dimanche en politique", France 3 Côte d'Azur channel, October 14, 2018 (P. Goatin).

10. Bibliography

Major publications by the team in recent years

[1] A. AGGARWAL, R. M. COLOMBO, P. GOATIN.*Nonlocal systems of conservation laws in several space dimensions*, in "SIAM Journal on Numerical Analysis", 2015, vol. 52, n^{o} 2, p. 963-983, https://hal.inria.fr/hal-01016784

[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

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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

[8] R. DUVIGNEAU, P. CHANDRASHEKAR.*Kriging-based optimization applied to flow control*, in "Int. J. for Numerical Methods in Fluids", 2012, vol. 69, n^o 11, p. 1701-1714

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[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

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[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

Articles in International Peer-Reviewed Journal

[16] F. BERTHELIN, P. GOATIN.*Regularity results for the solutions of a non-local model of traffic*, in "Discrete and Continuous Dynamical Systems - Series A", 2018, https://hal.archives-ouvertes.fr/hal-01813760

[17] K. CHAHOUR, R. ABOULAICH, A. HABBAL, C. ABDELKHIRANE, N. ZEMZEMI.*Numerical simulation of the fractional flow reserve (FFR)*, in "Mathematical Modelling of Natural Phenomena", 2018, https://hal.inria.fr/hal-01944566

[18] C. CHALONS, R. DUVIGNEAU, C. FIORINI.*Sensitivity analysis and numerical diffusion effects for hyperbolic PDE systems with discontinuous solutions. The case of barotropic Euler equations in Lagrangian coordinates*, in "SIAM Journal on Scientific Computing", November 2018, vol. 40, n^{o} 6, p. A3955-A3981, https://hal.inria.fr/hal-01589337

[19] R. CHAMEKH, A. HABBAL, M. KALLEL, N. ZEMZEMI.*A nash game algorithm for the solution of coupled conductivity identification and data completion in cardiac electrophysiology*, in "Mathematical Modelling of Natural Phenomena", 2018 [*DOI :* 10.1051/MMNP/180143], https://hal.archives-ouvertes.fr/hal-01923819

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[22] F. A. CHIARELLO, P. GOATIN, E. ROSSI.*Stability estimates for non-local scalar conservation laws*, in "Nonlinear Analysis: Real World Applications", 2019, vol. 45, p. 668-687, https://arxiv.org/abs/1801.05587 , https://hal.inria.fr/hal-01685806

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[26] S. GASHAW, P. GOATIN, J. HÄRRI.*Modeling and Analysis of Mixed Flow of Cars and Powered Two Wheelers*, in "Transportation research. Part C, Emerging technologies", 2018, p. 1-44, https://hal.inria.fr/hal-01708005

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[28] O. KOLB, G. COSTESEQUE, P. GOATIN, S. GÖTTLICH.*Pareto-optimal coupling conditions for the Aw-Rascle-Zhang traffic flow model at junctions*, in "SIAM Journal on Applied Mathematics", July 2018, vol. 78, n^{o} 4, p. 1981-2002, https://arxiv.org/abs/1707.01683 , https://hal.inria.fr/hal-01551100

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Project-Team AROMATH

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A8.3. - Geometry, Topology
A8.4. - Computer Algebra

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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 the seams. 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 is based 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 Software and Platforms

5.1. Platforms

5.1.1. Axl

KEYWORDS: Algorithm , CAD , Numerical algorithm , Geometric algorithms

SCIENTIFIC DESCRIPTION

Axl is an algebraic geometric modeler that aims at providing “algebraic modeling” tools for the manipulation and computation with curves, surfaces or volumes described by semi-algebraic representations. These include parametric and implicit representations of geometric objects. Axl also provides algorithms to compute intersection points or curves, singularities of algebraic curves or surfaces, certified topology of curves and surfaces, etc. A plugin mechanism allows to extend easily the data types and functions available in the plateform.

FUNCTIONAL DESCRIPTION

Axl is a cross platform software to visualize, manipulate and compute 3D objects. It is composed of a main application and several plugins. The main application provides atomic geometric data and processes, a viewer based on VTK, a GUI to handle objects, to select data, to apply process on them and to visualize the results. The plugins provides more data with their reader, writer, converter and interactors, more processes on the new or atomic data. It is written in C++ and thanks to a wrapping system using SWIG, its data structures and algorithms can be integrated into C# programs, as well as Python. The software is distributed as a source package, as well as binary packages for Linux, MacOSX and Windows.

- Participants: Emmanouil Christoforou, Nicolas Douillet, Anaïs Ducoffe, Valentin Michelet, Bernard Mourrain, Meriadeg Perrinel, Stéphane Chau and Julien Wintz
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Collaboration with Elisa Berrini (MyCFD, Sophia), Tor Dokken (Gotools library, Oslo, Norway), Angelos Mantzaflaris (GISMO library, Linz, Austria), Laura Saini (Post-Doc GALAAD/Missler, TopSolid), Gang Xu (Hangzhou Dianzi University, China), Meng Wu (Hefei University of Technology, China).

5.1.2. Skelton

KEYWORDS: Algorithm, Numerical algorithm, Geometric algorithm, Scaffolding, Implicit surface, Mesh generation

SCIENTIFIC DESCRIPTION

Skelton is a C++ library for skeleton-based modeling with convolution surfaces. It supports skeletons made of line segments and arcs of circle, including circular splines, and features an anisotropic extension to circular splines. The library can generate a quad dominant mesh that surrounds, and follows, the structure of the skeleton. The mesh is generated with an advanced scaffolding algorithm that works for skeletons of any topology.

FUNCTIONAL DESCRIPTION

Skelton is a multi-platform C++ library distributed as source code. It provides a class hierarchy for creating and manipulating geometric objects generated with anisotropic convolution. It can take the skeleton as an input file or defined directly by the user. The library supports an improved version of convolution surfaces and permits the design of anisotropic surfaces. The scaffolding algorithm can be used independently of the implicit surface definition. The library has a command line interface that controls most of the functionality. The user can subclass elements of the library for extended behavior.

- Participants: Alvaro Fuentes, Evelyne Hubert.
- Contacts: Alvaro Fuentes, Evelyne Hubert.
- URL: https://gitlab.inria.fr/afuentes/Skelton

6. New Results

6.1. Solving Polynomial Systems via Truncated Normal Forms

Participant: Bernard Mourrain.

In [12], 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 $\mathbb{C}$. We propose a general algebraic framework to find the solutions and to compute the structure of the quotient ring R/I from the null space of a Macaulay-type matrix. The affine dense, affine sparse, homogeneous, and multihomogeneous cases are treated. In the presented framework, the concept of a border basis is generalized by relaxing the conditions on the set of basis elements. This allows for algorithms to adapt the choice of basis in order to enhance the numerical stability. We present such an algorithm and show numerical results.

This is a joint work with Simon Telen and Marc Van Barel (Univ. Leuven, Belgium)

6.2. On supersolvable and nearly supersolvable line arrangements

Participant: Alexandru Dimca.

In the paper [3], we introduce a new class of line arrangements in the projective plane, called nearly supersolvable, and show that any arrangement in this class is either free or nearly free. More precisely, we show that the minimal degree of a Jacobian syzygy for the defining equation of the line arrangement, which is a subtle algebraic invariant, is determined in this case by the combinatorics. When such a line arrangement is nearly free, we discuss the splitting types and the jumping lines of the associated rank two vector bundle, as well as the corresponding jumping points, introduced recently by S. Marchesi and J. Vallès.

Joint work with Gabriel Sticlaru (Faculty of Mathematics and Informatics, Ovidius University, Romania).

6.3. Computing the monodromy and pole order filtration on Milnor fiber cohomology of plane curves

Participant: Alexandru Dimca.

In the paper [4], we describe an algorithm computing the monodromy and the pole order filtration on the Milnor fiber cohomology of any reduced projective plane curve C. The relation to the zero set of Bernstein-Sato polynomial of the defining homogeneous polynomial for C is also discussed. When C has some non weighted homogeneous singularities, then we have to assume that a conjecture holds in order to get some of our results. In all the examples computed so far this conjecture holds.

Joint work with Gabriel Sticlaru (Faculty of Mathematics and Informatics, Ovidius University, Romania).

6.4. Invariant Algebraic Sets and Symmetrization of Polynomial Systems

Participant: Evelyne Hubert.

Assuming the variety of a polynomial set is invariant under a group action, we construct, in [9], a set of invariants that cut the same variety. The construction can be seen as a generalization of the previously known construction for finite groups. The result though has to be understood outside an invariant variety which is independent of the polynomial set considered. We introduce the symmetrizations of a polynomial that are polynomials in a generating set of rational invariants. The generating set of rational invariants and the symmetrizations are constructed w.r.t. a section of the orbits of the group action.

6.5. Rational invariants of even ternary forms under the orthogonal group

Participant: Evelyne Hubert.

In [8], we determine a generating set of rational invariants of minimal cardinality for the action of the orthogonal group O_3 on the space $R[x, y, z]_{2d}$ of ternary forms of even degree $2d$. The construction relies on two key ingredients: On the one hand, the Slice Lemma allows us to reduce the problem to determining the invariants for the action on a subspace of the finite subgroup B_3 of signed permutations. On the other hand, our construction relies in a fundamental way on specific bases of harmonic polynomials. These bases provide maps with prescribed B_3-equivariance properties. Our explicit construction of these bases should be relevant well beyond the scope of this paper. The expression of the B_3-invariants can then be given in a compact form as the composition of two equivariant maps. Instead of providing (cumbersome) explicit expressions for the O_3-invariants, we provide efficient algorithms for their evaluation and rewriting. We also use the constructed B_3-invariants to determine the O_3-orbit locus and provide an algorithm for the inverse problem of finding an element in $R[x, y, z]_{2d}$ with prescribed values for its invariants. These are the computational issues relevant in brain imaging.

This is a joint work with P. Görlach (Max Planck institute, Leipzig) and T. Papadopoulo (EPI Athena, Inria SAM)

6.6. Algorithms for Computing Cubatures Based on Moment Theory

Participant: Evelyne Hubert.

Quadrature is an approximation of the definite integral of a function by a weighted sum of function values at specified points, or nodes, within the domain of integration. Gaussian quadratures are constructed to yield exact results for any polynomials of degree $2r - 1$ or less by a suitable choice of r nodes and weights. Cubature is a generalization of quadrature in higher dimension. In [2] we elaborate algorithms to compute all minimal cubatures for a given domain and a given degree. We propose first an algorithm in symbolic computation to characterize all cubatures of a given degree with a fixed number of nodes. The determination of the nodes and weights is then left to the computation of the eigenvectors of the matrix identified at the characterization stage and can be performed numerically. The characterisation of cubatures on which our algorithms are based stems from moment theory. We formulate the results there in a basis independent way : rather than considering the moment matrix, the central object in moment problems, we introduce the underlying linear map from the polynomial ring to its dual, the Hankel operator. This makes natural the use of bases of polynomials other than the monomial basis, and proves to be computationally relevant, either for numerical properties or to exploit symmetry.

Joint work with M. Collowald, (previously Université Nice Sophia Antipolis).

6.7. Products of Euclidean Metrics and Applications to Proximity Questions among Curves

Participants: Ioannis Emiris, Ioannis Psarros.

In [18], we study Approximate Nearest Neighbor (ANN) search on 1-dimensional shapes. We start with distance functions between discretized curves in Euclidean space: they appear in a wide range of applications, from road segments and molecular backbones to time-series in general dimension. For p-products of Euclidean metrics, for any positive integer p, we design simple and efficient data structures for ANN, based on randomized projections, which are of independent interest. They serve to solve proximity problems under a notion of distance between discretized curves, which generalizes both discrete Fréchet and Dynamic Time Warping distances. These are the most popular and practical approaches to comparing such curves. We offer the first data structures and query algorithms for ANN with arbitrarily good approximation factor, at the expense of increasing space usage and preprocessing time over existing methods. Query time complexity is comparable or significantly improved by our algorithms.

6.8. Efficient Random-Walk Methods for Approximating Polytope Volume

Participant: Ioannis Emiris.

In [5] we experimentally study the fundamental problem of computing the volume of a convex polytope given as an intersection of linear inequalities. We implement and evaluate practical randomized algorithms for accurately approximating the polytope's volume in high dimensions (e.g. one hundred). To carry out this efficiently we experimentally correlate the effect of parameters, such as random walk length and number of sample points, on accuracy and runtime. Moreover, we exploit the problem's geometry by implementing an iterative rounding procedure, computing partial generations of random points and designing fast polytope boundary oracles. Our publicly available code is significantly faster than exact computation and more accurate than existing approximation methods. We provide volume approximations for the Birkhoff polytopes of order 11 to 15, whereas exact methods have only computed that for order 10.

This is a joint work with Vissarion Fisikopoulos (Oracle Corp., Athens, Greece).

6.9. Randomized Embeddings with Slack and High-Dimensional Approximate Nearest Neighbor

Participants: Evangelos Anagnostopoulos, Ioannis Emiris, Ioannis Psarros.

In [1], we study the approximate nearest neighbor problem (e-ANN) in high dimensional Euclidean space with methods beyond Locality Sensitive Hashing (LSH), which has polynomial dependence in the dimension, sublinear query time, but subquadratic space requirement. In particular, we introduce a new definition of "low-quality" embeddings for metric spaces. It requires that, for some query point q, there exists an approximate nearest neighbor among the pre-images of the k approximate nearest neighbors in the target space. Focusing on Euclidean spaces, we employ random projections in order to reduce the original problem to one in a space of dimension inversely proportional to k. The k approximate nearest neighbors can be efficiently retrieved by a data structure such as BBD-trees. The same approach is applied to the problem of computing an approximate near neighbor, where we obtain a data structure requiring linear space, and query time in $O(dn^{\rho})$, for $\rho{\approx}1{-}e^2/\log(1/e)$. This directly implies a solution for e-ANN, while achieving a better exponent in the query time than the method based on BBD-trees. Better bounds are obtained in the case of doubling subsets of ℓ^2, by combining our method with r-nets. We implement our method in C++, and present experimental results in dimension up to 500 and 10^6 points, which show that performance is better than predicted by the analysis. In addition, we compare our ANN approach to E2LSH, which implements LSH, and we show that the theoretical advantages of each method are reflected on their actual performance.

6.10. Practical Volume Computation of Structured Convex Bodies, and an Application to Modeling Portfolio Dependencies and Financial Crises

Participants: Ioannis Emiris, Apostolos Chalkis.

In [16], we examine volume computation of general-dimensional polytopes and more general convex bodies, defined as the intersection of a simplex by a family of parallel hyperplanes, and another family of parallel hyperplanes or a family of concentric ellipsoids. Such convex bodies appear in modeling and predicting financial crises. The impact of crises on the economy (labor, income, etc.) makes its detection of prime interest for the public in general and for policy makers in particular. Certain features of dependencies in the markets clearly identify times of turmoil. We describe the relationship between asset characteristics by means of a copula; each characteristic is either a linear or quadratic form of the portfolio components, hence the copula can be constructed by computing volumes of convex bodies. We design and implement practical algorithms in the exact and approximate setting, we experimentally juxtapose them and study the tradeoff of exactness and accuracy for speed. We analyze the following methods in order of increasing generality: rejection sampling relying on uniformly sampling the simplex, which is the fastest approach, but inaccurate for small volumes; exact formulae based on the computation of integrals of probability distribution functions, which are the method of choice for intersections with a single hyperplane; an optimized Lawrence sign decomposition method, since the polytopes at hand are shown to be simple with additional structure; Markov chain Monte Carlo algorithms using random walks based on the hit-and-run paradigm generalized to nonlinear convex bodies and relying on new methods for computing a ball enclosed in the given body, such as a second-order cone program; the latter is experimentally extended to non-convex bodies with very encouraging results. Our C++ software, based on CGAL and Eigen and available on github, is shown to be very effective in up to 100 dimensions. Our results offer novel, effective means of computing portfolio dependencies and an indicator of financial crises, which is shown to correctly identify past crises. (The views expressed are those of the authors and do not necessarily reflect official positions of the European Commission.)

This is a joint work with Ludovic Calées (EU JRC, Ispra, Italy), and Vissarion Fisikopoulos (Oracle Corp., Athens, Greece).

6.11. On the maximal number of real embeddings of spatial minimally rigid graphs

Participants: Ioannis Emiris, Evangelos Bartzos.

In [15], we study the number of embeddings of minimally rigid graphs in Euclidean space R^D, which is (by definition) finite, modulo rigid transformations, for every generic choice of edge lengths. Even though various approaches have been proposed to compute it, the gap between upper and lower bounds is still enormous. Specific values and its asymptotic behavior are major and fascinating open problems in rigidity theory. Our work considers the maximal number of real embeddings of minimally rigid graphs in R^3. We modify a commonly used parametric semi-algebraic formulation that exploits the Cayley-Menger determinant to minimize the *a priori* number of complex embeddings, where the parameters correspond to edge lengths. To cope with the huge dimension of the parameter space and find specializations of the parameters that maximize the number of real embeddings, we introduce a method based on coupler curves that makes the sampling feasible for spatial minimally rigid graphs. Our methodology results in the first full classification of the number of real embeddings of graphs with 7 vertices in R^3, which was the smallest open case. Building on this and certain 8-vertex graphs, we improve the previously known general lower bound on the maximum number of real embeddings in R^3.

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

6.12. Curved Optimal Delaunay Triangulation

Participant: Laurent Busé.

Meshes with curvilinear elements hold the appealing promise of enhanced geometric flexibility and higher-order numerical accuracy compared to their commonly-used straight-edge counterparts. However, the generation of curved meshes remains a computationally expensive endeavor with current meshing approaches: high-order parametric elements are notoriously difficult to conform to a given boundary geometry, and enforcing a smooth and non-degenerate Jacobian everywhere brings additional numerical difficulties to the meshing of complex domains. In the paper [6], we propose an extension of Optimal Delaunay Triangulations (ODT) to curved and graded isotropic meshes. By exploiting a continuum mechanics interpretation of ODT instead of the usual approximation theoretical foundations, we formulate a very robust geometry and topology optimization of Bézier meshes based on a new simple functional promoting isotropic and uniform Jacobians throughout the domain. We demonstrate that our resulting curved meshes can adapt to complex domains with high precision even for a small count of elements thanks to the added flexibility afforded by more control points and higher order basis functions.

Joint work Leman Feng (ENPC), Pierre Alliez (EPI Titane), Hervé Delingette (EPI Asclepios) and Mathieu Desbrun (CalTech, USA),

6.13. Convolution surfaces with varying radius: Formulae for skeletons made of arcs of circles and line segments

Participants: Evelyne Hubert, Alvaro Javier Fuentes Suárez.

In [19], we develop closed form formulae for the computation of the defining fields of convolutions surfaces. The formulae are obtained for power inverse kernels with skeletons made of line segments or arcs of circle. To obtain the formulae we use Creative Telescoping and describe how this technique can be used for other families of kernels and skeleton primitives. We apply the new formulae to obtain convolution surfaces around $\mathcal{G}^1$ skeletons, some of them closed curves. We showcase how the use of arcs of circles greatly improves the visualization of the surface around a general curve compared with a segment based approach.

6.14. Scaffolding a Skeleton with Quadrangular Tubes

Participant: Evelyne Hubert.

The goal of [22] is to construct a quadrilateral mesh around a one-dimensional skeleton that is as coarse as possible, the "scaffold". A skeleton allows one to quickly describe a shape, in particular a complex shape of high genus. The constructed scaffold is then a potential support for the surface representation: it provides a topology for the mesh, a domain for parametric representation (a quad mesh is ideal for tensor product splines) or, together with the skeleton, a grid support on which to project an implicit surface that is naturally defined by the skeleton through convolution. We provide a constructive algorithm to derive a quad-mesh scaffold with topologically regular cross-sections (which are also quads), and no T-junctions. We show that this construction is optimal in the sense that no coarser quad mesh with topologically regular cross-sections may be constructed. Finally, we apply an existing rotation minimization algorithm along the skeleton branches, which produces a mesh with a natural edge flow along the shape.

This is joint work with A. Panotopoulou (Dartmouth College), E. Ross (MESH consultants), K. Welker (University of Trier), G. Morin (Intitut de Recherche en Informatique de Toulouse).

6.15. Scaffolding skeletons using spherical Voronoi diagrams: feasibility, regularity and symmetry

Participants: Evelyne Hubert, Alvaro Javier Fuentes Suárez.

Given a skeleton made of line segments, in [7] we describe how to obtain a coarse quad mesh of a surface that encloses tightly the skeleton and follows its structure - the scaffold. We formalize as an Integer Linear Program the problem of constructing an optimal scaffold that minimizes the total number of quads on the mesh. We prove the feasibility of the Integer Linear Program for any skeleton. In particular we can generate these scaffolds for skeletons with cycles. We additionally show how to obtain regular scaffolds, i.e. with the same number of quad patches around each line segment, and symmetric scaffolds that respect the symmetries of the skeleton. An application to polygonization of skeleton-based implicit surfaces is also presented.

6.16. Exact conversion from Bézier tetrahedra to Bézier hexahedra

Participant: Bernard Mourrain.

Modeling and computing of trivariate parametric volumes is an important research topic in the field of three-dimensional isogeometric analysis. In [13], we propose two kinds of exact conversion approaches from Bézier tetrahedra to Bézier hexahedra with the same degree by reparametrization technique. In the first method, a Bézier tetrahedron is converted into a degenerate Bézier hexahedron, and in the second approach, a non-degenerate Bézier tetrahedron is converted into four non-degenerate Bézier hexahedra. For the proposed methods, explicit formulae are given to compute the control points of the resulting tensor-product Bézier hexahedra. Furthermore, in the second method, we prove that tetrahedral spline solids with C^k-continuity can be converted into a set of tensor-product Bézier volumes with G^k-continuity. The proposed methods can be used for the volumetric data exchange problems between different trivariate spline representations in CAD/CAE. Several experimental results are presented to show the effectiveness of the proposed methods.

This is a joint work with Gang Xu (Hanghzou, China), Yaoli Jin (Hanghzou, China), Zhoufang Xiao (Hanghzou, China), Qing Wu (Hanghzou, China), Timon Rabczuk (Weimar, Germany).

6.17. Constructing IGA-suitable planar parameterization from complex CAD boundary by domain partition and global/local optimization

Participant: Bernard Mourrain.

In the paper [14], we propose a general framework for constructing IGA-suitable planar B-spline parameterizations from given complex CAD boundaries. Instead of the computational domain bounded by four B-spline curves, planar domains with high genus and more complex boundary curves are considered. Firstly, some pre-processing operations including Bézier extraction and subdivision are performed on each boundary curve in order to generate a high-quality planar parameterization; then a robust planar domain partition framework is proposed to construct high-quality patch-meshing results with few singularities from the discrete boundary formed by connecting the end points of the resulting boundary segments. After the topology information generation of quadrilateral decomposition, the optimal placement of interior Bézier curves corresponding to the interior edges of the quadrangulation is constructed by a global optimization method to achieve a patch-partition with high quality. Finally, after the imposition of C^1/G^1-continuity constraints on the interface of neighboring Bézier patches with respect to each quad in the quadrangulation, the high-quality Bézier patch parameterization is obtained by a local optimization method to achieve uniform and orthogonal iso-parametric structures while keeping the continuity conditions between patches. The efficiency and robustness of the proposed method are demonstrated by several examples which are compared to results obtained by the skeleton-based parameterization approach.

This is a joint work with Gang Xu (Hanghzou, China), Ming Li (Zhejiang, China), Timon Rabczuk (Weimar, Germany), Jinlan Xu (Hangzhou, China), Stéphane P.A. Bordas (Luxembourg).

6.18. A Classification Approach to Efficient Global Optimization in Presence of Non-Computable Domains

Participant: Elisa Berrini.

Gaussian-Process based optimization methods have become very popular in recent years for the global optimization of complex systems with high computational costs. These methods rely on the sequential construction of a statistical surrogate model, using a training set of computed objective function values, which is refined according to a prescribed infilling strategy. However, this sequential optimization procedure can stop prematurely if the objective function cannot be computed at a proposed point. Such a situation can occur when the search space encompasses design points corresponding to an unphysical configuration, an ill-posed problem, or a non-computable problem due to the limitation of numerical solvers. To avoid such a premature stop in the optimization procedure, we propose in [11] to use a classification model to learn non-computable areas and to adapt the infilling strategy accordingly. Specifically, the proposed method splits the training set into two subsets composed of computable and non-computable points. A surrogate model for the objective function is built using the training set of computable points, only, whereas a probabilistic classification model is built using the union of the computable and non-computable training sets. The classifier is then incorporated in the surrogate-based optimization procedure to avoid proposing new points in the non-computable domain while improving the classification uncertainty if needed. The method has the advantage to automatically adapt both the surrogate of the objective function and the classifier during the iterative optimization process. Therefore, non-computable areas do not need to be a priori known. The proposed method is applied to several analytical problems presenting different types of difficulty, and to the optimization of a fully nonlinear fluid-structure interaction system. The latter problem concerns the drag minimization of a flexible hydrofoil with cavitation constraints. The efficiency of the proposed method compared favorably to a reference evolutionary algorithm, except for situations where the feasible domain is a small portion of the design space.

This is joint work with Matthieu Sacher (IRENAV), Régis Duvigneau (ACUMES), Olivier Le Maitre (LIMSI), Mathieu Durand (K-Epsilon), Frédéric Hauville (IRENAV), Jacques-André Astolfi (IRENAV).

6.19. Compressions of a polycarbonate honeycomb

Participant: André Galligo.

In [21], the in-plane compressive response of a polycarbonate honeycomb with circular close-packed cells is considered first experimentally then analytically. Under quasi-static uniaxial compression, we observed behaviors strongly depending on the orientation: for one of the two main orientations the compression is homogeneous, while for the other the deformation localizes in a very narrow band of cells. More surprisingly, for not crushing but extreme compression, when the load is released, the deformation is reversed, the localization disappears and the polycarbonate returns to its original shape. In order to explain this strange phenomena, we develop a geometric model of this honeycomb together with an expression of the bending energy. We focus on a basic mechanical element made of an elastica triangle. We also compare our description with previous experimental studies and simulations made with similar material. Finally , to illustrate mathematically this type of behavior, we present a simple model for buckling deformations with two degrees of freedom.

This is a joint work with Jean Rajchenbach (LPMC, UCA) and Bernard Rousselet (JAD, UCA).

6.20. Modeling and Computation of a liquid-vapor bubble formation

Participant: André Galligo.

The Capillary Equation correctly predicts the curvature evolution and the length of a quasi-static vapour formation. It describes a two-phase interface as a smooth curve resulting from a balance of curvatures that are influenced by surface tension and hydrostatic pressures. The present work provides insight into the application of the Capillary Equation to the prediction of single nu-cleate site phase change phenomena. In an effort to progress towards an application of the Capillary Equation to boiling events, a procedure to generating a numerical solution, in which the computational expense is reduced, is reported in [20].

This is a joint work with Frédéric Lesage (LCPI, UCA), Sebastian Minjeaud (JAD, UCA).

6.21. Axl, a geometric modeler for semi-algebraic shapes

Participants: Emmanouil Christoforou, Bernard Mourrain.

In [17], we describe the algebraic-geometric modeling platform Axl, which provides tools for the manipulation, computation and visualisation of semi-algebraic models. This includes meshes, basic geometric objects such as spheres, cylinders, cones, ellipsoids, torus, piecewise polynomial parameterisations of curves, surfaces or volumes such as B-spline parameterisations, as well as algebraic curves and surfaces defined by polynomial equations. Moreover, Axl provides algorithms for processing these geometric representations, such as computing intersection loci (points, curves) of parametric models, singularities of algebraic curves or surfaces, certified topology of curves and surfaces, etc. We present its main features and describe its generic extension mechanism, which allows one to define new data types and new processes on the data, which benefit from automatic visualisation and interaction facilities. The application capacities of the software are illustrated by short descriptions of plugins on algebraic curves and surfaces and on splines for Isogeometric Analysis.

This is a joint work with Angelos Mantzaflaris (JKU, Austria), Julien Wintz (SED, Inria).

7. Partnerships and Cooperations

7.1. Regional Initiatives

Our team AROMATH participates to the VADER project for VIRTUAL MODELING of RESPIRATION, UCA Jedi, axis “Modélisation, Physique et Mathématique du vivant". http://benjamin.mauroy.free.fr/VADER.

7.2. European Initiatives

7.2.1. FP7 & H2020 Projects

Program: Marie Skłodowska-Curie ITN

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 & hydrodynamics, and to tools for motion design, robot kinematics, path planning, and control of machining tools.

7.3. International Initiatives

7.3.1. Inria International Partners

NSFC collaboration project with Gang Xu, Hangzhou Dianzi University, China, “Research on theory and method of time-varying parameterization for dynamic isogeometric analysis”, 2018-2021.

7.4. International Research Visitors

7.4.1. Visits of International Scientists

Aron Simis, University of Recife, Brazil, visited L. Busé for a week (October 8-12) to work on birationality of rational map by means of syzygy-based techniques.

Ibrahim Adamou, Univ. Dan Dicko Dankoulodo de Maradi, Niger, visited B. Mourrain (26 Nov.- 21 Dec.) to work on 3-dimensional VoronoïDiagrams of half-lines and medial axes of curve arcs.

7.4.1.1. Internships

Yairon Cid Ruiz, a PhD srudent at Barcelona in the Arcades network, visited L. Busé for 6 months (October 2017- March 2018) to work on birationality criteria for multi-graded rational maps with a view towards free form deformation problems.

Clément Laroche, a PhD student in Greece in the Arcades network, visited L. Busé and F. Yildirim for one month (October) for a collaboration on implicization matrices of rational curve in arbitrary dimension by means of quadratic relations.

Kim Perriguey, did a six months internship with L. Busé (December 2017-May 2018). She developed paramteric models for the human walk for the extraction of locomotive parameters. This work was done in collaboration with Pierre Alliez (EPI Titane) and the start-up Ekinnox (Sophia Antipolis).

7.4.2. Visits to International Teams

7.4.2.1. Research Stays Abroad

F. Yildirim was on secondment at MISSLER Topsolid (France), for 3 months (Mai-July).

From October 25th to November 25th, E. Hubert visited the Institute for Computational and Experimental Research in Mathematics (Providence USA) during the program *Nonlinear Algebra*.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. General Chair, Scientific Chair

Evelyne Hubert was the general and scientific chair for the conference *Symmetry and Computation* held at the Centre International de Recherche en Mathematiques (Marseille, France) April 3-7.

8.1.1.2. Member of the Organizing Committees

Laurent Busé organized the second “Learning Week” of the ARCADES Network : “Opportunity Recognition” at Inria Sophia Antipolis, March 19-23, 2018.

8.1.2. Scientific Events Selection

8.1.2.1. Reviewer

Bernard Mourrain was reviewer for the conference ISSAC.

8.1.3. Journal

8.1.3.1. Member of the Editorial Boards

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).

Ioannis Emiris is associate editor of the Journal of Symbolic Computation (since 2003) and of Mathematics for Computer Science (since 2017).

Evelyne Hubert is associate editor of the Journal of Symbolic Computation (since 2007) and of Foundations of Computational Mathematics (since 2017).

8.1.3.2. Reviewer - Reviewing Activities

Laurent Busé reviewed for the journal *Linear Algebra and its Applications*, the journal *Computer Aided Geometric Design*, the journal of *Advances in Applied Mathematics*, the *Journal of Computational and Applied Mathematics*, the journal *Applicable Algebra in Engineering, Communication and Computing*, the journal *Computer Aided Design*, the *SIAM Journal on Applied Algebra and Geometry*.

Ioannis Emiris reviewed for the *SIAM Journal on Applied Algebra and Geometry*, the *Symposium of Computational Geometry*.

Bernard Mourrain reviewed for the *Journal of Algebra and its Application*, the journal *Computer Methods in Applied Mechanics and Engineering*, the journal *Computer Aided Geometric Design*, the *Journal of Computational and Applied Mathematics*, the *Journal of Symbolic Computation*, the journal *Mathematics of Computation*. He is also guest editor of the Special Issue of the *Journal Of Symbolic Computation* after MEGA 2017 [24].

Evelyne Hubert reviewed for the *Journal of Symbolic Computation*, the journal *Foundations of Comptutational Mathematics*, and the *Journal of Algebra*.

8.1.4. Invited Talks

Laurent Busé was an invited speaker at the conference “Applied and Computational Geometry” that took place at Loughborough University, Centre for Geometry and Applications, September 12-14, 2018.

Ioannis Emiris was an invited speaker at JRC Ispra, Italy, February 2018, at JK University (and gave a course), Linz, Austria, April-May 2018, at the “2nd Intern. Workshop on Geometry and Machine Learning” , within Computational Geometry Week, Budapest, Hungary, June 2018, at the “Symposium on Discrete Mathematics”, of the German Mathematical Society, Graz, Austria, June 2018, at CHIPSET Training School on Large-Scale Data Mining and Machine Learning for Big Data Analytics (and gave a course), Thessaloniki, 19 September 2018.

Bernard Mourrain was an invited speaker at the Workshop “Structured Matrix Days”, Lyon, 14-15 May, at the International conference on Approximation and Matrix Functions, Lille, May 31 - June 1, at the Workshop “Tensors” (and gave a course), Torino, 10-14 September, at the Workshop “A two-day journey in Computational Algebra and Algebraic Geometry” dedicated to Margherita Roggero, Torino, 27-28 Sep. He was invited at Univ. of Texas, Austin, for a collaboration with Pr. Chandajit Bajaj (29 January - 9 February), an invited participant of the semester on Nonlinear Algebra at ICERM, Providence, RI, USA from 1 to 19 Oct.

Evelyne Hubert gave a keynote lecture at the conference *Symmetry & Computation*, CIRM (Marseille, France) and was invited to give talks at the conference *Algebraic and Geometric Aspects of Numerical Methods for Differential Equations* held at the Mittag-Leffler Institute (Stockholm, Sweden), the *Séminaire différentiel*, jointly organized by Université Versailles St Quentin and Inria SIF, and the conference *Nonlinear Algebra in Applications* held at the Institute for Computational and Experimental Mathematics (Providence, USA).

8.1.5. Scientific Expertise

Evelyne Hubert was part of the hiring committees for the positions of Directeur de Recherche 2ème classe at Inria and for the position of Chargé de Recherche at Inria NGE. As part of the Commission d’Evaluation, she was also part of the promotion committee of Inria researchers (CRHC, DR1, DR0).

Evelyne Hubert was the external reviewer for the promotion of Wei Li to the rank of associate professor at the Chinese Academy of Science (Beijing).

8.1.6. Research Administration

Laurent Busé is a board member of the (national) labex AMIES (CRI-SAM representative) and a member of the steering committee of the MSI, *Maison de la Modélisation, de la Simulation et des Interactions* of the University Côte d’Azur. He is also an elected member of the CPRH (Commission Permanente de Ressources Humaines) of the math laboratory of the university of Nice, and is the Inria Sophia Antipolis centre representative at the “Academic Council” and the “Research Commission” of the University of Nice Sophia Antipolis. He participated to the hiring jury of junior researchers in Inria Sophia Antipolis.

Evelyne Hubert is a member of the Comission d’Evaluation, the national Inria evaluation committee. She is nominated to represent Inria at the Academic Council of the Université Côte d’Azur.

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

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

- Master : Laurent Busé, Geometric Modeling, 27h ETD, M2, EPU of the University of Nice-Sophia Antipolis.
- Master 2: Bernard Mourrain, Symbolic-Numeric Computation, 6h, Master ACSYON, Limoges.

8.2.2. Supervision

PhD in progress: Evangelos Anagnostopoulos, Geometric algorithms for massive data, LAMBDA Marie Skłodowska-Curie RISE Network, started in September 2016, supervised by Ioannis Emiris.

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: Apostolos Chalkis, Sampling in high-dimensional convex regions, started in June 2018, supervised by Ioannis Emiris.

PhD in progress: Emmanouil Christoforou, Geometric approximation algorithms for clustering, Bioinformatics scholarship, started in January 2018, supervised by Ioannis Emiris.

PhD in progress: Alvaro-Javier Fuentes-Suàrez, Skeleton-based modeling of smooth shapes. ARCADES Marie Skłodowska-Curie ITN, started in October 2016, supervised by Evelyne Hubert.

PhD: Jouhayna Harmouch, Low rank structured matrix decomposition and applications. Cotutelle Univ. Liban, cosupervised by Houssam Khalil, Mustapha Jazar and Bernard Mourrain. Defended in December.

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 in progress: Evangelos Bartzos, Algebraic elimination and Distance graphs. ARCADES Marie Skłodowska-Curie ITN, started in June 2016, supervised by Ioannis Emiris.

PhD in progress: Clément Laroche, Algebraic representations of geometric objects. ARCADES Marie Skłodowska-Curie ITN, started in November 2016, supervised by Ioannis Emiris.

PhD in progress: Ioannis Psarros, Dimensionality reduction and Geometric search, Greek scholarship foundation, started in Sep. 2015, supervised by Ioannis Emiris.

PhD in progress: Erick David Rodriguez Bazan, Symmetry preserving algebraic computation. CORDI Inria SAM, started in November 2017, supervised by Evelyne Hubert.

PhD in progress: Fatmanur Yildirim, Distances between points, rational Bézier curves and surfaces by means of matrix-based implicit representations. ARCADES Marie Skłodowska-Curie ITN, started in October 2016, supervised by Laurent Busé.

8.2.3. Juries

L. Busé was a member of the committee of the PhD of Rémi Bignalet-Cazalet entitled *Géométrie de la projectivisation des idéaux et applications aux problèmes de birationalité*, University Bourgogne Franche-Comté, Dijon, France, October 24th.

I. Emiris was a member of two 3-person supervisory committees of PhD students Anuj Sharma and Emmanouil Kamarianakis, who defended their theses in December 2018, at NK University of Athens, and University of Crete, Greece, respectively.

E. Hubert was a member of the PhD committee of Timothé Pecatte from Ecole Normale Supérieure de Lyon, section informatique : *Bornes Inférieures et Algorithmes de Reconstruction pour des Sommes de Puissances Affines*.

8.3. Popularization

8.3.1. Interventions

- Ioannis Emiris was an invited speaker at “Open Science Days”, Athens, 29 November 2018, and at “Mathematics Education Forum” within the Greek Mathematical Society annual meeting, Athens, December 2018.

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[26] L. BUSÉ, Y. CID-RUIZ, C. D'ANDREA.*Degree and birationality of multi-graded rational maps*, May 2018, working paper or preprint, https://hal.inria.fr/hal-01793578

[27] L. BUSÉ, C. D'ANDREA, M. SOMBRA, M. WEIMANN.*The geometry of the flex locus of a hypersurface*, April 2018, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01779785

[28] L. BUSÉ, T. DEDIEU.*Generalized weight properties of resultants and discriminants, and applications to projective enumerative geometry*, November 2018, working paper or preprint, https://hal.inria.fr/hal-01936025

[29] L. BUSÉ, A. DIMCA, G. STICLARU.*Freeness and invariants of rational plane curves*, April 2018, https://arxiv.org/abs/1804.06194 - working paper or preprint, https://hal.inria.fr/hal-01767751

[30] C. JOSZ, J.-B. LASSERRE, B. MOURRAIN.*Sparse polynomial interpolation: sparse recovery, super resolution, or Prony?*, November 2018, https://arxiv.org/abs/1708.06187 - working paper or preprint, https://hal.archives-ouvertes.fr/hal-01575325

[31] B. MOURRAIN, A. ONETO.*On minimal decompositions of low rank symmetric tensors*, May 2018, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01803571

[32] B. MOURRAIN, S. TELEN, M. VAN BAREL.*Truncated Normal Forms for Solving Polynomial Systems: Generalized and Efficient Algorithms*, December 2018, https://arxiv.org/abs/1803.07974 - working paper or preprint, https://hal.inria.fr/hal-01738695

Project-Team ATHENA

Computational Imaging of the Central Nervous System

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Computational Neuroscience and Medicine

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Project-Team ATHENA

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

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1. Team, Visitors, External Collaborators

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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 (brain and spinal cord) anatomy and function. These models and tools will help to better understand the architecture and the functioning of human Central Nervous System (CNS) 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 Imaging of the CNS.

The relationship between CNS structure and function is fundamental in neuroscience. Developing computational models and techniques that recover the structural connectivity and the function of the CNS in vivo is thus of utmost importance: it will definitely improve the understanding of the CNS and its mechanisms. On the basis of our expertise and contributions to the field of Computational Imaging of the CNS and in order to have an impact on this field, our research focusses mainly on the Structural and Functional Imaging of the CNS 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 CNS 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 recent 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 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.

Connectivity represents the network infrastructure of the CNS. Electric activity corresponds to communications over this network. MEG and EEG (jointly as M/EEG) reveal part of the cortical electric activity. M/EEG are also instrumental in diagnosing diseases linked to anomalous brain function - that in some cases structural or functional MR images do not reveal. 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 EEG, and translate in real-time the electrical activity of the brain in commands to control 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 CNS signals and imaging data. Our main objective is to push forward the state-of-the-art in our research domain to better understand the architecture and function of the CNS and help address pressing and challenging clinical and neuroscience questions. This better understanding of the CNS will help the development of new biomarkers related to the progression of certain types of neurodegenerative diseases and will also help improving BCI systems with the goal of better interactive probing and training of the human brain. These long term and ambitious applications, if successful, will help us make true our dream to effectively contribute reducing the number of people suffering from CNS diseases.

In order to tackle these 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 CNS 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 recent field of research with a history of roughly three decades. It was introduced in the mid 80's by Le Bihan et al [71], Merboldt et al [77] and Taylor et al [88]. 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) [87], [53]. Historically, the first model in dMRI is the 2nd order diffusion tensor (DTI) [51], [50] 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 [72], [62]. 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 [74] and [73]).

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) [91] and High Angular Resolution Diffusion Imaging (HARDI) methods such as Q-ball imaging [89] and other multi-tensors and compartment models [84], [86], [44], [43], [80] 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 [89]. Those contributions are fundamental and have already started to impact on the Diffusion MRI, HARDI and Q-Ball Imaging community [61]. They are at the core of our probabilistic and deterministic tractography algorithms devised to best exploit the full distribution of the fiber ODF (see [58], [3] and [59], [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 recently proposed such as the Generalized Diffusion Tensor Imaging (G-DTI) model developed by Ozarslan et al [95], [96] or 4th order Tensor Model [49]. For more details, we refer the reader to our articles in [64], [84] where we review HOT models and to our articles in [73], 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. Recently, we started to work on Diffusion Kurtosis Imaging (DKI), of great interest for the company OLEA MEDICAL(http://www.olea-medical.com/). 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) [67].

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 [43], [44]. 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 [66], [84].

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. Recently, 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 [57]. Then, and more recently, 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 recent technique which has been proved to accurately reconstruct sparse signals from undersampled measurements acquired below the Shannon-Nyquist rate [78].

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 recent 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 [78], [54], [56].

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 [65].

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 [45], AxCaliber [46] and NODDI [92] 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 [48], [47], the Solid Harmonic (SoH) basis [60], the Simple Harmonic Oscillator based Reconstruction and Estimation (SHORE) basis [93] and more recent Mean Apparent Propagator or MAP-MRI basis [94].

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

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 invariant and intrinsic microstructure features, identify bio-physically important bio-markers and improve tractography. For short, there

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 tools and models for dMRI 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 [70], [7] and means to calibrate them [90] 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 [85].

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 [76], [79], but to our knowledge there are very few studies merging data coming both from M/EEG and dMRI at the analysis level [82], [63], [52], [83].

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. New Software and Platforms

5.1. 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: Maureen Clerc

5.2. DIPY

Diffusion Imaging in Python
KEYWORDS: MRI - Medical imaging

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

FUNCTIONAL DESCRIPTION: Diffusion Imaging in Python (Dipy) is a free and open source software project for computational neuroanatomy, focusing mainly on diffusion magnetic resonance imaging (dMRI) analysis. E. Garyfallidis (now Indiana University) is the founder and lead engineer of this open source project in the development of diffusion MRI methods. We continuously collaborate with this global effort and our effort is combined with Université de Sherbrooke, in Canada and Stanford University among others. See for example our registration, denoising, tractography and microstructures tutorials.

- Participants: Demian Wassermann and Rutger Fick
- Partner: Sherbrooke University
- Contact: Demian Wassermann
- URL: http://nipy.org/dipy/

5.3. 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

5.4. 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: OpenMEEG: opensource software for quasistatic bioelectromagnetics - Forward Field Computation with OpenMEEG. - Source modeling of ElectroCorticoGraphy (ECoG) data: Stability analysis and spatial filtering
- URL: http://openmeeg.github.io/

6. New Results

6.1. Computational Diffusion MRI

6.1.1. Reducing the Number of Samples in Spatio-Temporal dMRI Acquisition Design

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], Philippe Ciuciu [CEA, Université Paris-Saclay], Demian Wassermann [Inria Parietal], Rachid Deriche.

Acquisition time is a major limitation in recovering brain white matter microstructure with diffusion magnetic resonance imaging. The aim of this work is to bridge the gap between growing demands on spatiotemporal resolution of diffusion signal and the real-world time limitations. We introduce an acquisition scheme that reduces the number of samples under adjustable quality loss. Finding a sampling scheme that maximizes signal quality and satisfies given time constraints is NP-hard. Therefore, a heuristic method based on a genetic algorithm is proposed in order to find suboptimal solutions in acceptable time. The analyzed diffusion signal representation is defined in the $q\tau$ space, so that it captures both spatial and temporal phenomena. The experiments on synthetic data and in vivo diffusion images of the C57Bl6 wild-type mouse corpus callosum reveal superiority of the proposed approach over random sampling and even distribution in the $q\tau$ space.

This work has been published in [12].

6.1.2. Dmipy, a Diffusion Microstructure Imaging toolbox in Python to improve research reproducibility

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

The recovery of microstructure-related features of the brain's white matter is a current challenge in diffusion MRI (dMRI). In particular, multi-compartment (MC)-based models have been a popular approach to estimate these features. However, the usage of MC-models is often limited to those hard-coded in publicly available toolboxes.

In this work, we present Diffusion Microstructure Imaging in Python (Dmipy), a diffusion MRI toolbox which allows accessing any multi-compartment-based model and robustly estimates these important features from single-shell, multi-shell, and multi-diffusion time, and multi-TE data. Dmipy follows a *building block*-based philosophy to microstructure imaging, meaning an MC-model can be constructed and fitted to dMRI data using any combination of underlying tissue models, axon dispersion or diameter distributions, and optimization algorithms.using less than 10 lines of code, thus helps improve research reproducibility. In describing the toolbox, we show how Dmipy enables to easily design microstructure models and offers to the users the freedom to choose among different optimization strategies.We finally present three advanced examples of highly complex modeling approaches which are made easy using Dmipy.

This work has been published in [21], [30].

6.1.3. Non-parametric graphnet-regularized representation of dMRI in space and time

Participants: 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.

Effective representation of the four-dimensional diffusion MRI signal–varying over three-dimensional q-space and diffusion time τ – is a sought-after and still unsolved challenge in diffusion MRI (dMRI). We propose a functional basis approach that is specifically designed to represent the dMRI signal in this qτ-space. Following recent terminology, we refer to our qτ-functional basis as *qτ-dMRI*. qτ-dMRI can be seen as a time-dependent realization of q-space imaging by Paul Callaghan and colleagues. We use GraphNet regularization - imposing both signal smoothness and sparsity – to drastically reduce the number of diffusion-weighted images (DWIs) that is needed to represent the dMRI signal in the qτ-space. As the main contribution, qτ-dMRI provides the framework to – without making biophysical assumptions - represent the qτ-space signal and estimate time-dependent q-space indices (qτ-indices), providing a new means for studying diffusion in nervous tissue. We validate our method on both in-silico generated data using Monte–Carlo simulations and an in-vivo test-retest study of two C57Bl6 wild-type mice, where we found good reproducibility of estimated qτ-index values and trends. In the hope of opening up new τ-dependent venues of studying nervous tissues, qτ-dMRI is the first of its kind in being specifically designed to provide open interpretation of the qτ-diffusion signal.

This work has been published in [11].

6.1.4. Resolving the crossing/kissing fiber ambiguity using functionallyCOMMIT (Convex Optimization Modeling for Microstructure Informed Tractography)

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

The architecture of the white matter is endowed with kissing and crossing bundles configurations. When these white matter tracts are reconstructed using diffusion MRI tractography, this systematically induces the reconstruction of many fiber tracts that are not coherent with the structure of the brain. The question on how to discriminate between true positive connections and false positive connections is the one addressed in this work. State-of-the-art techniques provide a partial solution to this problem by considering anatomical priors in the false positives detection process. We propose a novel model that tackles the same issue but takes into account both structural and functional information by combining them in a convex optimization problem. We validate it on two toy phantoms that reproduce the kissing and the crossing bundles configurations, showing that, through this approach, we are able to correctly distinguish true positives and false positives.

This work has been published in [25].

6.1.5. Reducing false positive connection in tractograms using joint structure-function filtering

Participants: Matteo Frigo, Guillermo Gallardo Diez, Isa Costantini, Alessandro Daducci [EPFL, Lausanne], Demian Wassermann [Inria Parietal], Samuel Deslauriers-Gauthier, Rachid Deriche.

Due to its ill-posed nature, tractography generates a significant number of false positive connections between brain regions. To reduce the number of false positives, Daducci et al. proposed the COMMIT framework, which has the goal of re-establishing the link between tractography and tissue microstructure. In this framework, the diffusion MRI signal is modeled as a linear combination of local models associated with streamlines where the weights are identified by solving a convex optimization problem. Streamlines with a weight of zero do not contribute to the diffusion MRI data and are assumed to be false positives. Removing these false positives yields a subset of streamlines supporting the anatomical data. However, COMMIT does not make use of the link between structure and function and thus weights all bundles equally. In this work, we propose a new strategy that enhances the COMMIT framework by injecting the functional information provided by functional MRI. The result is an enhanced tractogram filtering strategy that considers both functional and structural data.

This work has been published in [31].

6.1.6. Combining Improved Euler and Runge-Kutta 4th order for Tractography in Diffusion-Weighted MRI

Participants: Cherifi Dalila [IEEE University of Boumerdes, Algeria], Boudjada Messaoud [IEEE University of Boumerdes, Algeria], Morsli Abdelatif [IEEE University of Boumerdes, Algeria], Girard Gabriel [EPFL, Lausanne], Rachid Deriche.

In this work, we develop a general, deterministic tractography algorithm (CIERTE), which is a combination of Improved Euler and Range-Kutta fourth-order algorithm and test it on synthetic and real data. The proposed tractography method is validated using seven metrics of the tractometer evaluation system and positively compared to state-of-the-art tractography algorithms.

This work has been published in [9].

6.1.7. Fiber orientation distribution function from non-negative sparse recovery with quantitative analysis of local fiber orientations and tractography using DW-MRI datasets

Participants: Thinhinane Megherbi [USTHB, Algiers], Gabriel Girard [EPFL, Lausanne], Ghosh Aurobrata [AI Innovation Lab, Verisk Analytics], Fatima Oulebsir-Boumghar [USTHB, Algiers], Rachid Deriche.

In this work, we propose, evaluate and validate a new Diffusion Weighted MRI method to model and recover high quality tractograms even with multiple fiber populations in a voxel and from a limited number of acquisitions.

Our method relies on the estimation of the Fiber Orientation Distribution (FOD) function, parameterized as a non-negative sum of rank-1 tensors and the use of a non-negative sparse recovery scheme to efficiently recover the tensors, and their number. Each fiber population of a voxel is characterized by the orientation and the weight of a rank-1 tensor.

Using both deterministic and probabilistic tractography algorithms, we show that our method is able to accurately reconstruct narrow crossing fibers and obtain a high quality connectivity reconstruction even from a limited number of acquisitions. To this end, a validation scheme based on the connectivity recovered from tractography is developed to quantitatively evaluate and analyze the performance of our method. The tractometer tool is used to quantify the tractography obtained from a simulated DW-MRI dataset including a high angular resolution dataset of 60 gradient directions and a dataset of 30 gradient directions, each of them corrupted with Rician noise of SNR 10 and 20. The performance of our FOD model and its impact on the tractography results are also demonstrated and illustrated on in vivo DW-MRI datasets with high and low angular resolutions.

This work has been published in [15].

6.1.8. Solving the Cross-Subject Parcel Matching Problem Using Optimal Transport

Participants: Guillermo Gallardo Diez, Nathalie Gayraud, Maureen Clerc, Demian Wassermann [Inria Parietal], Samuel Deslauriers-Gauthier, Rachid Deriche.

Matching structural parcels across different subjects is an open problem in neuroscience. Even when produced by the same technique, parcellations tend to differ in the number, shape, and spatial localization of parcels across subjects. In this work, we propose a parcel matching method based on Optimal Transport. We test its performance by matching parcels of the Desikan atlas, parcels based on a functional criteria and structural parcels. We compare our technique against three other ways to match parcels which are based on the Euclidean distance, the cosine similarity, and the Kullback-Leibler divergence. Our results show that our method achieves the highest number of correct matches.

This work has been published in [32], [26].

6.1.9. A Closed-Form Solution of Rotation Invariant Spherical Harmonic Features in Diffusion MRI

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

Rotation invariant features are an indispensable tool for characterizing diffusion Magnetic Resonance Imaging (MRI) and in particular for brain tissue microstructure estimation. In this work, we propose a new mathematical framework for efficiently calculating a complete set of such invariants from any spherical function. Specifically, our method is based on the spherical harmonics series expansion of a given function of any order and can be applied directly to the resulting coefficients by performing a simple integral operation analytically. This enable us to derive a general closed-form equation for the invariants. We test our invariants on the diffusion MRI fiber orientation distribution function obtained from the diffusion signal both in-vivo and in synthetic data. Results show how it is possible to use these invariants for characterizing the white matter using a small but complete set of features.

This work has been published in [29].

6.1.10. Rational invariants of ternary forms under the orthogonal group

Participants: Paul Görlach [MPI for Mathematics in the Sciences], Evelyne Hubert [Inria, AROMATH], Théodore Papadopoulo, Rachid Deriche.

In [68], [69], [81] we started to explore the theory of tensor invariants as a mathematical framework for computing new biomarkers for HARDI. We pursued this work and, in collaboration with the project-team GALAAD/AROMATH, we succeeded to develop a complete set of rational invariants for ternary quartics [39]. Being rational, they are very close to the polynomial invariants developed in [69] but they constitute a complete set of invariants. They are also good tools to understand better the algebraic invariants of [81] and some others based on spherical harmonics decomposition [55]. We determined a generating set of rational invariants of minimal cardinality for the action of the orthogonal group $O(3)$ on the space $R[x,y,z]_{2d}$ of ternary forms of even degree 2d. The construction relies on two key ingredients. On one hand, the Slice Lemma allows us to reduce the problem to dermining the invariants for the action on a subspace of the finite subgroup $B(3)$ of signed permutations. On the other hand, our construction relies in a fundamental way on specific bases of harmonic polynomials. These bases provide maps with prescribed $B(3)$-equivariance properties. Our explicit construction of these bases should be relevant well beyond the scope of this work. The expression of the $B(3)$-invariants can then be given in a compact form as the composition of two equivariant maps. Instead of providing (cumbersome) explicit expressions for the $O(3)$-invariants, we provide efficient algorithms for their evaluation and rewriting. We also use the constructed $B(3)$-invariants to determine the $O(3)$-orbit locus and provide an algorithm for the inverse problem of finding an element in $R[x,y,z]_{2d}$ with prescribed values for its invariants. These are the computational issues relevant in brain imaging.

This work has been sumitted and is currently under review. A preprint is available in [39].

6.1.11. Edema-informed anatomically constrained particle filter tractography

Participants: Samuel Deslauriers-Gauthier, Drew Parker [UPenn, USA], François Rheault [SCIL, Sherbrooke University, CA], Steven Brem [UPenn, USA], Maxime Descoteaux [SCIL, Sherbrooke University, CA], Ragini Verma [UPenn, USA], Rachid Deriche.

In this work, we propose an edema-informed anatomically constrained tractography paradigm that enables reconstructing larger spatial extent of white matter bundles as well as increased cortical coverage in the presence of edema. These improvements will help surgeons to maximize the extent of the resection while minimizing the risk of cognitive deficits. The new paradigm is based on a segmentation of the brain into gray matter, white matter, corticospinal fluid, edema and tumor regions which utilizes a tumor growth model. Using this segmentation, a valid tracking domain is generated and, in combination with anatomically constrained particle filter tractography, allows streamlines to cross the edema region and reach the cortex. Using subjects with brain tumors, we show that our edema-informed anatomically constrained tractography paradigm increases the cortico-cortical connections that cross edema-contaminated regions when compared to traditional fractional anisotropy thresholded tracking.

This work has been published in [24].

6.1.12. Towards the assessment of myelination using time-dependent diffusion MRI indices

Participants: Abib Olushola Yessouffou Alimi, 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.

In this work, we study the sensitivity of time-dependent diffusion MRI indices or qτ-indices to demyelination in the mouse brain. For this, we acquire in vivo four-dimentional diffusion-weighted images-varying over gradient strength, direction and diffusion time-and estimate the qτ-indices from the corpus callosum. First order Taylor approximation of each index gives fitting coefficients α and β whose variance we investigate. Results indicate that, cuprizone intoxication affects mainly index coefficient β by introducing inequality of variances between the two mice groups, most significantly in the splenium and that MSD increases and RTOP decreases over diffusion time τ.

This work has been published in [35].

6.1.13. An Analytical Fiber ODF Reconstruction in 3D Polarized Light Imaging

Participants: Abib Olushola Yessouffou Alimi, Yves Usson [UMR5525 TIMC-IMAG CNRS], Pierre-Simon Jouk [CHU Grenoble-Alpes], Gabrielle Michalowicz [CHU Grenoble-Alpes], Rachid Deriche.

Three dimensional polarized light imaging (3D-PLI) utilizes the birefringence in postmortem tissue to map its spatial fiber structure at a submillimeter resolution. In this work, we propose an analytical method to compute the fiber orientation distribution function (ODF) from high-resolution vector data provided by 3D-PLI. This strategy enables the bridging of high resolution 3D-PLI to diffusion magnetic resonance imaging with relatively low spatial resolution. First, the fiber ODF is modeled as a sum of K orientations on the unit sphere and expanded with a high order spherical harmonics series. Then, the coefficients of the spherical harmonics are derived directly with the spherical Fourier transform. We quantitatively validate the accuracy of the reconstruction against synthetic data and show that we can recover complex fiber configurations in the human heart at different scales.

This work has been published in [22].

6.1.14. fMRI Deconvolution via Temporal Regularization using a LASSO model and the LARS algorithm

Participants: Isa Costantini, Patryk Filipiak, Kostiantyn Maksymenko, Samuel Deslauriers-Gauthier, Rachid Deriche.

In the context of functional MRI (fMRI), methods based on the deconvolution of the blood oxygenated level dependent (BOLD) signal have been developed to investigate the brain activity, without a need of a priori knowledge about activations occurrence. In this work, we propose a novel temporal regularized deconvolution of the BOLD signal using the Least Absolute Shrinkage and Selection Operator (LASSO) model, solved by means of the Least-Angle Regression (LARS) algorithm. In this way, we were able to recover the underlying neurons activations and their dynamics.

This work has been published in [23], [37].

6.1.15. A Second Order Multi-Stencil Fast Marching Method with a Non-Constant Local Cost Model

Participants: Susana Merino-Caviedes [Universidad de Valladolid], Lucilio Cordero-Grande [King's College London], Maria Tereza Perez [Universidad de Valladolid], Pablo Casaseca-de-La-Higuera [Universidad de Valladolid], Marcos Martín-Fernández [Universidad de Valladolid], Carlos Alberola-Lopez [Universidad de Valladolid], Rachid Deriche.

The Fast Marching method is widely employed in several fields of image processing. Some years ago a Multi-Stencil version (MSFM) was introduced to improve its accuracy by solving the Eikonal equation for a set of stencils and choosing the best solution at each considered node. The following work proposes a modified numerical scheme for MSFM to take into account the variation of the local cost, which has proven to be second order. The influence of the stencil set choice on the algorithm outcome with respect to stencil orthogonality and axis swapping is also explored, where stencils are taken from neighborhoods of varying radius. The experimental results show that the proposed schemes improve the accuracy of their original counterparts, and that the use of permutation-invariant stencil sets provides robustness against shifted vector coordinates in the stencil set.

This work has been published in [16].

6.2. Unveiling brain activity using M/EEG

6.2.1. 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 is published in [41].

6.2.2. Fast approximation of EEG forward problem and application to tissue conductivity estimation

Participants: Maureen Clerc, Kostiantyn Maksymenko, 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 suitably 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 submitted to a journal and is available as a preprint [40].

6.2.3. Model based optimal multipolar stimulation without a priori knowledge of nerve structure

Participants: Maureen Clerc, Mélissa Dali [Inria Camin], David Guiraud [Inria Camin], Jérémy Laforêt [Inria Camin], Olivier Rossel [Inria Camin].

Multipolar cuff electrode can selectively stimulate areas of peripheral nerves and therefore enable to control independent functions. However, the branching and fascicularization are known for a limited set of nerves and the specific organization remains subject-dependent. This work presents general modeling and optimization methods in the context of multipolar stimulation using a cuff electrode without a priori knowledge of the nerve structure. Vagus nerve stimulation experiments based on the optimization results were then investigated.

The model consisted of two independent components: a lead field matrix representing the transfer function from the applied current to the extracellular voltage present on the nodes of Ranvier along each axon, and a linear activation model. The optimization process consisted in finding the best current repartition (ratios) to reach activation of a targeted area depending on three criteria: selectivity, efficiency and robustness.

The results showed that state-of-the-art configurations (tripolar transverse, tripolar longitudinal) were part of the optimized solutions but new ones could emerge depending on the trade-off between the three criteria and the targeted area. Besides, the choice of appropriate current ratios was more important than the choice of the stimulation amplitude for a stimulation without a priori knowledge of the nerve structure. We successfully assessed the solutions in vivo to selectively induce a decrease in cardiac rhythm through vagus nerve stimulation while limiting side effects. Compared to the standard whole ring configuration, a selective solution found by simulation provided on average 2.6 less adverse effects.

The preliminary results showed the correctness of the simulation, using a generic nerve geometry. It suggested that this approach will have broader applications that would benefit from multicontact cuff electrodes to elicit selective responses. In the context of the vagus nerve stimulation for heart failure therapy, we show that the simulation results were confirmed and improved the therapy while decreasing the side effects.

This work has been published in [10].

6.3. Combined M/EEG and dMRI

6.3.1. Linking resting-state functional connectivity and the structural connectome – investigation of an eigen-structure model

Participants: Rebecca Bonham-Carter, Samuel Deslauriers-Gauthier, Rachid Deriche.

Resting-state functional connectivity (rs-FC) dynamics are not random but rather structured with common dominant patterns called resting-state networks (RSNs). These dynamics are influenced by the underlying network of white-matter connections. Specifically, temporal correlations in resting-state BOLD fMRI signals have been correlated with the structural network determined via diffusion weighted imaging (DWI). The literature on this structure-function relationship encompasses generative non-linear models and a variety of linear models. The objective of this study is to provide new validation and understanding of two linear models. Both models enforce that the structural network Laplacian and rs-FC share a common eigen-structure. In contrast to previous work, in this work two linear models of resting-state functional connectivity (rs-FC), developed by Abdelnour et al., are validated on simulated BOLD fMRI data generated using The Virtual Brain18 (TVB) and 49 HCP subjects real structural connectomes. Both consider rs-FC as a diffusion process on the structural network. The mean correlations between rs-FC matrices we obtain 0.699 ± 0.086 and 0.518 ± 0.095, and between rs-FC eigenvalues 0.981 ± 0.013, agree with the original model implementations on empirical data. Using The Virtual Brain simulator together with real structural data is shown to offer a new and efficient test and validation framework for approaches predicting rs-FC from structure.

This work is under review.

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

Participants: Samuel Deslauriers-Gauthier, Jean-Marc Lina [Ecole de Technologie Supérieure, Montréal, CA], Russel Butler [Sherbrooke University, CA], Kevin Whittingstall [Sherbrooke University, CA], Pierre-Michel Bernier [Sherbrooke University, CA], Maxime Descoteaux [SCIL, Sherbrooke University, CA], 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 is under review.

6.3.3. Bridging Brain Structure and Function by Correlating Structural Connectivity and Cortico-Cortical Transmission

Participants: Fabien Almairac [CHU Nice], Patryk Filipiak, Lavinia Slabu, Maureen Clerc, Théodore Papadopoulo, Denys Fontaine [CHU Nice], Lydiane Mondot [CHU Nice], Stéphan Chanalet [CHU Nice], Demian Wassermann [Inria Parietal], Rachid Deriche.

Elucidating the structure-function relationship of the brain is one of the main open questions in neuroscience. The capabilities of diffusion MRI-based (dMRI) techniques to quantify the connectivity strength between brain areas, namely structural connectivity, in combination with modalities such as electrocorticography (ECoG) to quantify brain function have enabled advances in this field. In this work, we aim to establish a relationship between: i) dMRI structural connectivity measures, ii) direct measures of electrical properties of the human brain cortex obtained with ECoG, iii) response elicited by direct electrostimulation of the brain (DES).

The results of this multi-modal approach combining structure and function explorations of the brain should: i) help to elucidate the relationship between non-invasive (dMRI) structural connectivity measures and cortico-cortical transmission properties (delays, transfer functions), ii) help in understanding the organization of the brain for cognitive functions as well as neurosurgical planning for resection of brain tumors and drug-resistant epilepsy

This work has been presented in [36].

6.4. Brain Computer Interfaces

6.4.1. Online enhancement of visuospatial attention performance

Participants: Maureen Clerc, Thomas Brochier [Institut des Neurosciences de la Timone], Romain Trachel.

This study on real-time decoding of visuospatial attention has two objectives: first, to reliably decode self-directed shifts of attention from electroencephalography (EEG) data, and second, to analyze whether this information can be used to enhance visuospatial performance. Visuospatial performance was measured in a target orientation discrimination task, in terms of reaction time, and error rate. Our experiment extends the Posner paradigm by introducing a new type of ambiguous cues to indicate upcoming target location. The cues are designed so that their ambiguity is imperceptible to the user. This entails endogenous shifts of attention which are truly self-directed. Two protocols were implemented to exploit the decoding of attention shifts. The first 'adaptive' protocol uses the decoded locus to display the target. In the second 'warning' protocol, the target position is defined in advance, but a warning is flashed when the target mismatches the decoded locus. Both protocols were tested in an online experiment involving ten subjects. The reaction time improved in both the adaptive and the warning protocol. The error rate was improved in the adaptive protocol only. This proof of concept study brings evidence that visuospatial brain–computer interfaces (BCIs) can be used to enhance improving human–machine interaction in situations where humans must react to off-center events in the visual field.

This work has been published in [8].

6.4.2. Review of classification methods for EEG-based Brain-Computer Interfaces: A 10-year update

Participants: Maureen Clerc, Laurent Bougrain [Neurosys, Inria Nancy], Fabien Lotte [Potioc, Inria Bordeaux], Alain Rakotomamonjy [Université de Rouen].

Most current Electroencephalography (EEG)-based Brain-Computer Interfaces (BCIs) are based on machine learning algorithms. There is a large diversity of classifier types that are used in this field, as described in the 2007 review paper [75]. Now, approximately 10 years after this review publication, many new algorithms have been developed and tested to classify EEG signals in BCIs. The time is therefore ripe for an updated review of EEG classification algorithms for BCIs. We surveyed the BCI and machine learning literature from 2007 to 2017 to identify the new classification approaches that have been investigated to design BCIs. We synthesize these studies in order to present such algorithms, to report how they were used for BCIs, what were the outcomes, and to identify their pros and cons. We found that the recently designed classification algorithms for EEG-based BCIs can be divided into four main categories: adaptive classifiers, matrix and tensor classifiers, transfer learning and deep learning, plus a few other miscellaneous classifiers. Among these, adaptive classifiers were demonstrated to be generally superior to static ones, even with unsupervised adaptation. Transfer learning can also prove useful although the benefits of transfer learning remain unpredictable. Riemannian geometry-based methods have reached state-of-the-art performances on multiple BCI problems and deserve to be explored more thoroughly, along with tensor-based methods. Shrinkage linear discriminant analysis and random forests also appear particularly useful for small training samples settings. On the other hand, deep learning methods have not yet shown convincing improvement over state-of-the-art BCI methods. This paper provides a comprehensive overview of the modern classification algorithms used in EEG-based BCIs, presents the principles of these Review of Classification Algorithms for EEG-based BCI 2 methods and guidelines on when and how to use them. It also identifies a number of challenges to further advance EEG classification in BCI.

This work has been published in [14].

6.4.3. Automatizing calibration

Participants: Maureen Clerc, Federica Turi, Nathalie Gayraud.

Brain Computer Interfaces (BCIs) based on visual evoked potentials (VEP) allow for spelling from a keyboard of flashing characters. Among VEP BCIs, code-modulated visual evoked potentials (c-VEPs) are designed for high-speed communication. In c-VEPs, all characters flash simultaneously. In particular, each character flashes according to a predefined 63-bit binary sequence (m-sequence), circular-shifted by a different time lag. For a given character, the m-sequence evokes a VEP in the electroencephalogram (EEG) of the subject, which can be used as a template. This template is obtained during a calibration phase at the beginning of each session. Then, the system outputs the desired character after a predefined number of repetitions by estimating its time lag with respect to the template. Our work avoids the calibration phase, by extracting from the VEP relative lags between successive characters, and predicting the full word using a dictionary.

This work has been published in [28].

7. Partnerships and Cooperations

7.1. Regional Initiatives

7.1.1. Université Côte d'Azur projects

7.1.1.1. Tech-ICOPA

Participants: Maureen Clerc, Théodore Papadopoulo, Sofiane Guebba, Marie-Hélène Soriani [CHU Nice], Mariane Bruno [CHU Nice], Violaine Guy [CHU Nice].

Duration: 24 months

Improving autonomy is a main priority for people with disabilities. The goal of this project is to create a version usable by patients at their home of a brain-computer interface (BCI) research prototype system developped in our project-team. Making this technology actually usable in the context of pathology inducing severe disabilities such as ALS (Amyotrophic Lateral Sclerosis) is a challenge. Tackling this challenge would allow both to meet the expectations of dependent people and to envision a more widespread use of this technology. To reach this goal, several technological advances and industrial developments are needed : (i) developing a suitable ergonomic headset, wireless, functional, comfortable, incorporating a miniaturized amplifier (Nice University Hospital Center - ALS Center), (ii) reducing the number of electrodes while maintaining signal quality (Inria - UCA) and (iii) testing the prolonged use of dry electrodes. In addition to these technological advances, the Tech-ICOPA translational project aims at (1) improving the use of BCI in communication, in accessing the digital world, home automation and robotics and (2) enhancing the use of BCI in commercial applications.

7.1.1.2. EPI-ANALYSE

Participants: Fabrice Duprat [IPMC], Théodore Papadopoulo, Massimo Mantegazza [IPMC], Maureen Clerc.

Duration: 12 months

This project aims at developing two complementary analysis softwares dedicated to the detection of epileptic seizures in mice in order to study epileptogenesis and the consequences of spontaneous seizures. The first software will be the adaptation to the mouse EEG of a powerful algorithm based on a dictionary learning method developed by our project-team. We will use video-EEG recordings already made and analyzed at the IPMC to optimize and validate the new software. This will allow a detailed analysis of seizures and events occurring between seizures (e.g., interictal spikes). The second software deals with the analysis of video recordings of 3 models of mice not recordable until now with EEG. The implementation, recordings and the analysis of the 3 models will be carried out during this project. A prototype of this software already exists at IPMC (in Python, with OpenCV) but the analysis algorithm must be optimized. Semi-automatic video analysis will allow an easy identification of temporal segments corresponding to epileptic seizures. This will help the experimenter to classify the behavioral severity of seizures.

7.1.1.3. MICADome

Participants: Maureen Clerc, Michel Pascal [CNR Nice].

Duration: 24 months

The MICA-Dome project (MICA : Musique Interactive Côte d'Azur) initiates collaborative research between arts, science and humanities within a laboratory for exploring the sound spatialization in 3D, and its usage for an immersive music composition. For this MICADome will be equipped with a "Dome" of loudspeakers for 3D spatialization. Our team collaborates in MICADome in order to develop and anlyze EEG experiments to analyze the neural correlates of spatial auditory attention.

7.2. National Initiatives

7.2.1. Inria Project Lab

7.2.1.1. IPL BCI-LIFT

Participants: Maureen Clerc, Théodore Papadopoulo, Nathalie Gayraud, Federica Turi, Romain Lacroix.

Duration: *January 2015 to December 2018*

The Inria Project-Lab BCI-LIFT is an Inria-funded reasearch consortium to foster collaborative research on Brain-Computer Interfaces on the topic of Learning, Interaction, Feedback and Training. It is coordinated by Maureen Clerc. Its members are from 6 Inria teams: ATHENA, CAMIN, HYBRID, MJOLNIR, NEUROSYS, POTIOC, and from Dycog team from CRNL Lyon, and University of Rouen. The goal is to reach a next generation of non-invasive Brain-Computer Interfaces (BCI), more specifically BCI that are easier to appropriate, more efficient, and suit a larger number of people. For more information, refer to the BCI-LIFT website.

7.2.2. ANR

7.2.2.1. ANR NeuroRef

Participants: Demian Wassermann [Inria Parietal], Antonia Machlouziredes, Guillermo Gallardo Diez, Rachid Deriche.

Duration: *October 2016 to September 2019*
Call: *NSF-ANR Program Collaborative Research in Computational Neuroscience 2015*

This project is a collaboration with Pr. S. Bouix and his team at the Psychiatry NeuroImaging Lab, Dept of Radiology, Brigham and Women's Hospital, Harvard Medical School (USA) to build MRI reference atlases to analyze brain trauma and post-traumatic stress. The goal is to develop a robust framework to perform subject-specific neuroimaging analyses of Diffusion MRI (dMRI), as this modality has shown excellent sensitivity to brain injuries and can locate subtle brain abnormalities that are not detected using routine clinical neuroradiological readings.

7.2.2.2. ANR MOSIFAH

Participants: Rachid Deriche, Abib Olushola Yessouffou Alimi, Rutger Fick [TheraPanacea, Paris], Demian Wassermann [Inria Parietal], Théodore Papadopoulo.

Duration: *October 2013 to September 2018*
Call: *ANR Numerical Models 2013*

This ANR project is about multimodal and multiscale modelling and simulation of the fiber architecture of the human heart. It started on October 2013 and involves three partners: Creatis Team, INSA, Lyon (I. Magnin, Y. Zhu); TIMC-IMAG, CNRS, Grenoble (Y. Uson) and the ATHENA project team.

It consists in modelling and simulating the ex vivo and in vivo 3D fiber architectures at various scales using multiphysical data from different imaging modalities working at different spatial resolutions. To this end, the myocardium of the human heart will be imaged using respectively Polarized Light Imaging (PLI) and dMRI.

7.2.2.3. ANR VIBRATIONS

Participants: Théodore Papadopoulo, Maureen Clerc, Rachid Deriche, Demian Wassermann [Inria Parietal].

Duration: *February 2014 to February 2019*
Call:ANR Programme de Recherche Translationnelle en Santé (PRTS) 2013

The VIBRATIONS project proposes to simulate in a biologically realistic way MEG and EEG fields produced by different configurations of brain sources, which will differ in terms of spatial and dynamic characteristics. The research hypothesis is that computational and biophysical models can bring crucial information to clinically interpret the signals measured by MEG and EEG. In particular, they can help to efficiently address some complementary questions faced by epileptologists when analyzing electrophysiological data.

7.2.3. ADT

7.2.3.1. 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.

7.2.3.2. ADT BOLIS 2

Participants: Théodore Papadopoulo, Juliette Leblond [FACTAS project-team], Jean-Paul Marmorat [CMA Ecole des Mines Paritech].

Duration: *6 months.*

This contract is a follow-up of ADT BOLIS which aimed at building a sofware platform dedicated to inverse source localisation, building upon the elements of software found in FindSources3D. The platform is modular, ergonomic, accessible and interactive and offers a detailed visualisation of the processing steps and the results. Its goal is to provide a convenient graphical interface and a tool that can be easily distributed and used by professionals (target audience: clinicians and researchers). BOLIS 2 aims at simplifying some maintenance aspects of the software.

This contract is part of the AMDT initiative.

7.2.3.3. 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.

7.3. European Initiatives

7.3.1. FP7 & H2020 Projects

7.3.1.1. 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.

7.3.1.2. ChildBrain ETN

ATHENA is an Associated Partner in the ChildBrain European Training Network: the team participates in training workshops and receive PhD students in secondments.

Program: European Training Network

Project acronym: ChildBrain

Project title: Advancing brain research in children's developmental neurocognitive disorders

Duration: March 2015 to March 2019

Coordinator: Prof. Paavo Leppänen, University of Jyváskylä, Finland

Other partners: University of Leuven (Belgium), University of Münster (Germany), Rabboud University (The Netherlands), Aston University (United Kingdom), IcoMetrix (Belgium), Elekta (Finland), BESA (Germany)

Abstract: The purpose of the ChildBrain ETN is to train young scientists, i.e. Early Stage Researchers (ESRs), to utilise evidence-based neuroscientific knowledge for helping children, especially those at high risk for dropout due to neurocognitive disorders, to meet future educational and societal demands.

7.4. International Initiatives

7.4.1. Inria International Partners

7.4.1.1. 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.

7.4.1.2. Informal International Partners

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

7.5. International Research Visitors

7.5.1. Visits of International Scientists

- Dr. Ragini Verma, Section of Biomedical Image Analysis, Center for Biomedical Image Computing and Analytics, Department of Radiology, University of Pennsylvania, USA (Oct 1st, 2018 - Dec 21st, 2018)
- Dr. Moo K. Chung, Waisman Laboratory for Brain Imaging and Behavior, University of Wisconsin-Madison, From Sept.10 to 14, 2018

7.5.1.1. Internships

- Rebecca Bonham-Carter - Queen's University, Kingston, Canada, From early May to late July, 2918.
- Max Amatsuji-Berry - Queen's University, Kingston, Canada, From early May to late July, 2918.
- Etienne Saint-Onge - Sherbrooke University, From Early Feb. to early June 2018.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. Member of Organizing Committees

- M. Clerc organized the "journées C@UCA" for Université Côte d'Azur in Fréjus, June 14-15, 2018.

8.1.2. Scientific Events Selection

8.1.2.1. Member of Conference Program Committees

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

8.1.2.2. 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 (ICIP, ISBI, ICASSP, VISAPP).

8.1.3. Journal

8.1.3.1. Member of 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

8.1.3.2. 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 (IEEE access, Transactions on Pattern Analysis and Machine Intelligence, Frontiers in Neuroscience, Brain Topography, Transactions on Biomedical Engneering).

8.1.4. Invited Talks

- M. Clerc gave an invited talk at the ICM Colloquium, Paris, January 15, 2018.
- M. Clerc gave an invited talk at the ENS Data Science Colloquium, Paris, February 6, 2018.
- M. Clerc gave an invited talk at the SIAM Symposium on Imaging Sciences, Bologna, June 6, 2018.
- M. Clerc gave an invited talk at the Journées Scientifiques Inria, Bordeaux, June 27, 2018.
- M. Clerc gave an invited talk at the Colloque “Physique et Interrogations Fondamentales”, Bibliothèque Nationale de France, Paris, Nov 10, 2018.
- M. Clerc gave an invited talk at the “Journées des Jeunes Mathématiciens et Jeunes Mathématiciennes”, Orléans, Nov 29, 2018.
- R. Deriche gave an invited keynote speech at SPIE Medical Imaging,Houston, Texas United States (Feb. 12th, 2018).
- R. Deriche gave an invited keynote speech at EDITE ParisTech-Sorbonne Université, Paris (Dec. 10th, 2018).
- T. Papadopoulo gave an invited talk at “Inverse Problems: Modelling and Simulation”, Malta (May, 2018) [20].

8.1.5. Leadership within the Scientific Community

- M. Clerc is the coordinator of the Inria Project-Lab BCI-LIFT.
- M. Clerc is on the board of the CORTICO association (Collectif pour la Recherche Transdisciplinaire sur les Interfaces Cerveau Ordinateur).
- R. Deriche is the P.I. of the ERC AdG CoBCoM.

8.1.6. Scientific Expertise

- M. Clerc served Cordis-H2020 for FET-OPEN prosals evaluations.
- M. Clerc participated in an HCERES visiting commitee in November 2018 (CentraleSupélec).

- R. Deriche serves several international institutions in reviewing applications : ERC Grants, Swiss National Science Foundation, the Netherlands Organisation for Scientific Research (NWO).
- T. Papadopoulo served Cordis-H2020 for FET-OPEN prosals evaluations.

8.1.7. Research Administration

- M. Clerc was adjoint deputy director for Science of Inria Sophia Antipolis (until August 2018).
- M. Clerc was member of the Evaluation Committee of Inria (until August 2018).
- M. Clerc was member of the Commission Scientifique Interne of Inria (until August 2018).
- M. Clerc was vice-president of the CRCN Selection Committee in Inria Sophia Antipolis.
- M. Clerc was a member of the CRCN Selection Committee in Inria Grenoble.
- M. Clerc is member of the Scientific Council of Academy 4 of Université Côte d'Azur.
- M. Clerc is co-animator of a structuring program on Neurosciences at Université Côte d'Azur.
- 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 (http://www.olea-medical.com/).
- T. Papadopoulo represents Inria at the Administration Council of the CIU Santé (till July 2018).
- T. Papadopoulo is member of the Software Development Committee at Inria.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Master: M. Clerc, Functional neuroimaging and data analysis, 36 ETD, MSc "Mod4NeuCog", Université Côte d'Azur, France.

Master: R. Deriche, Variational approaches and Geometrical Flows for Computational Brain Imaging, 36 ETD, M2 "Computational Biology and Biomedicine", Université Côte d'Azur, France.

Master: R. Deriche, Advanced Image Processing Techniques, 12 ETD, M1 International CBB & Ubinet, Université Côte d'Azur, France.

Master: T. Papadopoulo, *3D Computer Vision*, 12 ETD, M1 International Ubinet, Université Côte d'Azur, France.

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

8.2.2. Supervision

PhD in progress: Thinhinane Megherbi, "HARDI & High Order Tensors", started Sept. 2011. 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 in progress: Kostiantyn Maksymenko, "Inverse problem in EEG/MEG/SSEG: towards a better consideration of anatomo-functional constraints", Université Côte d'Azur,, started Oct. 2016. Supervisors: Théodore Papadopoulo and Maureen Clerc.

PhD defended on Dec. 21st, 2018: Guillermo Gallardo Diez, "Connectivity-Based Brain Parcellation", started Nov. 2015, Université Côte d'Azur. Supervisors: D. Wassermann and R. Deriche

PhD defended on Dec. 11th, 2018: Nathalie Gayraud, “Structured Dictionary Learning”, Université Côte d’Azur, started November 2015. Supervisor: 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 Papadopolo 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 Papadopolo and Samuel Deslauriers-Gauthier.

8.2.3. Juries

- M. Clerc participated as a reviewer in the HDR jury of Denis Schwartz at Sorbonne Université, Paris on November 7. 2018.
- M. Clerc participated as a reviewer in the PhD jury of Fardin Afdideh, Université Grenoble Alpes on October 12, 2018.
- M. Clerc participated as a reviewer in the PhD jury of Aldo Mora Sanchez at Sorbonne Université, Paris on November 19, 2018.
- M. Clerc participated in the PhD jury of Yousra Bekhti at Telecom ParisTech on March 22, 2018.
- M. Clerc participated in the PhD jury of Tom Dupré Latour at Telecom ParisTech on November 26, 2018.
- M. Clerc participated in the PhD jury of N. Gayraud at Université Côte d’Azur on December 11, 2018.
- R. Deriche participated as a reviewer in the HDR jury of G. Varoquaux at UPMC, Paris on May 23, 2018.
- R. Deriche participated in the HDR jury of D. Tschumperle at GREYC Ecole Nationale Supérieure d’Ingénieurs de Caen, Oct. 3, 2018.
- R. Deriche chaired the PhD jury of Lorenza Brusini at Università di Verona on April 19th, 2018.
- R. Deriche participated as a reviewer in the PhD jury of Chendi Wang at the University of British Columbia - Vancouver, CA on May 2018.
- R. Deriche participated in the PhD jury of G. Gallardo at Université Côte d’Azur on Dec. 21, 2018.

8.3. Popularization

8.3.1. Interventions

- M. Clerc participated in the Brain Awareness Week with a talk about Brain Computer Interfaces at CHU Nice Pasteur, March 16 2018.
- M. Clerc participated in the Brain Awareness Week with a talk about Music and the Brain at Villa Arson, Nice, March 17 2018.
- M. Clerc, T. Papadopoulo, F. Turi and R. Lacroix participated in the Fête de la Science with a BCI demo where the general public could test a P300 speller system.

9. Bibliography

Major publications by the team in recent years

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[5] R. FICK, D. WASSERMANN, E. CARUYER, R. DERICHE.*MAPL: Tissue microstructure estimation using Laplacian-regularized MAP-MRI and its application to HCP data*, in "Neuroimage", July 2016, vol. 134, p. 365–385 [*DOI :* 10.1016/J.NEUROIMAGE.2016.03.046], https://hal.inria.fr/hal-01291929

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[7] S. VALLAGHÉ, T. PAPADOPOULO.*A Trilinear Immersed Finite Element Method for Solving the Electroencephalography Forward Problem*, in "SIAM Journal on Scientific Computing", 2010, vol. 32, n^o 4, p. 2379–2394, http://epubs.siam.org/doi/pdf/10.1137/09075038X

Publications of the year

Articles in International Peer-Reviewed Journal

[8] T. BROCHIER, R. TRACHEL, M. CLERC.*Brain-computer interaction for online enhancement of visuospatial attention performance*, in "Journal of Neural Engineering", 2018, vol. 15, n^o 4 [*DOI :* 10.1088/1741-2552/AABF16], https://hal.archives-ouvertes.fr/hal-01794034

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Project-Team BIOCORE

Biological control of artificial ecosystems

IN PARTNERSHIP WITH:
CNRS

INRA

Sorbonne Université (UPMC)

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Modeling and Control for Life Sciences

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Creation of the Project-Team: 2011 January 01

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A6. - Modeling, simulation and control
A6.1.1. - Continuous Modeling (PDE, ODE)
A6.1.3. - Discrete Modeling (multi-agent, people centered)
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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 Grigno,. IAM Nancy, Agrocampus Ouest, MaIAGE Jouy-en-en-Josas, BioEpAR Nantes), CIRAD Montpellier, Institut Méditerranéen d'Océanologie, LOCEAN (Paris), GIPSA Grenoble, IBIS, BANG, and ANGE 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, FunFit, ICycle, and Maximic, Plan Cancer Imodrez, UMT Fiorimed, and Labex SIGNALIFE.
- International collaborations: Université Catholique de Louvain (Belgium), Université de Mons (Belgium), University of Stuttgart (Germany), 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), Roslin Institute / 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 [81]. 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 [84], 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 [88] must be extended from a theoretical point of view and validated experimentally.

5. Highlights of the Year

5.1. Highlights of the Year

- A graph theoretical tool for analysis of the coupling between two Boolean networks. This tool generalizes the asymptotic graph (previously developed in [96] and [78]), by adding a quantitative dimension through the computation of relative probabilities. This tool is used for coupling two biological networks and predicting the possible attractors or asymptotic behaviors of the full system. The outcome of the probabilistic asymptotic graph is the set of attractors the full system, each attractor with an associated probability. This work was published in the journal Frontiers in Physiology [22].
- A study that predicts the evolution of phytoplankton biodiversity with global warming. After calibration of our models with experimental data on growth of various species of the microalgae Micromonas, we have shown that the pattern of temperature response is strongly related to the site where cells were isolated. With this approach, we proved that the oceanwide diversity of Micromonas species is very similar to the oceanwide diversity of the phytoplankton. Using 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 generations to avoid a drastic reduction in biodiversity. This work was published in the ISME journal [23].

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. Model reduction and sensitivity analysis
Participants: Suzanne Touzeau, Jean-Luc Gouzé, Valentina Baldazzi.

Analysis and reduction of biochemical models. Dynamic models representing complex biological systems with numerous interactions can reach high dimensions and include complex nonlinearities. A model reduction method based on process weighing and pruning was developed and implemented on various models. A global sensitivity analysis was performed to check the method robustness against parameter uncertainty and variability ([16]). This work was part of Stefano Casagranda's PhD thesis (2017), and is also a collaboration with Bayer (Sophia Antipolis).

7.1.1.2. Estimation and control
Participants: Suzanne Touzeau, Jean-Luc Gouzé.

Parameter identification in compartmental systems. In collaboration with F. Dayan (Startup Exactcure), we work on practical problems of identifiability of parameters in linear pharmacokinetic models. This was the subject of the internship of Jean-Baptiste Excoffier.

Parameter identification in complex systems. In complex biological systems, especially when data are scarce, identifying the model parameters is a challenge and raises identifiability issues. To fit a within-host immunological model to a large data set of individual viremia profiles, we developed an ABC-like method, less computationally expensive than standard Bayesian fitting procedures. Rather than reproducing individual profiles, we ientified several parameter sets compatible with the data and reflecting the variability among individuals [59], [26]. This work was part of Natacha Go's post-doctorate, supported by the ANR MIHMES project, in collaboration with the Roslin Institute, Edinburgh, UK. It benefited from the resources and support of NEF computation cluster.

7.1.1.3. Mathematical study of ecological models

Participants: Frédéric Grognard, Ludovic Mailleret, Pierre Bernhard, Nicolas Bajeux, Suzanne Touzeau, Israël Tankam Chedjou, Samuel Nilusmas.

Semi-discrete models have shown their relevance in the modeling of biological phenomena whose nature presents abrupt changes over the course of their evolution [85]. We used such models and analyzed their properties in several practical situations that are developed in Section 7.2.3, some of them requiring such a modeling to describe external perturbations of natural systems, and others to take seasonality into account [11]. External perturbations of interacting populations occur when some individuals are introduced or removed from a natural system, which occurs frequently in pest control applications, either through the direct removal of pests, through the introduction of artificial habitats for the predators or through the introduction of biological control agents in deterministic or stochastic fashion [72].

Seasonality is an important property of most agricultural systems in temperate environments since the year is divided into a cropping season and a 'winter' season; it gives the reference time for crop rotation between resistant and sensitive strains in a mutli-seasonal optimization of root-knot nematodes control [56]. However, it can also arise in tropical environments where, in the absence of weather-related season, time is divided into cropping and fallow seasons, and where the duration of the latter can for example be used as a control method against phytopathogenic nematodes of the plantain plant [46], [58].

7.1.1.4. Analysis of periodic behavior with hybrid models

Participants: Jean-Luc Gouzé, Madalena Chaves.

Periodic orbits in non monotonic negative feedback circuits. In [91], we studied the occurrence of periodic solutions in an n-dimensional class of negative feedback systems defined by smooth vector fields with a window of not necessarily monotonic activity. We have now [36] further established uniqueness and stability of the periodic solution under some conditions on the parameters.

Analysis tools for interconnection of Boolean networks. Following the work in [96] and [78], we have generalized the method for computation of the asymptotic graph. In [22], a quantitative dimension is added to the asymptotic graph, through the computation of relative probabilities for each final attractor. In [19], we have extended this methodology for the case of Boolean networks with synchronous updates, in a collaboration with D. Figueiredo and M.A. Martins from the University of Aveiro, Portugal (project PHC Pessoa).

7.1.1.5. Dynamics of complex feedback architectures

Participants: Jean-Luc Gouzé, Madalena Chaves.

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 [20]. 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 [21].

7.1.2. Metabolic and genomic models

Participants: Jean-Luc Gouzé, Olivier Bernard, Valentina Baldazzi, Claudia Lopez Zazueta, Lucie Chambon, Agustin Yabo.

Transcription and translation models in bacteria. We study detailed models of transcription and translation for genes in a bacterium, in particular the model of gene expression of RNA polymerase [12]. This is part of the PhD thesis of Stefano Casagranda (2017), and done in collaboration with Inria IBIS project-team, in particular with D. Ropers.

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 [25]. A reduction pipeline combining serveral strategies is currently 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).

Analysis of an integrated cell division-endoreduplication and expansion model. The development of a new organ depends on cell-cyle progression and cell expansion, but the interaction and coordination between these processes, under different environments, is still unclear [29]. An integrated model of fruit development has been developed and used to test different interaction schemes, by comparing simulation results to observed cell ditribution data in tomato fruit [65], [47].

7.1.2.1. Estimation and control

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 project-team. We showed that a good suboptimal control solution could be implemented in the cell by ppGpp (a small molecule involved in the regulation of ribosomes) [80]. We developed different versions of the problem [40], and consider a new problem where the aim is to optimize the production of a product [39],(ANR projects Reset and Maximic, new PhD thesis of A. Yabo, collaboration with McTao Team). We also study variations of the model, including energy (ATP and ADP).

Control of a model of synthesis of a virulence factor. In collaboration with J.-A. Sepulchre (INLN Nice), we model 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. A nonlinear control is built [94], [38].

Hybrid control of genetic networks. We design 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 [48] . This is part of the thesis of L. Chambon.

7.1.2.2. Slow-Fast analysis of metabolic models

Metabolic modeling generally assumes balanced growth, *i.e.* that there is no accumulation of intermediate compound, and that the metabolism is rapidly at quasi steady state. We go beyond this hypothesis by considering that some metabolic reactions are slow, while other are fast. Then we analyse the differential system using Tikhonov's Theorem. We compare the results obtained using the Drum approach [2], and show that Drum is a reasonable approximation, provided that growth rate stays low. This is part of the PhD thesis of Claudia Lopez Zazueta [31], [30], [54], [55].

7.1.2.3. Large scale metabolic modeling

Metabolic modeling generally assumes balanced growth, *i.e.* that there is no accumulation of intermediate compound, and that the metabolism is rapidly at quasi steady state. We have proposed a new approach called DRUM where this hypothesis is relaxed by splitting the metabolic network into subnetworks and assuming that some compounds can accumulate between the subnetworks [2], [73]. This approach was successfully applied to several cases where the variations in light or nutrient resources induce a strong accumulation in the microalgal cells which could not be represented by the state of the art approaches [74]. More recently we have expended this approach to identify the genomic regulations explaining the change in metabolism especially when considering nitrogen starvation under a light/dark regime.

7.1.3. Biochemical and signaling models

7.1.3.1. Analysis and coupling of biological oscillators

Participants: Sofia Almeida, Madalena Chaves, Eleni Firippi.

Modeling, analysis and coupling of the mammalian cell cycle and clock. Each biological oscillator was modeled by a system of non-linear ordinary differential equations and its parameters calibrated against experimental data (both from the literature and from F. Delaunay's lab). The interactions between the two oscillators are investigated under uni- or bi-directional coupling schemes. 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) mycitePhD:almeida. This work is in collaboration with F. Delaunay (ANR ICycle) and part of the PhD thesis of Sofia Almeida.

Improving the design of a synthetic oscillator. We analyse a two-variable model (the "Smolen" oscillator) using both numerical simulations and theoretical analysis through a piecewise affine approximation. Our objective is to investigate the existence of oscillatory behaviour and, in particular, to characterize and increase the region of parameters which admits sustained oscillations. This work is part of the PhD thesis of Eleni Firippi (ANR ICycle).

7.1.3.2. Modeling the apoptotic signaling pathway

Participants: Madalena Chaves, Luis Gomes Pereira, Jérémie Roux.

The 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. To do this, we have been analysing models of the apoptosis pathway to compare the effects of different sources of variability at the transcriptional, translational and receptor levels [57] (collaboration with J. Roux, for the PhD thesis of Luis Pereira; project Imodrez).

7.2. Fields of application

7.2.1. Bioenergy

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

7.2.1.1. Modeling microalgae production

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.

This experimental platform was used to control the long term stress applied to a population of microalgae. This Darwinian selection procedure generated two new strains after more than 6 months in the so called selectiostats.

Other experiments were carried out to reproduce the light signal percept by a cell in a raceway pond [24], derived from Lagrangian hydrodynamical computations. The experiments show that pigments content of the microalgae is highly related to the experimented hydrodynamic regime.

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. This is the topic of Bruno Assis Pessi's master thesis. The impact of process configuration on CO_2 transfer rate has also been tested and quantified [17].

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 developped by I. Lopez to represent the dynamics of polar lipids, especially when faced to higher oxygen concentration.

Modeling the coupling between hydrodynamics and biology. In collaboration with the Inria ANGE team, a model coupling the hydrodynamics of the raceway (based on an original multilayer discretisation of Navier-Stokes equations) with microalgae growth was developed [75]. This model is supported by the work of ANGE aiming at improving the discretization scheme of the Navier-Stokes equations and eventually to more accurately represent the hydrodynamics of the raceway and reconstruct Lagrangian trajectories. The accurate reconstruction of the trajectories is verified by a statistical analysis of the probability densities. As a consequence, more relevant experimental protocols have been proposed to more realistically design simplified light signal for experiments [24].

Modeling photosynthetic biofilms. Several models have been developed to represent the growth of microalgae within a biofilm. A first structured physiological model 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 [92]. Another approach accounts for the dynamics of the light harvesting systems when cells are submitted to rapid successions of light and dark phases. 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 [41].

Modeling microalgae production processes. The integration of different models developed within BIOCORE [76] was performed to represent the dynamics of microalgae growth and lipid production in raceway systems. The model was validated at industrial scale with cultivation of the microalgae *Dunaliella salina* [15].

This model was then used to predict productivity in raceway systems, depending on climatic conditions. A Model Predictive Control strategy was developed to on-line adapt influent flow rate and water depth to temperature and light.

We have shown in [87] that a control strategy based on shadowing with solar panel can significantly improve productivity, especially during the early growth stage of the culture.

Modeling thermal adaptation in microalgae. We have studied and compared several models of microalgae growth to different temperatures [82]. 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. 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 [23].

Modeling viral infection in microalgae. Experiments have been carried out in collaboration with A.-C. Baudoux (Biological Station of Roscoff) in order to study the impact of viral infections on the development of populations of *Micromonas* at different temperatures. This work revealed a qualitative change in viral infection when temperature increases. 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 [79].

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.

Interactions between species. We have proposed an optimal control strategy to select the microalgal strain with the lowest pigment content. The control takes benefit from photoinhibition to compute light stresses penalizing the strains with a higher pigment content and finally select microalgae with lower chlorophyll content. This characteristic is of particular interest for maximizing biomass production in dense cultures. The strategy has been carried out at the LOV and eventually the productivity of *Tisochrysis lutea* was improved by 75%.

Finaly, optimal strategies when selecting the strain of interest within two species competing for the same substrate has been proposed, when dynamics is represented by a Droop model [42].

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 [18].

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 [95].

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 [33]. Optimal control strategies playing with the dilution rate, shadowing or modifying depth were then studied [32].

7.2.2.3. Life Cycle Assessment

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

Environmental impact assessment. In the sequel of the pioneering life cycle assessment (LCA) work of [83], we continued to identify the obstacles and limitations which should receive specific research efforts to make microalgae production environmentally sustainable [62].
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 is studied. Depending on the period of the year, changing the species can both improve productivity and reduce environmental footprint.

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

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, Nicolas Bajeux, 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 [84], [90] [71], and was one of the key features of L. Mailleret's HDR thesis [11]. 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 on the multi-agent programmable modeling environment 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 [67], [68].

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 [72].

Characteristics of space and the behavior and population dynamics of parasitoids. 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 [89] and is the topic of Marjorie Haond's PhD thesis (ISA, 2015-). The two last articles associated with Thibaut Morel Journel's Thesis appeared this year. In the first one [34], we investigated the effect of habitat fragmentation on the establishment and early spread of an introduced population. We showed that by increasing the risks of dispersal from the introduction site to unfavourable habitat early during the invasion, fragmentation decreased establishment success. However, by decreasing the distance between favourable habitat patches, it also improved the subsequent spread of introduced species over larger areas. In the second paper [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 [27] as represented by its local carrying capacity can positively influence the spreading speeed of an expanding population. This work is being performed in collaboration with Elodie Vercken (ISA) and Lionel Roques (BioSP, Avignon).

In a metapopulation context, we studied the invasion success into an environment where part of the patches are sources (favourable environments) and the others are sinks; a criterion has been obtained predicting invasion success when the number of sources is larger than some threshold [70].

Modeling 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. An optimal control problem was formulated by implementing chemical control (insecticides) and/or biological control (entomopathogenic fungi such as *Beauveria bassiana*, microbial parasitoids, traps). 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. The existence of an optimal solution was shown and the problem was solved numerically [49], [44]. This ODE model was extended to integrate the berry maturation age. The well-posedness of the resulting PDE model was shown and an asymptotic analysis was conducted. This research pertains to Yves Fotso Fotso's PhD thesis, who visited BIOCORE during 5 months in 2018 through the EPITAG associate team.

7.2.3.2. Controlling plant pathogens

Participants: Frédéric Grognard, Ludovic Mailleret, Suzanne Touzeau, Pauline Clin.

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.

Experiments were conducted in INRA Avignon for Potato Virus Y on pepper plants to evaluate the effect of four traits influencing evolutionary forces leading to resistance breakdown: virus effective population sizes, either at plant inoculation or during infection, virus accumulation and differential selection during infection. A generalized linear model showed a strong impact of the second and third one while a positive interection between differential selection and virus accumulation was identified [37]. Also, a stochastic model was developed to help determine the efficiency of pyramiding qualitative resistance and quantitative resistance narrowing population bottlenecks exerted on 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 [93]. These studies 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).

We pursued the calibration of the (spatio-)temporal epidemiological model of the phoma stem canker of oilseed rape, using field data on resistance deployment and virulence of phoma populations. Ongoing work includes the development of a simulation tool designed for researchers as well as non academic partners from technical institutes and agriculture cooperatives, who interact through the MoGeR project. It benefits from the resources and support of NEF computation cluster.

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 [51], [52]. This was the topic of Pauline Clin's master thesis and was done in collaboration with 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.

Phytophagous 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.

We developed a first physiological model of plant–nematode interactions, explicitly describing resource (water and carbon) allocation between roots and shoots. Indeed, nematodes draw on root carbon pool and reduce plant water uptake from the soil. The consequences on plant growth were analyzed as a function of plant physiological characteristics. In parallel, an experiment was conducted on pepper and tomato plants to monitor plant growth with or without nematodes. Data will be used to calibrate the model. This work was the topic of Thomas Brenière [77] and was done in collaboration with Caroline Djian-Caporalino (ISA, INRA Sophia Antipolis).

We studied the stability of the hybrid interaction model between nematodes and plantain roots [46]. An optimisation problem was formulated to determine 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. We first considered that the farmer buys and plants pest-free suckers at the beginning of each cropping season. This allows for a fallow period which reduces the nematode population in the soil, as these pests need roots to feed on and reproduce. Two cases were considered: a fixed or a variable fallow period. In the first case, the existence of an optimal solution was proven and its location was computed for small infestations. In the second case, the existence of an optimal strategy was proven and was numerically computed [58]. This research pertains to Israël Tankam Chedjou's PhD thesis, who visited BIOCORE during 5 months in 2018 through the EPITAG associate team.

We studied the resistance-based nematode control. As virulent nematodes exhibit a reduced fitness on susceptible crops, combining both resistant and susceptible plants can help increase the efficacy and sustainability of such control methods. In the *Solanaceae* family, there are two major resistance genes: the first one induces an early reaction when the nematode enters in the root system and the second one induces a late reaction when the nematode creates its feeding site. We used a semi-discrete model describing the plant-nematode interactions within and between cropping season to implement the action of both resistance genes. We computed and compared the optimal deployment strategies of both resistant crops [56]. This research pertains to Samuel Nilusmas' PhD thesis (2016–).

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 [97]. The solution of this dynamic game has been shown to be the equilibrium of two-trait adaptive dynamics [50]. This work, in the framework of the ANR Funfit project, 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. This work was published through the novel preprint reviewing system of Peer Community In Ecology [66].

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 funded the M2 internship of J.B. Excoffier.

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.

- **ANR-FunFit:** The objective of this project (2013-2018) is to develop a trait-based approach linking individual fitness of fungal plant pathogens to ecological strategies. The idea is to derive eco-epidemiological strategies from fitness optimization in colonized environments and during colonization, as well as understanding the coexistence of sibling species. This project is co-coordinated by F. Grognard.
- **ANR-TripTic:** The objective of this project (2014-2018) is to document the biological diversity in the genus of the minute wasps *Trichogramma*, and to study the behavioral and populational traits relevant to their use in biological control programs.
- **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 from 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.
- **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.

9.1.2. Inria funding

- **Inria Project Lab, Algae** *in silico***:** (2014-2018) 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, NON-A, the Inria Action Exploratoire 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.

9.1.4. Networks

- **GDR Invasions Biologiques:** The objectives of this GDR are to encourage multidisciplinary research approaches on invasion biology. It has five different thematic axes: 1) invasion biology scenarios, 2) biological invasions and ecosystem functioning, 3) environmental impact of invasive species, 4) modeling biological invasions, 5) socio-economics of invasion biology. L. Mailleret is a member of the scientific comittee of the GDR .
- **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: 01/2018 - 12/2018

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),

Modeling and optimization of microalgal based processes.

University of Padova, Italy.

Modeling and control of microalgal production at industrial scale.

9.3. International Initiatives

9.3.1. Inria International Labs

Associate Team involved in the International Lab: **Inria Chile**

9.3.1.1. GREENCORE

Title: Modeling 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.

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

9.3.1.2. EPITAG

Title: Epidemiological Modeling and Control for Tropical Agriculture

International Partner (Institution - Laboratory - Researcher):

Université de Douala (Cameroon) - Department of Mathematics and Computer Science - 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. 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, “end users” are closely associated. We focus on various pathosystems, such as cocoa plant mirids, coffee berry borers, coffee leaf rust and plantain plant-parasitic nematodes.

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

- University of Manitoba: Department of Mathematics (Canada). Julien Arino hosted Nicolas Bajeux for 5 months. Invasion in metapopulations.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

Luca Scardovi, University of Toronto, Canada, from Feb 2018 until June 2018. Long-term visit, to establish a new collaboration on the coupling and synchronization of biological oscillators.

Daniel Figueiredo, University of Aveiro, Portugal, 17-25 Oct 2018. 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, April-August 2018. 5-month stay in the context of the EPITAG associate team.

Yves Fotso Fotso, University of Dschang, Cameroon, April-September 2018. 5-month stay in the context of the EPITAG associate team.

Clotilde Djuikem, University of Douala, Cameroon, May-July 2018. 3-month stay in the context of the EPITAG associate team.

9.4.2. Visits to International Teams

9.4.2.1. Sabbatical programme

O. Bernard is currently spending a one year sabbatical at NTNU (Norwegian University of Science and Technology), Trondheim, Norway. He works on a project to turn wastes into bioenergy with anaerobic digestion. Many challenges must be solved, from the theoretical stage up to the implementation.

9.5. Other Visits

Hussein Kanso, PhD student at INRA Avignon, a 2-week visit in the context of the work on modeling of sugar metabolism in peach fruit (collaboration with V. Baldazzi).

9.6. Project-team seminar

BIOCORE organized a 3-day seminar in September in Bauduen (Var). 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 is the Co-Chair of the next Dycops-CAB conference (CAB 2019 Florianópolis, Brazil, 23-26 April).

M. Chaves is organizing co-chair for the International Symposium on Molecular Logic and Computational Synthetic Biology (Santiago Chile, 17-18 December, 2018).

10.1.1.2. Member of the Organizing Committees

M. Chaves is part of the organizing committee for the Summer School on "Modélisation formelle des réseaux de régulation biologique" (Porquerolles, France, June 2019).

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.

M. Chaves is a member of the program committee of Journées ouvertes de biologie informatique et mathématiques (JOBIM 2018, Marseille, France, 3-6 June; JOBIM 2019, Nantes). She is in the program committee of Foundations of Systems Biology in Engineering (FOSBE 2019).

J.-L. Gouzé is a member of the program committee for the International Conference on Positive Systems (POSTA 2018, Hangzhou, China, 25-27 August).

10.1.2.2. Reviewer

All BIOCORE members have been reviewers for the major 2018 conferences in our field: CDC, ECC, IFAC World Congress,...

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, 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 PROMES Laboratory for solar ernergy (Odeillo) “Purple Sun-sharing photons between semi transparent PV panels and microalgae production” (July, 13rd, 2018).

M. Chaves and J. Roux gave a paired presentation on modeling heterogeneity in cell-death drug response at the group UCancer (a UCA structuring project) (December 2018).

M. Chaves gave a Colloquium at the Department of Mathematics at Universidade de Aveiro, Portugal (June 2018).

10.1.5. Other Selected Talks

M. Chaves gave a presentation on ANR project ICycle at the workshop ComplexDays, organized by Université Côte d’Azur (January 2018).

J.-L. Gouzé gave a talk at the SFBT meeting (St Flour, June 2018).

L. Chambon participated at the Workshop MOMI 2018 on the 26th and 27th of February, organised by Inria in Sophia-Antipolis about Mathematics in industry, where she presented a poster of her research. On the 18th and 19th of June, she presented a poster at the "Modelife Days" of the UCA Jedi Idex Core program "Modeling, physics and mathematics of living systems" in Nice.

10.1.6. Scientific Expertise

O. Bernard is a member of the scientific committee of the companies Inalve and BioEnTech.

J.-L. Gouzé was in several evaluation committees or juries: FWO, NWO, FNRS...

S. Touzeau evaluated a project for the “Centre d’excellence africain en Mathématiques, Informatique et Technologies de l’Information et de la Communication” (CEA-MITIC), Senegal.

10.1.7. 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 is a member of the CLHSCT of Inria Sophia Antipolis (local committee for the safety of working conditions).

M. Chaves is in the Pedagogical Committee 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. He is a member of the scientific committee of the doctoral school "Sciences de la Vie" at the University of Nice-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 metaprogramme SMaCH *Sustainable Management of Crop Health*, INRA (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: 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 : 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: 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

HdR : L. Mailleret. Modélisation et contrôle en dynamiques de populations. Applications en protection des plantes, 16 February 2018, Université Côte d'Azur.

PhD : S. Almeida. "Synchronization of biological oscillators: modeling, analysis and coupling of the mammalian cell cycle and circadian clock", 17 December 2018, Université Côte d'Azur. Supervisors: M. Chaves and F. Delaunay (Univ. Nice, iBV).

PhD : M. Caïa, "Characterization and modeling of a mixotrophic algae - bacteria ecosystem for waste recovery", 13 December 2018, Université Montpellier. Supervisors: J.-P. Steyer and O. Bernard.

PhD : C. Lopez-Zazueta. "Réduction dynamique de réseaux métaboliques par la théorie des perturbations singulières : application aux microalgues", 14 December 2018, Université Côte d'Azur. Supervisors O. Bernard and J.-L. Gouzé.

PhD : V. Burte. "Étude des stratégies de mouvement chez les parasitoïdes du genre Trichogramma : apports des techniques d'analyse d'images automatiques", 14 December 2018, Université Côte d'Azur. Supervisors V. Calcagno et L. Mailleret.

PhD in progress : M. Haond. "Causes et conséquences des fronts de colonisation poussés", since October 2015, Univ. Nice Sophia Antipolis. Supervisors: E. Vercken (UMR ISA), L. Mailleret and L. Roques (UR BioSP).

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 : L. Pereira. "Experimental and computational approaches to understanding the molecular origins of drug response heterogeneity, underlying resistance to cancer therapies", since October 2016, Université Côte d'Azur. Supervisors: M. Chaves and J. Roux (IRCAN, Nice).

PhD in progress: M. Gachelin, "Selection pressure to improve lipid productivity of microalgae", since March 2017, Sorbonne Université. 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, Université Côte d'Azur. Supervisor: 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 (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 (Valse, Inria Lille).

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: I. Tankam Chedjou, "Modeling, analysis and control of plantain plant-parasitic nematodes", University of Yaoundé 1, since December 2015. Supervisors: J.-J. Tewa, F. Grognard, L. Mailleret, S. Touzeau.

PhD in progress: Y. Fotso Fotso, "Modeling, analysis and control of coffee berry borers", University of Dschang, since January 2017. Supervisors: S. Bowong, B. Tsanou, F. Grognard, L. Mailleret, S. Touzeau.

10.2.3. Master thesis and internships

PFE: Adrien Boudin, "Controle optimal des ressources dans une cellule", EPU MAM, supervisors J.-L. Gouzé et JB. Caillau (McTao).

Engineer: Bruno Assis Pessi, "Modeling microalgal growth under a greenhouse", Ecole CentraleSupelec, supervisor O. Bernard.

M2: Jenna Balaguer, "Effect of background turbidity on microalgae growth", Sorbonne Université, supervisor O. Bernard.

M2: Jean-Baptiste Excoffier, “Modélisation in silico de médicaments, et personnalisation des traitements”, Université Côte d’Azur, supervisors J.-L. Gouzé and F. Dayan (Exactcure).

M2: Pauline Clin, “Résistance systémique acquise, mélanges variétaux et épidémiologie évolutive des interactions plantes-pathogènes”, Université de Rennes 1, supervisors F. Grognard and F. Hamelin (Agrocampus Ouest).

M1: David Davtian, “Modélisation multi-agent pour l’étude et l’optimisation des introductions biologiques”, Université Côte d’Azur, supervisors L. Mailleret and F. Grognard.

M1: Thomas Brenière, “Physiologie de la plante attaqué par les nématodes: Modélisation et expérimentation”, INSA Lyon, supervisors V. Baldazzi and C. Djian-Caporalino (ISA, INRA Sophia Antipolis).

Other: O. Bernard supervised a project involving 4 students from CentraleSupelec (first year of engineering school), 4 months, to design a system for detecting contamination in microalgae cultures.

10.2.4. Juries

V. Baldazzi and L.Mailleret participated in the thesis comitee of Marta Zaffaroni (INRA Avignon) in October 2018.

O. Bernard was reviewer for the PhD thesis of G. Jeanne “Optimization of bioprocess design: towards an intergated approach synthetic biology and process control”. University Paris-Saclay (27 Sept. 2018).

M. Chaves was member of the jury for the PhD thesis of Sofia Almeida, December 2018.

J.-L. Gouzé and O. Bernard were in the jury of the PhD of Claudia Lopez Zazueta “Réduction dynamique de réseaux métaboliques par la théorie des perturbations singulières : application aux microalgues.” Université Côte d’Azur, December 14, 2018.

J.-L. Gouzé was reviewer of the PhD of Hongjun Ji “Systèmes dynamiques coopératifs appliqués en biologie”, Sorbonne Université, October 11, 2018.

S. Touzeau was the external examiner of Rebecca Bekker’s MSc thesis in Applied Mathematics “Mathematical models of the epidemiological dynamics of soil-borne pathogens”, University of Pretoria, South Africa, 2018.

S. Touzeau was a member of the selection committee MC 25–26 “Analyse des EDP pour la dynamique des populations”, University of Bordeaux, France, 2018.

10.3. Popularization

10.3.1. Articles and contents

- A popularization paper has been published on the study of peach sugar metabolism [64].
- L. Mailleret was a co-author of the press kit “Les conquêtes de l’INRA pour le biocontrôle” [86].
- The activities related to microalgae have generated many articles in national newspapers (Le Monde, Nice Matin, ,...), and broadcasts on national TV (France 3). See, for instance, https://www.nicematin.com/vie-locale/ces-azureens-inventent-223249.

10.3.2. Interventions

- O. Bernard together with R. Lemée gave a general public conference on the topic “Les microalgues en Méditerranée: quels avenirs environnementaux, énergétiques, sanitaires et industriels?” (MAMAC, Nice, 6 Apr 2018).
- L. Chambon and O. Bara participated in the open doors days of Inria Sophia-Antipolis on the 7th of October. L. Chambon presented a popularization poster about Biocore scientific methodologies to general public.

- L. Chambon represented Biocore, Inria in the national event “Fête de la Science” in Mouans-Sartoux and Juan-les-Pins (13th and 20th of October). She presented scientific popularization games and experiments to children and general public.
- L. Mailleret presented three Posters on biological control with predatory mites during the visit of the national press (AFP, France Inter, Le Parisien,...) at Institut Sophia Agrobiotech on the 30th of May 2018.

11. Bibliography

Major publications by the team in recent years

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Publications of the year

Doctoral Dissertations and Habilitation Theses

[11] L. MAILLERET.*Modélisation et contrôle en dynamiques de populations. Applications en protection des plantes*, Université Côte d'Azur, February 2018, Habilitation à diriger des recherches, https://hal.inria.fr/tel-01954099

Articles in International Peer-Reviewed Journal

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Project-Team BIOVISION

Biological vision: integrative models and vision aid-systems for visually impaired people

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Computational Neuroscience and Medicine

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Project-Team BIOVISION

Creation of the Team: 2016 January 01, updated into Project-Team: 2018 August 01

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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) [34], [31]. 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 [53], [43]. 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.

[0] Source: VisionAware

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). Our goal is to develop solutions based on head mounted displays, especially low cost and large public systems, with full consideration of comfort and **ergonomics**. In particular, we focus on three main goals:

1. Developing **reading aids in virtual reality**. This includes functional vision testing, allowing display and interaction to be personalized.
2. Developing broader **vision aid-systems in augmented reality** for other daily living activities, such as social interaction, visual search and navigation.
3. Proposing **image enhancements** which can be customized for each patient depending on their needs and **pathology**.

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 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 spike-response to visual and prosthetic simulations, in normal and pathological conditions.

Finally, although this is not the main goal of our team, another natural avenue of our research is to develop novel synergistic solutions to solve computer vision tasks based on bio-inspired mechanisms [7].

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 [28], [38], [39], [32], [29]. 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 informations (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 words 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 this technology can 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). We have launched several projects using different platforms (see sections 5.3.1 and 6.1.1). 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 objective. 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 Biovision team we adopt the point of view of physicists: 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, get out analytic 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], [12].

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).

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], [30].

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 [42] used by numerous authors in the context of the retina (see, e.g., [45], [47], [41], [40], [48]). 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] [49], [33]. 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 [19], [26], [27].

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 plateform 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 respond to visual stimuli.

5. New Software and Platforms

5.1. 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/

5.2. 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 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 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/

5.3. Platforms

5.3.1. VRead

We are currently developing the VRead platform, a reading platform for digital content. We are now in the phase of building and testing prototypes with low-vision patients. We have started to conduct a qualitative Market research with patients to get a continuous feedback from them, discover their needs and thus better drive the developments. A special care is taken for ergonomics to optimize user experience in virtual reality. This is a crucial aspect in this project, especially because we primarily target a more fragile population so that we have to take into account their vision loss and cognitive skills. As for the technical aspect, we are using the Unity game engine along with the Oculus SDK, allowing us to deploy and test early on the Samsung GearVR mobile platform. For scripting the engine we code in C# using the proprietary directives of Unity. We ship the VRead Viewer with an operator application which allows for supervision and tuning of parameters of the reader in realtime. This application is written using the Unity SDK and is deployable under macOS, Windows and Linux.

This project received financial support from Université Côte d'Azur (France) (duration: 18 months, period: Aug. 2017– Jan. 2019 and Inria (via InriaHUB programme). It is done in collaboration with Aix-Marseille Université (CNRS, Laboratoire de Psychologie Cognitive, Marseille, France), Centre hospitalier Pasteur 2 (service d'ophtalmologie, Nice, France) and University of Genoa (DIBRIS, Genoa, Italy).

5.3.2. Macular

We are currently developing the platform Macular, a large-scale simulations platform of impaired retinas, allowing to mimic specific degeneracies or pharmacologically induced impairments, as well as to emulate electric stimulation by prostheses. With this tool scientists will be able to design a simulation gui adapted to their need, so as to test hypotheses, make in-silico experiments prior to real experiments, test models, change the equations of a model and look at the impact of the dynamics. We hope it will become a standard for the community of modelers, experimentalists in the academic word, as well as for companies doing research and development. Macular will also help to better understand how to design algorithms to help visually impaired individuals. Especially, the Biovision team wants to develop computer algorithms for retinal prostheses that reproduce the functions performed by the bypassed parts of the eye: these algorithms can then be used as a "camera to eye translator" in retinal prosthetics.

6. New Results

6.1. High tech vision aid-systems for low-vision patients

6.1.1. Improving social interaction through augmented reality

Participants: Josselin Gautier, Pierre Kornprobst, Nicolas Chleq, Frédéric Dosière [Bosch Visiontec (Sophia Antipolis, France)], David Coupé [Bosch Visiontec (Sophia Antipolis, France)].

Today's visual enhancement systems for low-vision people consist of dedicated augmented reality hardware allowing to magnify or enhance the overall scene, independently of the image content or patient needs. For example, for patients with central vision loss, interacting with others may become a painful activity when faces and expressions can hardly be recognized. In [17], we introduce a new augmented reality system allowing to selectively enhance faces, using two image processing techniques [44], [50]. Our system is based on a Fove 0 head-mounted display (FOVE Inc, San Mateo, CA, USA). It has the capacity to adjust the enhancement to the detected faces' size and distance, hence maintaining a constant boost in the critical range of spatial frequency. It offers a binocular and large Field-of-View and performs at near real-time with a modest laptop computer using multithreading. Preliminary experiments with three patients with central vision loss suggest that the enhancements chosen strongly depends on each patient's condition and lead to improved recognition abilities when patients find their optimal settings.

This work is presented in [17].

6.1.2. Text auto-illustration for improving reading accessibility to low-vision people

Participants: Paula Pawlowski, Pierre Kornprobst, Elena Cabrio [Inria, EPI WIMMICS], Marco Benzi [Université Côte d'Azur (France)].

We have started to explore how to make reading more efficient and more enjoyable for low-vision patients through text auto-illustration. Text auto-illustration consists in automatically extracting images from the web which are related to a given text, using natural language processing methods.

6.2. Human vision understanding through joint experimental and modeling studies, for normal and distrophic vision

6.2.1. Retinal waves

Participants: Dora Karvouniari, Lionel Gil [Institut Non Linéaire de Nice - Institut de Physique de Nice (INLN, Université Côte d'Azur (France), France)], Olivier Marre [Institut de la Vision (Paris, France)], Serge Picaud [Institut de la Vision (Paris, France)], Bruno Cessac.

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 [51], [36], [46], [37]. 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 [35]. 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 [52].

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. 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. We have proposed a testable experimental prediction providing a possible link of the evolution of voltage-dependent potassium channels along development with their role on the excitability properties of SACs. We have reproduced experimental findings (statistical characteristics of waves size, duration and frequency of appearance) and analysed how the evolution of cholinergic conductance due to the maturation of nicotinic receptors dramatically changes the retinal wave characteristics. We have also shown that the nonlinear dynamics generates heterogeneous local spatial structures inside which retinal waves propagate. This induces a wide variability in waves characteristics even though the network is perfectly homogeneous.

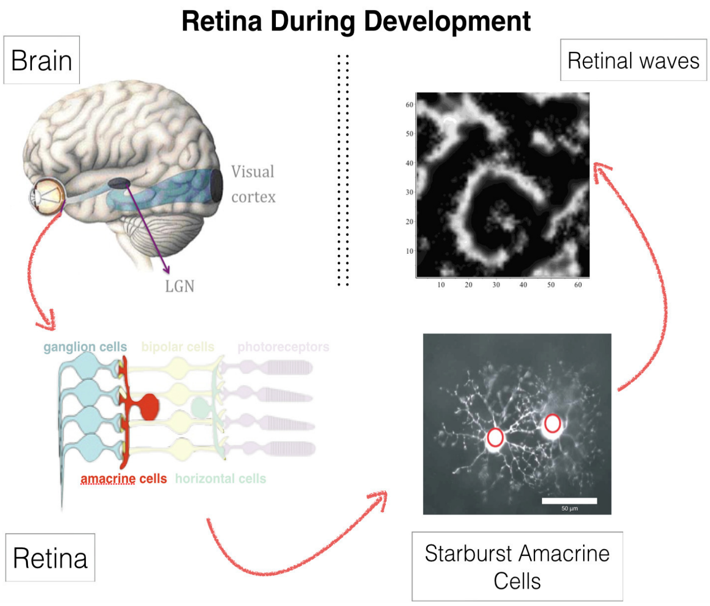

Figure 1. Multiscale dynamics of retinal waves

This work has been presented in [11], [13], [14], [16], [20], [12], [24].

6.2.2. Trajectory anticipation, from retina to V1

Participants: Bruno Cessac, Selma Souihel, Frédéric Chavane, Alain Destexhe, Matteo Di Volo, Olivier Marre.

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 feedforward stream. At the present stage of knowledge, it is still unclear how the early visual system processes motion trajectories. 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 problem is particularly challenging, as it requires to probe these sequences of events at multiple scales (from individual cells to large networks) and multiple stages (retina, primary visual cortex V1).

In the context of the ANR Trajectory, we are working on such an integrated approach. We aim at modelling the population responses at two key stages of visual motion encoding: the retina and V1 based on simultaneous micro- and mesoscopic recordings made by our partners Institut de Neurosciences de la Timone (CNRS and Aix-Marseille Université, France), Institut de la Vision (Paris, France) and Unité de Neurosciences Information et Complexité, Gif sur Yvette, France. We are designing a simulator of retinal output + V1, reproducing both the retinal anticipation and the cortical response measured by optical imaging. We are also analyzing the effects of lateral connectivity in the retina, via amacrine cells, in processing motion. This lateral connectivity is accountable for the correlated activity of RGCs in experimental data. We are measuring these correlations to add further biological plausibility to our model. This study is a step toward understanding mechanisms of motion coding and anticipation with strong impact on our understanding of the visual system.

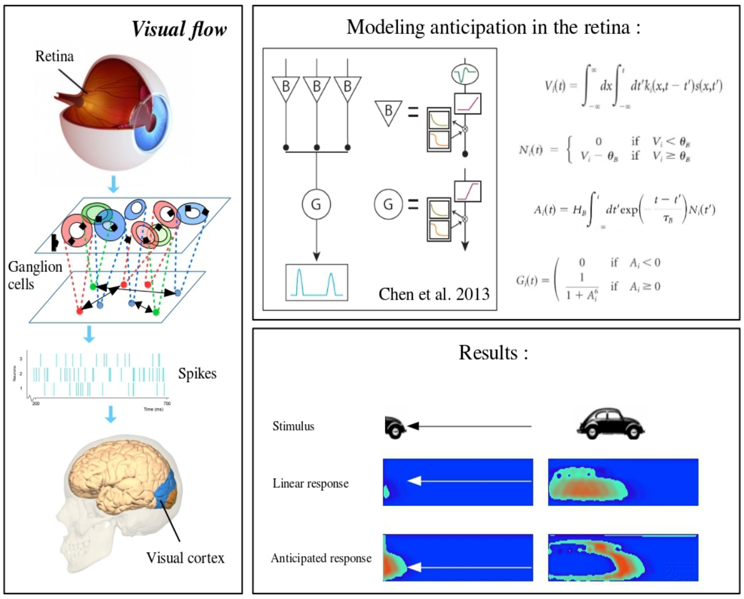

Figure 2. Motion anticipation

These results have been presented in [26], [27]

6.2.3. Dimensionality reduction in spatio-temporal MaxEnt models and analysis of retinal ganglion cell spiking activity in experiments

Participants: Rubén Herzog [Centro Interdisciplinario de Neurociencia de Valparaíso (CINV, Valparaíso, Chile)], Rodrigo Cofré [Centro Interdisciplinario de Neurociencia de Valparaíso (CINV, Valparaíso, Chile)], Maria-Jose Escobar [Universidad Tecnico Federico Santa María (Electronics Engineering Department, Valparaíso, Chile)], Adrian Palacios [Centro Interdisciplinario de Neurociencia de Valparaíso (CINV, Valparaíso, Chile)], Bruno Cessac.

Retinal spike response to stimuli is constrained, on one hand by short range correlations (receptive field overlap) and on the other hand by lateral connectivity (cells connectivity). This last effect is difficult to handle from statistics because it requires to consider spatio-temporal correlations with a time delay long enough to take into account the time of propagation along synapses. Although MaxEnt models are useful to fit optimal model (maximizing entropy) under the constraints of reproducing observed correlations, they do address spatio-temporal correlations in their classical form (Ising or higher order interactions but without time delay). Binning in such models somewhat integrates propagation effects, but in an implicit form, and increasing binning severely bias data. To resolve this issue we have considered spatio-temporal MaxEnt model formerly developed e.g. by Vasquez et al. [49]. The price to pay, however is a huge set of parameters that must be fitted to experimental data to explain the observed spiking patterns statistics. There is no a priori knowledge of which parameters are relevant and which ones are contributing to overfitting. We propose here a method of dimension reduction, i.e. a projection on a relevant subset of parameters, relying on the so-called Susceptibility matrix closely related to the Fisher information. In contrast to standard methods in information geometry though, this matrix handles space and time correlations. We have applied this method for retina data obtained in a diurnal rodent (Octodon degus, having 30% of cones photoreceptors) and a 252-MEA system. Three types of stimuli were used: spatio-temporal uniform light, white noise and a natural movie. We show the role played by time-delayed pairwise interactions in the neural response to stimuli both for close and distant cells. Our conclusion is that, to explain the population spiking statistics we need both short-distance interactions as well as long-distance interactions, meaning that the relevant functional correlations are mediated not only by common input (i.e. receptive field overlap, electrical coupling; spillover) but also by long range connections.

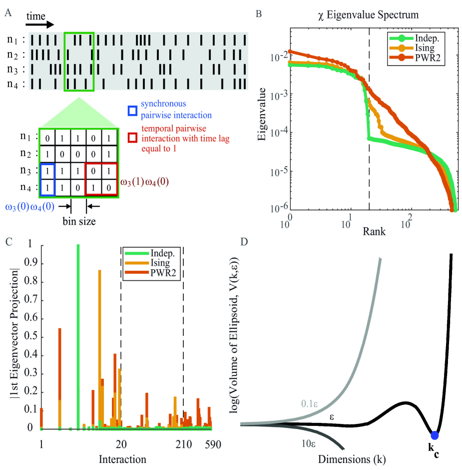

Figure 3. Dimension reduction method

This work has been submitted to Plos Comp Bio [22].

6.2.4. Linear response for spiking neuronal networks with unbounded memory

Participants: Bruno Cessac, Rodrigo Cofré [Centro Interdisciplinario de Neurociencia de Valparaíso (CINV, Valparaíso, Chile)].

The activity of a neuronal network, characterized by action potentials (spikes), is constrained by the intrinsic properties of neurons and their interactions. When a neuronal network is submitted to external stimuli, the statistics of spikes changes, and it is difficult to disentangle the influence of the stimuli from the intrinsic dynamics. We have established a general linear response relation for spiking neuronal networks, based on chains with unbounded memory. This relation allows quantifying the influence of a weak amplitude external stimuli on spatio-temporal spike correlations, in a general context where the memory in spike dynamics can go arbitrarily far in the past. With this approach, we show how linear response is explicitly related to neuron dynamics with an example, the gIF model, introduced by M. Rudolph and A. Destexhe [91]. This illustrates the effect of the stimuli, intrinsic neuronal dynamics, and network connectivity on spike statistics.

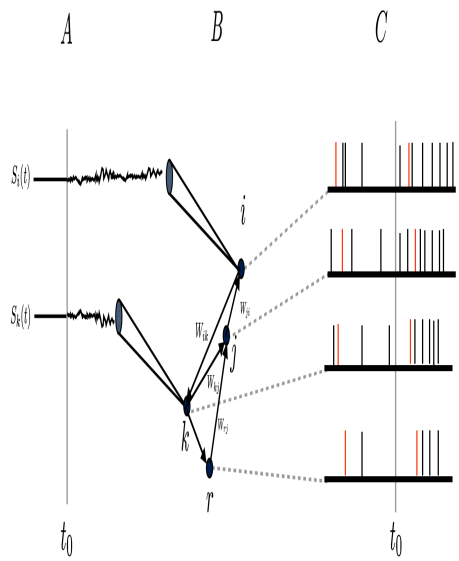

Figure 4. Linear response. The excitation of some neurons in a network will induce a variation in spike correlations between all connected neurons, even those which are not excited. We have computed this effect in [19].

This work has been submitted to Journal of Mathematical Neurosciences [19].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. Could hardware solutions coming from the automotive industry be useful in the context of low vision?

Participants: Josselin Gautier, Nicolas Chleq [Inria, SED], Pierre Kornprobst, Frédéric Dosière [Bosch Visiontec (Sophia Antipolis, France)], David Coupé [Bosch Visiontec (Sophia Antipolis, France)]

Duration: August 2017 to March 2018

Thanks to a partnership with Bosch Visiontec (Sophia Antipolis, France), we have investigated how hardware solutions coming from the automotive industry (RENESAS Starter-Kit RCar H3) could be used to design real-time vision-aid-systems based on augmented reality. We focused on the detection and enhancement of faces. We analysed the performance of a selection of enhancement algorithms and optimised them taking into consideration the hardware limitations.

Based on the same ideas, a working prototype has also been developed using a Fove 0 head-mounted display and tested with three patients with central vision loss (see Sec.6.1.1).

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. Modélisation Théorique et Computationnelle en Neurosciences et Sciences Cognitives

The Biovision team is a member of this "Axe Interdisciplinaire de Recherche de l'Université de Nice – Sophia Antipolis" and of the Institute Neuromod of neuroscience modelling . Biovision team has participated to the Rencontre C@UCA 2018 in Fréjus (June 2018). This axe is partly funding our work on retinal waves.

8.2. National Initiatives

8.2.1. ANR

8.2.1.1. 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 (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 multiple scales (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.

8.3. European Initiatives

- 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)
- 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.

8.4. International Initiatives

8.4.1. International Research Network to Study Predictive Coding in the Retina

Program: CHILEAN SUPPORT OF INTERNATIONAL NETWORKING BETWEEN RESEARCH CENTRES

Project title: International Research Network to Study Predictive Coding in the Retina

Duration: 2018-2020

Coordinator: Maria-José Escobar, Advanced Center for Electrical and Electronic Engineering, Universidad Técnica Federico Santa María, Chile

Other partners:

Advanced Center for Electrical and Electronic Engineering (Valparaiso, Chili)

Centro Interdisciplinario de Neurociencia de Valparaíso (CINV, Valparaíso, Chile)

Abstract: The retina, a well-structured multilayer neural system, encodes the visual information of the environment from an input of photon flux to a series of electrical pulses that are ultimately readout by the brain to create perception and program motor actions. The retina, from an engineering point of view, can be seen as a series of circuits computing visual features from the visual world in parallel encoding only informative inputs that are then sent to the brain. Regarding all the visual features that can be detected from the outer world, motion processing represents a fundamental visual computation ruling many visuomotor behaviours. Motion sensitive neurons have been early reported in the retina, but recently additional features have been added to the pool of capabilities present in this organ: especially motion direction selectivity and predictive coding. Motion processing presents predictive coding characteristics, in the sense that there is an anticipatory response of the visual system when an object in motion follows a trajectory in the visual field. Motion anticipation is fundamental for survival. Interestingly, this mechanism, observed in the visual cortex, has been also reported in the retina. Understanding how the visual system accumulates information along a certain trajectory raises fundamental questions about neural computation, its dynamics, and implementation. This understanding could be also extended to new algorithms to image/video processing, and also, autonomous navigation of robots.

In this project, we propose the formal establishment of a collaborative network between the AC3E Biomedical System group (AC3E-UTFSM), Centro Interdisciplinario de Neurociencia de Valparaíso (CINV -UV) and Biovision team (Inria Sophia-Antipolis Mediterranée), gathering together skills related with physiological recording in the retina, data analysis and theoretical tools to implement functional and biophysical models. This network aims to study the anticipatory response observed in the mammalian retina, characterizing its underlying mechanisms and the predictive coding capabilities present in this part of the nervous system.

8.4.2. Inria International Partners

8.4.2.1. Declared Inria International Partners

Institute of Neuroscience (ION, Newcastle, UK)

Institute for Adaptive and Neural Computation (ANC, School of Informatics University of Edinburgh, UK)

Universidad Tecnico Federico Santa María (Electronics Engineering Department, Valparaíso, Chile)

Centro Interdisciplinario de Neurociencia de Valparaíso (CINV, Valparaíso, Chile)

University of Genoa (DIBRIS, Genoa, Italy)

8.5. International Research Visitors

8.5.1. Visits of International Scientists

Prof. Sarah Barman (School of Computer Science and Mathematics, Kingston University)

Dr Matteo Di Volo (Unité de Neurosciences Information et Complexité, Gif sur Yvette, France)

Dr Cyril Eleftheriou (IIT, Genova)

Dr Maria-José Escobar (Universidad Tecnico Federico Santa María (Electronics Engineering Department, Valparaíso, Chile))

8.5.1.1. Internships

Téva Andréoletti (Apr–Aug 2018)

Adrianna Janik (Oct 2017–Mar 2018)

Paula Pawlowski (Apr–Sept 2018)

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. General Chair, Scientific Chair,Member of the Organizing Committees

- Bruno Cessac has co-organized the conference Inspire New Insights on Complex Neural Dynamics, Cergy-Pontoise, France, June 2018 https://inspire2018parisseine.wordpress.com/
- Bruno Cessac has co-organized the scientific event 2nd structuring event UCA Cognitive systems, normality and pathology of the human brain, computational neuroscience http://univ-cotedazur.fr/events/deuxieme-rencontre-c@uca
- Selma Souihel and Evgenia Kartsaki participated to the organizing committee of "Le MOnde des Mathématiques Industrielles (MOMI 2018)", a two-day workshop on applied and industrial mathematics. The workshop took place on the 26th and 27th of February, 2018 at the Inria Sophia Antipolis-Mediteranée research center. It was supported by Inria and financed by the Société des Mathématiques Appliquées (SMAI) as a BOUge tes Maths (BOUM) project, by the Agence pour les Mathématiques en Interaction avec l'Entreprise et la Société (AMIES) and by the Labex User Centric Network @ Sophia within the context of Investissement d'Avenir (IA) projects – projets "Laboratoires d'excellence", and by the Université Côte d'Azur within the context of the "Joint, Excellent and Dynamic Initiative" (JEDI) projects. In total, 3 keynote speakers, 8 industrial speakers and 80 participants (researchers, PhDs , and engineers) attended MOMI 2018.
- Pierre Kornprobst was a Technical Program Committee (TPC) member for the 25th European Signal Processing Conference (EUSIPCO 2017).

9.1.2. Reviewer

Bruno Cessac was a reviewer for the conference ICMNS, International Conference on Mathematical Neuro-Science .

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

Pierre Kornprobst has been associate editor for the Computer Vision and Image Understanding Journal (CVIU) since Jul 2016.

9.1.4. Invited Talks

- B. Cessac, D. Karvouniari, L. Gil, O. Marre, S. Picaud. Multi scale dynamics in retinal waves, in: Inspire New Insights on Complex Neural Dynamics, Cergy-Pontoise, France, June 2018.
- B. Cessac, Ion channels and properties of large neuronal networks: a computational study of re.nal waves during development, in: Symposium on Ion channels and Channelopathies - IPMC, Sophia Antipolis, France, November 2018.

9.1.5. Research Administration

- The PhD Seminars of Inria Sophia Antipolis - Méditerranée are 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 are current members of the organizing committee have been involved in the scheduling, communication and diffusion. These tasks include calls for presentations, calendar planning and promotion of each seminar. Finally, they are also involved in the organization of the MOMI 2018 conference.
- Bruno Cessac is a member of the scientific council of the Institut NeuroMod de "Modélisation en Neurosciences et Cognition".
- Pierre Kornprobst is an elected member of the Academic Board of UCA (since November 2015). The role of this council is to proceed with the appointment of selection committees and the recruitment of public servants. Also, it validates the global training offer of Nice area, is involved in the global policy of doctoral training, and awards research funding. The council meets one a month and each member also participate to the evaluation of research proposals submitted to UCA $^{\text{JEDI}}$ calls.
- Pierre Kornprobst has been a member of the Comité de Suivi Doctoral (CSD) since March 2017.

9.2. Teaching - Supervision - Juries

9.2.1. 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 D. Karvouniari and F. Lavigne), *Introduction to Modelling in Neuroscience*, 36 hours, Master Mod4NeuCog, Université Nice Sophia Antipolis, France.

9.2.2. Supervision

- PhD defended on March 15th, 2018. Theodora Karvouniari, "Retinal waves in the retina: theory and experiments". Started in October 2014. Defense scheduled in March 2018. Supervisor, B. Cessac.
- PhD in progress: 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.

9.2.3. Juries

- Bruno Cessac was member of the Comité de suivi de thèse of Matthieu Sarrazin (U. Paris Sorbonne).
- Pierre Kornprobst was reviewer of the PhD of Charles Hessel, entitled “The automatic decomposition of an image in base and detail: Application to contrast enhancement”, from Université de Paris-Saclay, Ecole Normale Supérieure de Paris-Saclay, France.
- Pierre Kornprobst was reviewer of the HDR of David Tschumperlé, entitled “Champs tensoriels pour la modélisation géométrique locale et non-locale des images et leurs applications”, from Université de Caen, France.

9.3. Popularization

9.3.1. Internal or external Inria responsibilities

- E. Kartsaki and S. Souihel are participating to the organization of the Inria Sophia PhD seminars.

9.3.2. Interventions

- The Biovision team participated to the "fête de la science 2018".

10. Bibliography

Major publications by the team in recent years

[1] R. Cofré, B. Cessac.*Dynamics and spike trains statistics in conductance-based integrate-and-fire neural networks with chemical and electric synapses*, in "Chaos, Solitons & Fractals", 2013, vol. 50, n^o^ 13, 3

[2] R. Cofré, B. Cessac.*Exact computation of the maximum-entropy potential of spiking neural-network models*, in "Phys. Rev. E", 2014, vol. 89, n^o^ 052117

[3] M.-J. Escobar, G. S. Masson, T. Viéville, P. Kornprobst.*Action Recognition Using a Bio-Inspired Feedforward Spiking Network*, in "International Journal of Computer Vision", 2009, vol. 82, n^o^ 3, 284, ftp://ftp-sop.inria.fr/neuromathcomp/publications/2009/escobar-masson-etal:09.pdf

[4] O. Faugeras, J. Touboul, B. Cessac.*A constructive mean field analysis of multi population neural networks with random synaptic weights and stochastic inputs*, in "Frontiers in Computational Neuroscience", 2009, vol. 3, n^o^ 1 [*DOI :* 10.3389/neuro.10.001.2010], http://arxiv.org/abs/0808.1113

[5] D. Karvouniari, L. Gil, O. Marre, S. Picaud, B. Cessac.*A biophysical model explains the oscillatory behaviour of immature starburst amacrine cells*, 2018, submitted to Scientific Reports, https://hal.inria.fr/hal-01484133

[6] T. Masquelier, G. Portelli, P. Kornprobst.*Microsaccades enable efficient synchrony-based coding in the retina: a simulation study*, in "Scientific Reports", April 2016, vol. 6, 24086 [*DOI :* 10.1038/srep24086], http://hal.upmc.fr/hal-01301838

[7] N. V. K. Medathati, H. Neumann, G. S. Masson, P. Kornprobst.*Bio-Inspired Computer Vision: Towards a Synergistic Approach of Artificial and Biological Vision*, in "Computer Vision and Image Understanding (CVIU)", April 2016 [*DOI :* 10.1016/j.cviu.2016.04.009], https://hal.inria.fr/hal-01316103

[8] J. NAUDÉ, B. CESSAC, H. BERRY, B. DELORD.*Effects of Cellular Homeostatic Intrinsic Plasticity on Dynamical and Computational Properties of Biological Recurrent Neural Networks*, in "Journal of Neuroscience", 2013, vol. 33, n^o^ 38, p. 15032-15043 [*DOI :* 10.1523/JNEUROSCI.0870-13.2013], https://hal.inria.fr/hal-00844218

[9] J. RANKIN, A. I. MESO, G. S. MASSON, O. FAUGERAS, P. KORNPROBST.*Bifurcation Study of a Neural Fields Competition Model with an Application to Perceptual Switching in Motion Integration*, in "Journal of Computational Neuroscience", 2014, vol. 36, n^o^ 2, p. 193–213, http://www.springerlink.com/openurl.asp?genre=article&id=doi:10.1007/s10827-013-0465-5

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Publications of the year

Doctoral Dissertations and Habilitation Theses

[11] T. KARVOUNIARI.*Retinal waves : theory, numerics, experiments*, Université Côte d'Azur, March 2018, https://tel.archives-ouvertes.fr/tel-01818522

Articles in International Peer-Reviewed Journal

[12] D. KARVOUNIARI, L. GIL, O. MARRE, S. PICAUD, B. CESSAC.*A biophysical model explains the oscillatory behaviour of immature starburst amacrine cells*, in "Scientific Reports", 2018, https://arxiv.org/abs/1711.09199 - 25 pages, 15 figures, submitted, https://hal.inria.fr/hal-01484133

Invited Conferences

[13] B. CESSAC, D. KARVOUNIARI, L. GIL, O. MARRE, S. PICAUD.*Ion channels and properties of large neuronal networks: a computational study of re.nal waves during development*, in "Symposium on Ion channels and Channelopathies - IPMC", Sophia Antipolis, France, November 2018, https://hal.archives-ouvertes.fr/hal-01925829

[14] B. CESSAC, D. KARVOUNIARI, L. GIL, O. MARRE, S. PICAUD.*Multi scale dynamics in retinal waves*, in "Inspire New Insights on Complex Neural Dynamics", Cergy-Pontoise, France, June 2018, https://hal.inria.fr/hal-01816919

International Conferences with Proceedings

[15] B. CESSAC, R. COFRÉ.*Linear Response of General Observables in Spiking Neuronal Network Models*, in "ICMNS 2018 - 4th International Conférence on Mathematical Neuroscience", Juan les Pins, France, June 2018, p. 1-70, https://hal.inria.fr/hal-01816920

Scientific Books (or Scientific Book chapters)

[16] B. CESSAC.*The retina: a fascinating object of study for a physicist*, in "UCA COMPLEX DAYS", 2018, https://hal.archives-ouvertes.fr/hal-01807518

Research Reports

[17] J. GAUTIER, N. CHLEQ, P. KORNPROBST.*A Binocular LVA Device based on Mixed Reality to Enhance Face Recognition*, Université Côte d'Azur, Inria, France, October 2018, n^{o} RR-9216, p. 1-19, https://hal.inria.fr/hal-01900574

Other Publications

[18] T. ANDRÉOLETTI, B. CESSAC, F. CHAVANE.*Decoding cortical activity evoked by artificial retinal implants*, ENSEA-Inria, August 2018, https://hal.inria.fr/hal-01895100

[19] B. CESSAC, R. COFRÉ.*Linear response for spiking neuronal networks with unbounded memory*, October 2018, https://arxiv.org/abs/1704.05344 - working paper or preprint, https://hal.inria.fr/hal-01895095

[20] B. CESSAC, D. KARVOUNIARI, L. GIL, O. MARRE, S. PICAUD.*Retinal waves: experiments and theory*, June 2018, Journées scientifiques de l'Inria, https://hal.inria.fr/hal-01895099

[21] B. CESSAC, P. KORNPROBST, M. BENZI, I. CAUGANT, D. KARVOUNIARI, E. KARTSAKI, S. SOUIHEL.*Biovision project-team: Biological vision: integrative models and vision aid systems for visually impaired people*, October 2018, Fête de la science, Poster, https://hal.inria.fr/hal-01896505

[22] R. HERZOG, M.-J. ESCOBAR, R. COFRÉ, A. PALACIOS, B. CESSAC.*Dimensionality Reduction on Spatio-Temporal Maximum Entropy Models of Spiking Networks*, November 2018, working paper or preprint [*DOI :* 10.1101/278606], https://hal.inria.fr/hal-01917485

[23] E. KARTSAKI, B. CESSAC, G. HILGEN, E. SERNAGOR.*How specific classes of retinal cells contribute to vision: A Computational Model*, June 2018, C@uca 2018 Meeting, Poster, https://hal.inria.fr/hal-01816921

[24] D. KARVOUNIARI, L. GIL, O. MARRE, S. PICAUD, B. CESSAC.*Pattern formation and criticality in the developing retina*, June 2018, International Conference on Mathematical Neuroscience, Poster, https://hal.archives-ouvertes.fr/hal-01807929

[25] S. SOUIHEL, B. CESSAC.*A computational study of anticipation in the retina*, September 2018, Bernstein conference 2018, Poster, https://hal.inria.fr/hal-01942516

[26] S. SOUIHEL, F. CHAVANE, O. MARRE, B. CESSAC.*Processing various motion features and measuring RGCs pairwise correlations with a 2D retinal model*, June 2018, International Conference on Mathematical Neuroscience ICMNS 2018, Poster, https://hal.inria.fr/hal-01809589

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[30] F. M. ATAY, S. BANISCH, P. BLANCHARD, B. CESSAC, E. OLBRICH.*Perspectives on Multi-Level Dynamics*, in "The interdisciplinary journal of Discontinuity, Nonlinearity, and Complexity", 2016, vol. 5, p. 313 - 339 [*DOI :* 10.5890/DNC.2016.09.009], https://hal.inria.fr/hal-01387733

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Team CAMIN

Control of Artificial Movement & Intuitive Neuroprosthesis

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
Computational Neuroscience and Medicine

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Team CAMIN

Creation of the Team: 2016 January 01

Keywords:

Computer Science and Digital Science:

A1.2.6. - Sensor networks
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
B2.2.2. - Nervous system and endocrinology
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, from Oct 2018, HDR]
David Guiraud [Inria, Senior Researcher, HDR]
Daniel Simon [Inria, Researcher, HDR]
Charles Fattal [MD, Researcher, CRF La Châtaigneraie, HDR]

Faculty Members

David Andreu [Univ de Montpellier, Associate Professor, HDR]
François Bonnetblanc [Univ de Bourgogne, Associate Professor, until Aug 2018, HDR]

External Collaborators

Karen Godary-Dejean [Univ de Montpellier]
Philippe Fraisse [Univ de Montpellier, HDR]
David Gasq [Univ Paul Sabatier, from Oct 2018]
Sofiane Ramdani [Univ de Montpellier]
Hugues Duffau [PU-PH,CHU Montpellier]

Technical Staff

Ronan Le Guillou [Inria, from Mar 2018]

PhD Students

Anthony Boyer [Univ de Montpellier]

Vincent Iampietro [Univ de Montpellier, from Oct 2018]
Xinyue Lu [Neuroresp]
Ibrahim Merzoug [Algerian grant, until Jan 2018]
Benoît Sijobert [Univ de Montpellier]
Victor Vagné [Association ARNGDC]

Post-Doctoral Fellows
Mélissa Dali [Univ de Montpellier, until Aug 2018]
Roberto de Souza Baptista [Inria, until Jan 2018]

Visiting Scientists
Lucas Fonseca [Univ. Brasilia, until Jan 2018]
Ibrahim Merzoug [Inria, until Mar 2018]

Administrative Assistant
Annie Aliaga [Inria]

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.

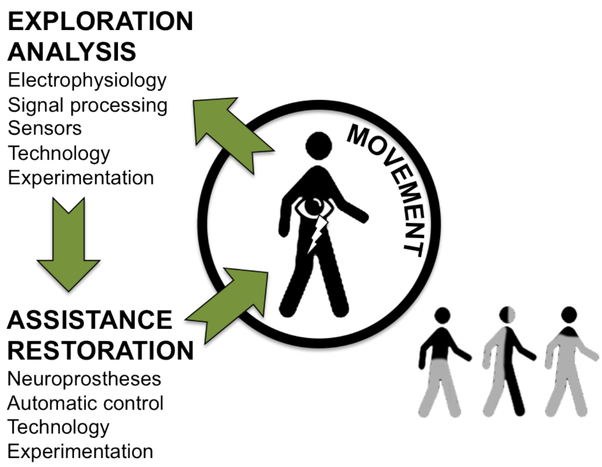


Figure 1. Overview of CAMIN *general scientific approach.*

CAMIN research will be 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.

The expertise and skills of our individual team members will be combined to design and develop solutions to restore movement functions.
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**.

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.

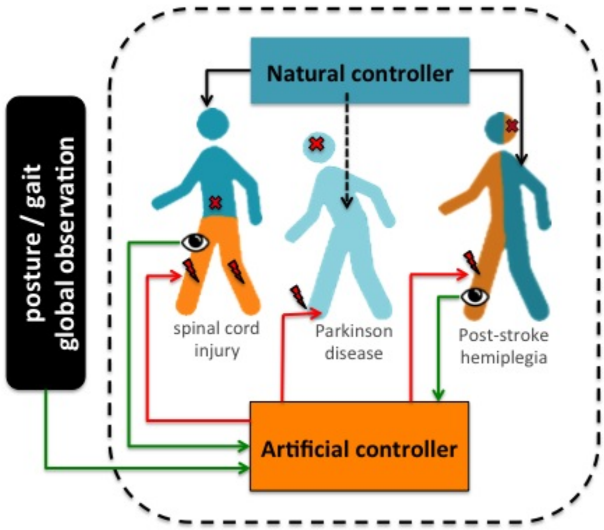


Figure 2. FES assistance should take into account the coexistence of artificial and natural controllers. Artificial controllers should integrate both global (posture/gait) and local (limb/joint) observations.

4. Highlights of the Year

4.1. Highlights of the Year

- The startup NEURINNOV was created in November 2018, David Andreu and David Guiraud will leave CAMIN team to join the company. A first research collaboration was established between CAMIN and Neurinnov as part of the Isite MUSE, through the Spin Stim project. The Spin Stim project focuses on severe impairments of vesico-sphincteric functions. It is a deep partnership based on the implementation of Neurinnov staff directly in the research unit.
- François Bonnetblanc was laureat of the French Scholars Lecture Series 2018 – Peter Wall Institute of Advanced Studies - University of British Columbia / Embassy of France in Canada, (https://pwias.ubc.ca/program/french-scholars-lecture-series) and laureat of the TOR Program 2018 between France and Sweden, (https://www.institutfrancais-suede.com/tout-sur-tor/).
- Benoît Sijobert was finalist of the Handitech Trophy (https://www.lahanditech.fr/), presenting a project related to his Phd work in CAMIN team, among 156 projects awarding inclusive technologies.
- Wafa Tigra got the 2017 IFRATH [0] PhD thesis price on October 2018.
- Ana Claudia Lopes (UnB, Brazil) presented the paper « Quadriceps electrical stimulation to assist sitting pivot transfer by a person with paraplegia » at IFESS conference 2018 and won the Vodovnik Award student paper competition (2nd position). This work was done within the context of CACAO associate team.

5. New Software and Platforms

5.1. RT_Stim

Real-Time simulation for functional electrical Stimulation

[0] Institut Fédératif de Recherche sur les Aides Techniques pour les personnes Handicapées

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.

- Contact: Daniel Simon

5.2. Platforms

5.2.1. Modular embedded architecture for real time control of a FES system

Participants: Christine Azevedo Coste, Benoît Sijobert, Ronan Le Guillou.

The results presented in section 6.2 and 6.3 have led to the development of a new hardware and software architecture embedding a network of sensors and actuators interfaced to a controller, as part of Benoît Sijobert's PhD work and ADT STIMBIO (Ronan Le Guillou). In order to solve numerous issues and constraints observed during experiments, a new hardware and software architecture has been elaborated. The decision was made to decentralize the controller (i.e. the computer) directly on the participant, thereby relocating the essential wireless links around the user. For this purpose, 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 the data from all the IMUs, therefore highly decreasing the data flow when multiple IMUs were 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 stimulator used in the experiments was a wireless programmable and controllable device. Latency issues and communication losses were observed when the computer sending the command to the stimulator was too far or if an obstacle was present between the computer and the participant wearing the stimulator. Taking advantage of the FES controller located on the subject to control the stimulator nearby has enabled us to solve this issue.

In this configuration, this autonomous FES controller is able to acquire the data, process them, execute control algorithms and send the appropriate stimulation 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 of a network infrastructure where the connection is not always possible (e.g. Wi-Fi network from the hospital).

This scalable architecture (Figure 3), developed as a modular system, now allows us to implement various new commands laws for Real Time closed loop control as well as giving us the ability to switch sensors and stimulators to meet the needs of specific applications. As part of making this system available for future projects in the team, the ability to easily change stimulators depending of the requirements was needed. To achieve this and in order for the FES architecture to directly control them, 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 by pod, while being scalable. The BerkelBike Stimulator v2.0 presents a cumbersome but extended control compromise with 8 independent stimulation channels, which is an ideal solution for recumbent FES-assisted cycling. And finally the Hasomed Rehastim v1.0 allowing fine control but isn't battery powered in its commercial version and is not produced anymore.

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. A funding (EDF Foundation) has been obtained by our clinical partner "CRF La Châtaigneraie" to perform a clinical protocol including 6 patients from which one will participate in the Cybathlon 2020 using this hardware and software architecture. The inclusions will begin in January 2019.

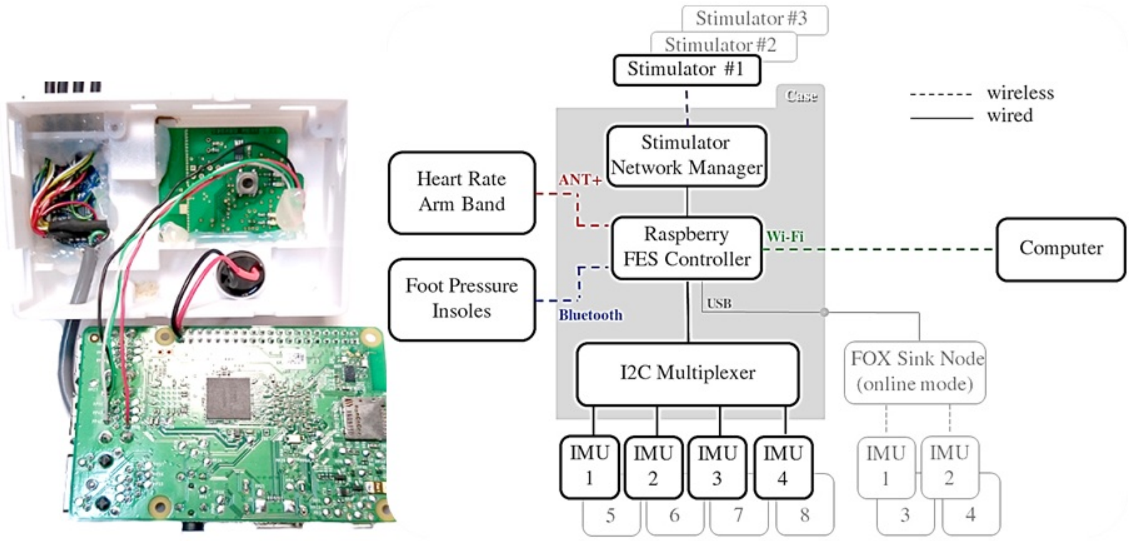


Figure 3. Experimental protocols have led to the development of a scalable hardware architecture decentralized on the subject.

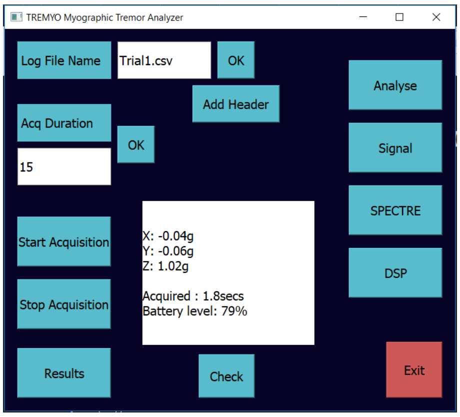
5.2.2. Tremor monitoring system based on acceleration detection in Parkinson's Disease

Participants: Christine Azevedo Coste, Ronan Le Guillou.

As part of a preliminary study on the effects of Mindfulness meditation for patients with Parkinson's Disease (PD), an application was developed to monitor the accelerometer of a wrist worn device. The hypothesis being that reducing the cognitive load of a PD patient might reduce the severity of the tremors. We investigated a few devices that might correspond to our requirements : smartwatches, Myo armbands, Inertial Measurement Units,...Having already a Thalmic Myo Armband (Figure 4) we developed a program acquiring the accelerometer data in Real Time and logging it, as well as doing pre-processing and displaying it on the screen of the clinician to allow him to monitor the session. While this system was ready and already tested, we had to search for another solution due to the termination of the commercial product. We then selected the smartwatch Samsung Gear S3 as a possible alternative and the dedicated application is currently under development.

6. New Results

6.1. A sensor fusion approach for inertial sensors based 3D kinematics and pathological gait assessments



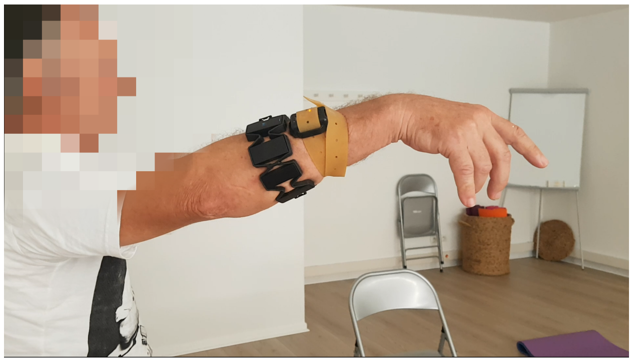


Figure 4. i) Graphical User Interface of the TREMYO Armband monitoring application during acquisition ii) Baseline test with straight extended arm for temporal comparison of the tremors severity.

Participants: Benoît Sijobert, Christine Azevedo, Jérôme Froger, Francois Feuvrier.

Pathological gait assessment and assistive control based on functional electrical stimulation (FES) in post-stroke individuals, brings out a common need to robustly quantify kinematics facing multiple constraints.

Through an experimental study(Figure 5), we proposed a novel approach using inertial sensors to compute dorsiflexion angles and spatio-temporal parameters, in order to be later used as inputs for online close-loop control of FES. 26 post-stroke subjects were asked to walk on a pressure mat (GaitRite®) equipped with inertial measurement units (IMU) and passive reflective markers (Vicon®). A total of 930 strides were individually analyzed and results between IMU-based algorithms and reference systems compared. The novel methods integrated two aspects: 1) robust stance phase detection based on acceleration and angular rate combination and 2) estimation of joint angles based on an Attitude and Heading Reference System (non linear observer) algorithm and gravity cancellation for reconstructing 3D trajectory of individual steps. Mean absolute (MA) errors of dorsiflexion angles were found to be less than 4°, while stride lengths were robustly segmented and estimated with a MA error less than 10 cm [30]. These results open new doors to rehabilitation using adaptive FES closed-loop control strategies.

6.2. FES-based online closed-loop control of knee joint to reduce stance phase asymmetry in post-stroke gait

Participants: Benoît Sijobert, Christine Azevedo, Charles Fattal.

Numerous stimulation strategies have been investigated over the past thirty years to assist or restore gait (Figure 6). The studies using FES to restore gait have been mostly conducted in post-stroke individuals and focused on correcting the drop foot syndrome by supplementing the absence of dorsiflexion. The state-of-the-art reflects a real lack of interest in using FES to improve the paretic knee rehabilitation, which however plays a key role in post-stroke gait recovery.
An experimental protocol (#RCB 2017-A03611-52, CRF La Chataigneraie, Menucourt, France) was designed with the main purpose of proposing a novel approach using a FES-based control of knee joint to reduce stance phase asymmetry and study the feasibility of using such FES systems in clinical rehabilitation, compared to classical knee orthosis. Secondary objectives aimed at improving gait quality, walking range and comfortable speed using the same modality. The main hypothesis was to determine if using FES to real-time control the paretic knee angle could reduce the time needed to recover a normal balance while providing a secure

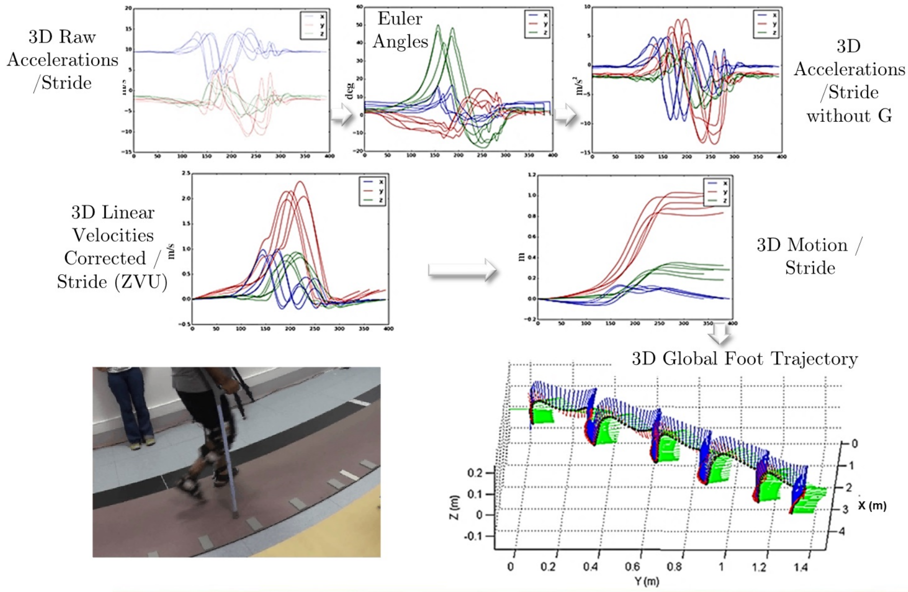


Figure 5. Illustration of the global approach needed to obtain gait trajectories from raw magneto-inertial data of a foot-mounted Inertial Measurement Unit to assess a circumduction gait.

stance phase. To monitor weight bearing and stance time asymmetry the participants were equipped with instrumented insoles. The subjects were also equipped with 2 inertial measurement units located on the thigh and the tibia, wired to a Raspberry Pi3. Each IMU embedded a high speed based processor and a Kalman Filter directly providing quaternion estimation needed to compute knee angles. One IMU was installed in the back of the participants at the second sacral vertebra level to estimate vertical trunk displacement. Stimulation was sent via a two-channel wireless stimulator to the quadriceps and hamstrings via surface electrodes. A specific hardware architecture has been developed for this protocol. When required and depending on the participant's gait pattern, a "pre-stance" stimulation could be triggered either via an online detection of peak knee flexion or when the sagittal angular speed recorded via the gyroscope crossed zero. In stance phase, stimulation was triggered either to quadriceps or hamstrings, depending on the paretic knee angle (PKA) estimation relatively to the knee angle setpoint (KAS) defined by the practitioner as the optimal flexion during stance phase (around 5^{O}). A proportional (P) controller adjusted the pulse width depending on the error ϵ between PKA and KAS. Equipped with their usual technical aids (cane, ankle foot orthosis...) participants were asked to perform a 10m-path walking at a self-selected pace. An oral instruction was given at the beginning of each trial to encourage the participants to transfer their weight onto the paretic leg. This experiment is an ongoing experiment but preliminary tests have already validated the technical feasibility of the approach.

6.3. IMU-based FES cycling in individuals with SCI

Participants: Benoît Sijobert, Christine Azevedo, Ronan Le Guillou, Charles Fattal, Emerson Fachin Martin, Henrique Resende.

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

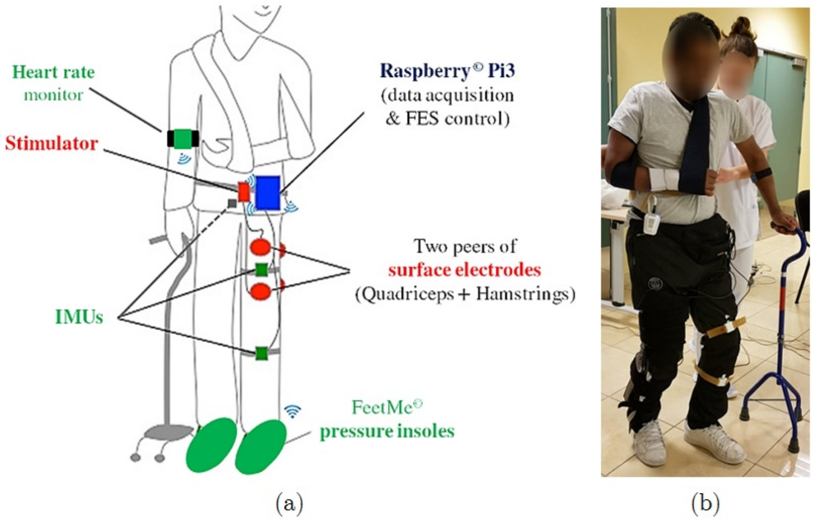


Figure 6. Experimental setup diagram (a) and picture (b). The participants are equipped with Bluetooth pressure insoles, 2 wired IMU on the leg and 1 wireless IMU in the back. A Raspberry records and processes the sensors data to send an appropriate command to a wireless stimulator to stimulate the quadriceps and hamstrings via surface electrodes

muscles with an adequate modality. In order to promote the research around this topic and more broadly the development of assistive technology for people with physical disabilities, we participated to the first Cybathlon in October 2016 (FreeWheels project), using a stimulation pattern based on crank angle. Taking part to this event highlighted the need for a simpler automated stimulation pattern generator, able to adapt the stimulation to the environment, to the muscle fatigue or to the individual (e.g. position on the bike, number of stimulable muscles, etc...). In order to further investigate control solutions, we first needed to be able to accurately quantify the influence of each parameter preliminarily used (stimulation pattern, stimulation parameters, fixed-wheel or free-wheel, individualized quadriceps, pilot position, etc...) on power produced and endurance and observe if other variables could be used as an input instead of the crank angle. The decision was made to develop an instrumented home trainer specifically designed to record a weak power (<200 W) while ensuring a minimum accuracy of 0.5 %: a rotating torquemeter (Scaime TSR 2300) was installed between the rear wheel and a flywheel thanks to a mechanical assembly built in collaboration with the National Engineering School of Saint-Étienne (ENISE, Loire, France)(Figure 7). The software part was developed as part of ADT STIMBIO.

Instead of using the crank angle, undergoing researches have also investigated the ability of using inertial sensors to automatically design a stimulation pattern on the bike depending on the knee angles. Based on the joint angle computation presented in section 6.1 and experimentally validated, a similar control modality have been studied and implemented. Using the online peak knee flexion algorithm developed in the study presented in section 6.2 to continuously detect this event, we developed a novel approach in order to trigger the quadriceps stimulation at the beginning of the pushing phase. This would enable 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. A study has been initiated with the University of Brasilia (UnB, District Federal, Brazil) as part of the CACAO collaboration, to explore advanced control approaches [31]. Experimental data have been recorded and are investigated in order to compare the different control approaches (Figure 8).

Figure 7. Experimental setup using IMUs to record joint angles and a specifically designed home trainer to monitor power output.

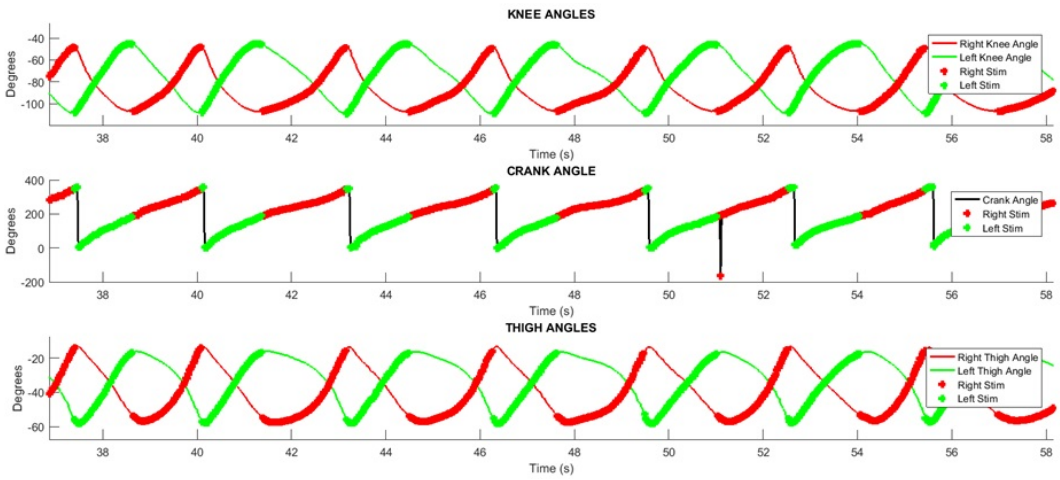


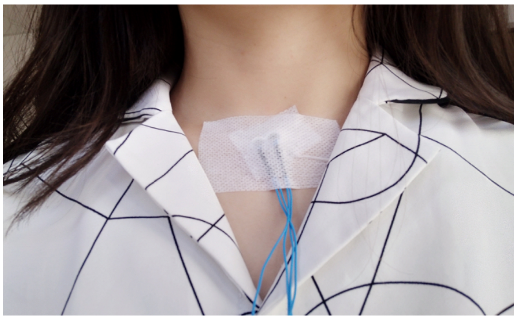
Figure 8. Comparison of stimulation patterns between crank angle and joint angle based triggering method.

6.4. Respiratory detection and monitoring

Participants: Xinyue Lu, Christine Azevedo, David Guiraud, Serge Renaux [Neuroresp], Thomas Similowski [Groupe Hospitalier Pitié-Salpêtrière].

This work is conducted within a CIFRE phd thesis. The general subject is the respiration induced by implanted stimulation for the tetraplegic and syndrome of Ondine. In France, every year, there is approximately 90 new spinal cord injuries who have a ventilatory dependence due to a high cervical involvement. The prevalence of syndrome of Ondine (central sleep apnea) would be 25.5 per million inhabitants. Because of many disadvantages of mechanical ventilation, the technique of implanted electrical stimulation to restore the respiratory function of the patients can be proposed. But existing systems are based on open-loop controllers, ie the phrenic nerve is stimulated with the same intensity, at the same frequency for the whole time, even when the patients can breathe spontaneously. The principle aim of the work is to develop a respiratory detection/monitoring module in this context.

A solution based on tracheal sounds analysis has been developed. Tracheal sounds are recorded by microphone which is inserted into a support and stuck on the neck of subject like showed in Figure 9.i. All the materials are showed in Figure 9.ii: microphones (yellow), analog ampli-filtering card (red), the acquisition machine POWERLAB (green), the numeric development card NUCLEO (blue).



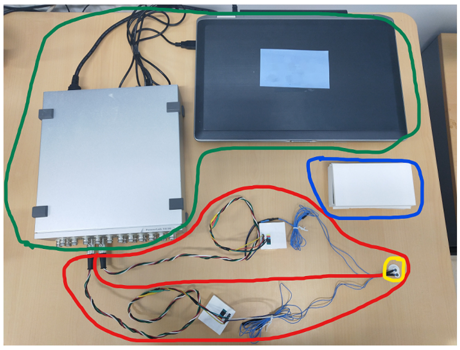


Figure 9. i)The placement of microphone ii)Recording materials

The signal is processed in its envelop (temporal domain) and frequency power (frequency domain). A threshold detection applied to detect respiration. An example of detection result is illustrated in Figure 10. Heart beating sounds can also be extracted to calculate cardiac rhythm.

Preliminary recordings on healthy individuals have been performed. Recordings on patients are in planning. Publications for conferences and journals are in preparation. The variation of cardiac amplitude will also be analyzed to give a secondary breathing detection. Advance signal processing techniques are now under study.

6.5. Attenuation and delay of remote potentials evoked by direct electrical stimulation during brain surgery.

Participants: Anthony Boyer, Sofiane Ramdani [LIRMM], Hugues Duffau [CHU Montpellier], David Guiraud, François Bonnetblanc.

Direct electrical stimulation (DES) is used during awake brain surgery for functional mapping as it generates transient behavioural disturbances, allowing the identification of both cortical areas and subcortical white matter pathways which are essential to the function. However, the electrophysiological effects of DES remain by far unknown. DES may be coupled with the measurement of Evoked Potentials (EPs) to study the

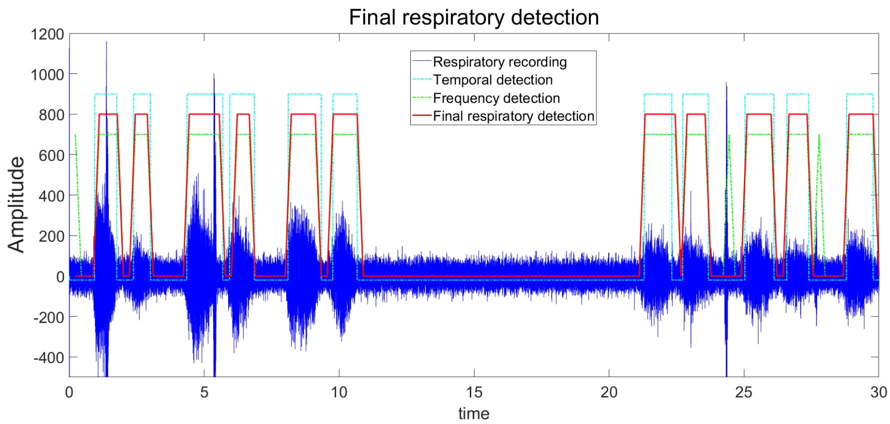


Figure 10. The detection result

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 (Figure 11). We were more particularly interested in the generation of evoked potentials (EPs) triggered by both close and remote stimulations. Obtained EPs were very similar in shape, suggesting a stereotyped electrophysiological response, but delayed in time and attenuated in amplitude when elicited from a different gyrus or remotely from the recording site. We were also able to observe the bidirectional nature of the arcuate fasciculus triggering EPs on 2 anatomically connected sites. We propose different activation and electrophysiological propagation mechanisms following DES based on recruited neural elements. The variations in amplitude and delay of EPs are most likely due to different propagation mechanisms, which can be intra- or sub- cortical, and correspond to commonly described DCRs and CCEPs.

6.6. High Frequency stimulation used for efficient and fiber type selective stimulation

Participants: David Guiraud, Mélissa Dali, Olivier Rossel, Thomas Guiho, Pawel Maciejasz.

In neural electrical stimulation, limiting the charge delivered during a stimulus pulse is essential to avoid nerve tissue damage and to save power. Previous experimental and modeling studies indicated that waveforms such as nonrectangular continuous pulses or rectangular chopped pulse were able to improve stimulation efficiency. The goal of this study is to evaluate if non-rectangular chopped pulses such as quarter sine and ramp are more charge efficient than rectangular chopped pulse. We performed in vivo study on 17 lumbricus terrestris and compared the charge per stimulating phase needed to activate lateral giant fibers (LGF) and medial giant fiber (MGF) using chopped non-rectangular pulses and rectangular pulse, varying stimulation duration parameters. Results indicated that non rectangular chopped pulses activated MGF and LGF with less charge than rectangular chopped pulses. For MGF (respectively LGF), the gain of charge was up to 33.9% (resp. 17.8%) using chopped ramp, and up to 22.8% (resp. 18.1%) using chopped quarter sine.

6.7. Early detection of stroke during the accute phase

Participants: Victor Vagné, David Guiraud, Vincent Costalat, Emmanuelle Le Bars, Stéphane Perrey.

Cerebral infarctions can now be treated with new techniques using intravenous thrombolysis and thrombectomy. Their proven efficacy is directly correlated to the time lapse between the start of symptoms and the

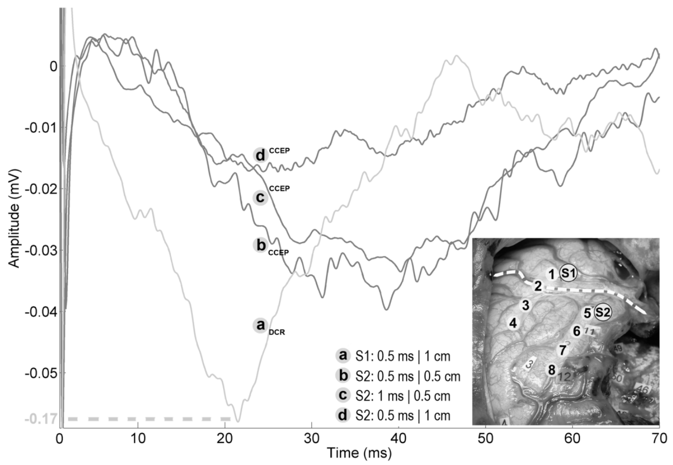


Figure 11. Differential recordings between electrodes 2 and 3 while stimulating S1 and S2. The picture illustrates the stimulation sites (S1, S2) and ECoG positioning with respect to the initial 60 Hz cortical brain mapping. Experimental DES was applied on: (1) the Wernicke's area (S1), associated with complete anomia; (2) the ventral premotor cortex (S2), which led to movement and counting interruptions. Tumor was about 164 cm3. The Sylvian fissure is highlighted by a thick dashed line.

initiation of treatment. Currently, a definitive diagnosis can only be made once the patient has performed a radiological imaging (CT scan or MRI) on a medical center equipped with these expensive devices, thus enabling the medical team to initiate the appropriate treatment. Transit times during the pre-hospitalization phase before diagnosis are therefore often longer and have the greatest negative impact on the patient's prognosis. In collaboration with the interventional neuroradiology department of Gui de Chauliac Hospital, I2FH and Euromov, the EleVANT project is aiming to prospectively evaluate new techniques to assess a diagnosis of acute cerebral ischaemia. This low cost technology could be used in a mobile way for the very early diagnosis of cerebral infarction and thus reduce treatment delays, opening the way to a new generation of diagnostic tools. The concept consist on evaluating the cerebral near-infrared spectroscopy (NIRS) response to different stimulus, and to evaluate its lateralization. Recently, we tested our device on healthy volunteers. Method: Left and right hemisphere reactivity index are recorded by NIRS and normalized (Figure 12). Result: The experiments present a suitable feasibility and repeatability. In healthy subjects, a good response to the stimulus is recorded, and no significant differences between hemispheres are observed. The confidence level is acceptable since the amplitude response in above the standard deviation level.

Discussion: The approach reveal interesting results on healthy subject group. We expect a discriminant difference between hemispheric signals in acute cerebral ischemia.

6.8. Real-time simulation of stimulation systems

Participant: Daniel Simon.

RT-STIM (Real-time FES simulation) is a C/C++ framework able to carry out realistic simulations of a fully featured functional electro-stimulation system. It allows for the temporally consistent co-simulation of both the continuous model of skeletal joints and muscles on one hand, and of numerical resources such as control tasks, schedulers and communication protocols on the other hand (Figure 13). Initial software-in-the-loop simulations can be seamlessly extended towards hardware-in-the-loop simulation by a progressive integration of real components such as a Raspberry portable control board or gateways towards Vivaltis stimulators and HiKoB sensors.

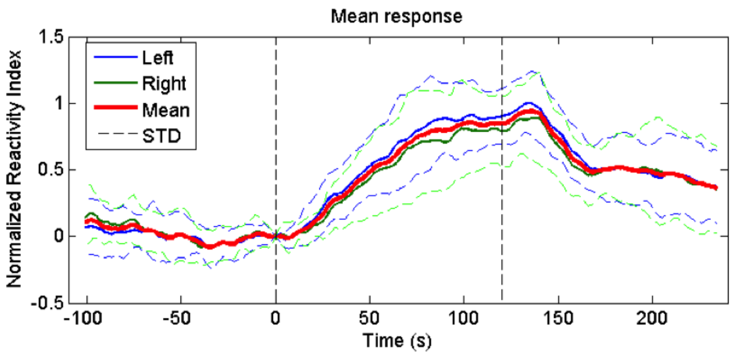


Figure 12. NIRS reactivity Index in response to a stimulus (bounded by the dashed lines)

It is intended to be a support for the design and implementation of safe stimulation feedback controllers in the team. Hence, the simulation software is designed around the bio-mechanical models of joints and muscles excited using electro-stimulation developed in the Demar and Camin teams during the past years. To cope with the objectives of the team which targets the restoration of grasping for tetraplegia, a model of a human hand, currently using 23 joints and 23 muscles, has been integrated. It is expected to be a central tool for the Agilis project starting in 2019.

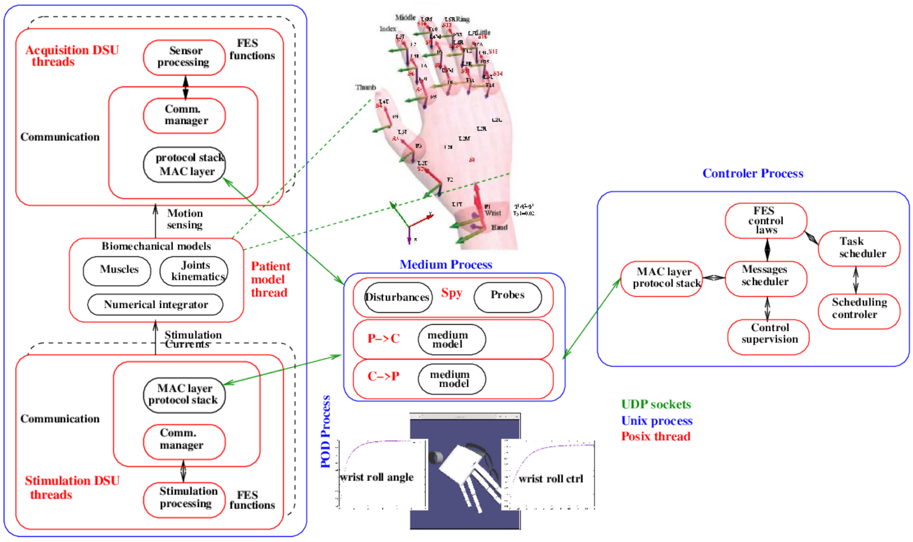


Figure 13. Simulation of a hand under FES

6.9. Real-time control for distributed stimulation systems

Participants: Daniel Simon, Ashwini Patil, Ronan Le Guillou.

Feedback control is needed to control complex movement, such as precise grasping, involving several muscles and nerves. Moreover, the components of the control loops (i.e., sensors, electrodes and micro-controllers) are distributed over communication links which induce data delivery scheduling, delays, and occasional data loss. A new approach gathering control and computation related design and implementation constraints was developed during the past years. From the feedback provided by experiments in real-time robot control,

Considering the non-linear and time varying models, simple controllers cannot provide reliable and robust solutions. the approach is developed along two main directions, control aware computing, e.g., using feedback schedulers, and real-time aware control, e.g. using feedback controllers designed to be robust and/or adaptive w.r.t. timing deviations [32].

Beyond simple control loops, a Model Predictive Control approach for FES using an adaptive horizon is under evaluation. Even if no conclusion about the control approach can be currently carried out, it was an occasion to positively evaluate the Julia programming language as an alternative to others high level languages for control design and real-time implementation.

A software control structure, primarily implemented and evaluated on a portable Rasperry3 micro-controller, is currently documented to become the root of a generic real-time control software template, usable even by non-specialists in the Camin team.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- collaboration contract with FEETME (http://www.feetme.fr) company.
- collaboration contract with Innopsys (https://www.innopsys.com/en) company.
- collaboration contract with ISIDU (https://isidu.eu/) company.
- collaboration contract with Berkelbike (https://berkelbike.com) company.

7.2. Bilateral Grants with Industry

- collaboration contract with NEURORESP (http://neuroresp.com/) company (CIFRE PhD thesis).
- collaboration contract with SubseaTech (https://www.subsea-tech.com/) company, CIFRE PhD thesis about the on-the-fly optimization of actuators steering for underwater vehicles.

8. Partnerships and Cooperations

8.1. Regional Initiatives

We have obtained a financial support from Occitanie Region for the CIFRE PhD thesis (Xynue Lu) with NEURORESP Company "PILE CIFRE" BREATHLOOP.

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

  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

  Collaboration with Montpellier Hospital (Neurology service) and the Montpellier Mindfulness Center to analyze the impact of meditation on upper limb tremor.

- EDF Foundation

  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.

8.3. European Initiatives

Program: EIT Health

Project acronym: Agilis

Project title: Restoration of Hand Functions in Tetraplegia through Selective Neural Electrical Stimulation

Duration: Jan. 2019 - June 2020

Coordinator: Camin Inria

Other partners: APHP, Univ. Heidelberg, CRF La Châtaigneraie, Neurinnov.

Abstract: Complete tetraplegia leads to inability to move, thus use, both hands. To date, there is no solution to restore this absolutely needed function for very common daily activities such as social interactions, washing, eating or self catheterizing. We aim at an innovative implanted stimulation of only two nerves associated with an intuitive interface. It will provide functional grasping without a third person and thus will drastically increase the autonomy of such people for the rest of their life.

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 Brasilia (Brazil), Physiotherapy department, Emerson Fachin Martins.

Start year: 2016

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

Electrical stimulation (ES) can activate paralyzed muscles to support rehabilitation. ES applied to fully or partially paralyzed muscles artificially induces muscle contraction substituting or completing the normal volitional control. In CACAO team we join our efforts and specific expertise to develop approaches of lower limb function restoration in spinal cord injured individuals. Two main applications have been addressed: 1) Functional Electrical Stimulation (FES) to assist SCI individuals to perform pivot transfers and 2) FES-assisted cycling. We aim at proposing solutions that can have an effect on patients' quality of life, thus our choices intend to be realistic form a practical point of view.

8.4.1.2. Informal International Partners

CAMIN collaborates with Dr JL Boulland (Norwegian Center for Stem Cell Research at Oslo University Hospital in Norway) on FES-assisted bladder and bowel functions restoration.

8.5. International Research Visitors

Henrique Resende (UFMG, Brazil) and Emerson Fachin (UNB, Brazil) will spend 3 months in CAMIN team from December 2018 to February 2019 to work on FES-cycling project.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. General Chair, Scientific Chair

Christine Azevedo organized a special session "Application of FES for lower limbs movement assistance" at ICNR conference (Pisa, Italy) on October 2018.

9.1.2. Member of the Conference Program Committees

- David Guiraud was Co-editor of the theme 6 at IEEE EMBC conference
- Daniel Simon is member of the ICINCO conference program committee
- David Andreu was member of the ERTS2 conference program committee

9.1.3. Reviewer

- Christine Azevedo was reviewer for IEEE EMBC, IROS, ICNR conferences
- David Guiraud was reviewer for IEEE EMBC and IEEE NER
- François Bonnetblanc was reviewer for IEEE EMBC
- Daniel Simon was reviewer for the IFAC CAMS, IFAC ICINCO, ECC and IEEE CCTA conferences
- David Andreu was reviewer for the ERTS2 conference

9.1.4. Member of the Editorial Boards

- Christine Azevedo is member if ERCIM News' Editorial Board as Inria representant.
- David Guiraud is Associate Editor of Journal of Neural Engineering and Medical and Biological Engineering and Computing.

9.1.5. Reviewer - Reviewing Activities

- David Guiraud is reviewer of several journals among which IEEE TNSRE, IEEE ACCESS, IEEE TCST, JNE, J. Of Neuroscience Method, Computer in Biology and Medicine, Science Advances (AAAS)...
- Daniel Simon was reviewer for IEEE Control Systems Technology and Real Time Systems.
- David Andreu was reviewer for Journal of Neural Engineering.

9.1.6. Invited Talks

François Bonnetblanc: University of British Columbia and Peter Wall Institute of Advanced Studies. "Awake Brain Surgery: the naked brain", 4 octobre 2018.

François Bonnetblanc : Karolinska Institute (Programme TOR). Neurosurgery Department, “Awake Neurosurgery and electrophysiology”). 5-9 novembre 2018.
Christine Azevedo was invited to give a lecture at Inria Rennes center "Pédalage assisté par stimulation électrique de muscles paralysés.".

9.1.7. Leadership within the Scientific Community

Christine Azevedo is member of the board of directors of International Functional Electrical Stimulation Society (IFESS).

9.1.8. Scientific Expertise

David Guiraud was reviewer for the ERC program (Starting and Advanced) in 2018
Christine Azevedo was examiner for APHP Delegation Clinical research and Innovation call for proposals for detached positions.

9.1.9. Research Administration

Christine Azevedo is member of Inria Evaluation Committee (CE). She participated in the competitive examinations for junior researcher recruitment in Inria Lille Center (April 2018) and Inria Grenoble Center (May 2018). She was also in the examination committee of CHRC and DR0 promotions as well as detachments.
Christine Azevedo is member of Inria Ethical Committee (COERLE).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

- Master SMH : David Guiraud, "Stimulation Electrique Fonctionnelle", 16h, M2, Université de Montpellier, France
- Master Neuroprothèses : Daniel Simon, "Control basics", 6.5h, M2, Université de Montpellier, France
- Master Neuroprothèses : Christine Azevedo, "Ethical considerations", 3h, M2, Université de Montpellier, France
- Master Neuroprothèses : François Bonnetblanc, "Motor Control", "Neuroplasticity", "Electrophysiology in Neurosurgery", 16h, M1, Université de Montpellier, France
- Master Mechanics and its Interactions : François Bonnetblanc, "Motor Control", 4,5h, M2, Université de Montpellier, Polytech, France
- DU Functional electrical stimulation : François Bonnetblanc, "Motor Control", "Neuroplasticity", "Electrophysiology in Neurosurgery", 12h, Université de Montpellier, France
- DU Functional electrical stimulation : David Andreu, "Neuroprosthesis: from functions to active medical implanted devices" , 6h, Université de Montpellier, France
- DU Functional electrical stimulation : David Guiraud, "Electrophysiology", "Biophysics", "Neuroprothesis", 6,5h, Université de Montpellier, France
- DU Functional electrical stimulation : Christine Azevedo, "Electrophysiology", "Functional Electrical Stimulation", "Clinical Applications", 7h, Université de Montpellier, France
- DU Functional electrical stimulation : Charles Fattal, "Functional Electrical Stimulation and Clinical Applications", 5h, Université de Montpellier, France

François Bonnetblanc is responsible for a DU about "Functional Electrical Stimulation"
D. Andreu teaches software engineering, real time OS, discrete event systems, control architectures, networks, neuro-prosthesis, 200 h, master and engineers degrees, Polytech Montpellier, France.

9.2.2. Supervision

- PhD: Benoît Sijobert, Assistive Control of Motion in SensoriMotor Impairments based on Functional Electrical Stimulation, Montpellier University, September 28th 2018, Christine Azevedo, David Andreu and Charles Fattal.
- PhD: Ibrahim Merzoug, Validation formelle des systèmes numériques critiques : génération d'espace d'états de réseaux de Petri exécutés en synchrone, Montpellier University, January 15th 2018, David Andreu and Karen Godary.
- PhD in progress: Antony Boyer, Neuroplasticity and recovery in remote (sub)cortical structures following wide-awake surgery of infiltrative low-grade gliomas: investigation of fMRI and EEG signals, 01/09/2016, François Bonnetblanc and Sofiane Ramdani.
- PhD in progress: Maxence Blond, Commande et modélisation d'un véhicule sous-marin, 18/01/2016, Daniel Simon, Vincent Creuze (LIRMM) and Ahmed Chemori (LIRMM).
- PhD in progress: Victor Vagne, "Couplage de la Spectroscopie en proche infrarouge et de la stimulation Transcrânienne (NIRS-tDCS) à courant continu dans l'Evaluation diagnostique de l'ischémie cérébrale lors d'un AVC", Oct. 2016, M. Hayashibe, D. Guiraud, Vincent Costalat (CHU Montpellier) and Emmanuelle Le Bars (CHU Montpellier)
- PhD in progress: XinYue Lu, Respiratory detection and monitoring Since March 2017, C. Azevedo Coste, T Similowski (Groupe Hospitalier Pitié-Salpêtrière), S Renaux (NEURORESP)
- PhD in progress (co-financing UM / Occitanie region): Vincent Iampietro, Contribution des méthodes formelles à la fiabilité des systèmes numériques complexes critiques : application aux dispositifs médicaux implantables innovants, since october 2018, D. Andreu, D. Delahaye (LIRMM).

9.2.3. Juries

Christine Azevedo was reviewer for the PhD thesis of Solenne Page (ISIR, UPMC University, Paris, France) "Control of a robotized walker based on postural characterization and application to obstacle avoidance." (May 2018).
Christine Azevedo was examiner in the defense committee of Mathilde Couraud (Bordeaux University, France) "Study of the sensori-motor control in a simplified artificial context with the aim to improve the control of myoelectric prostheses." (December 2018).
Christine Azevedo was examiner in the defense committee of Firas Kaddachi (Montpellier University, France) "Technological approach of early and non intrusive of health modification to better adapt services to elderly persons." (December 2018).
David Andreu was reviewer of the PhD thesis of T. Sotiropoulos (LAAS, Univ. Toulouse 3, France), "Test aléatoire de la navigation de robots dans des mondes virtuels." (May 2018).

9.3. Popularization

9.3.1. Education

Christine Azevedo Coste is mentor (2018-2019) for one Savanturiers project with Saussan school (CM1/CM2 level) https://les-savanturiers.cri-paris.org/
Christine Azevedo organized initiation sessions to informatics using Thymio robot at École Calendreta La Cardonilha (Mèze, France) in CP/CE1 level, 3 sessions of 2 hours (April 2018) .
Christine Azevedo organized initiation sessions to informatics using Thymio robot at École Valfalis (Montbazin, France) in CM1/CM2 level, 4 sessions of 2 hours (May-June 2018) .
As a COERLE member Christine Azevedo Coste was involved in one session on Ethics for phd students in Inria IRISA center (Rennes, france) (November 2018).

9.3.2. Interventions

- François Bonnetblanc : Pint of Science 16 mai 2018, François Bonnetblanc, Montpellier

10. Bibliography

Major publications by the team in recent years

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[3] T. Guiho, C. Delleci, C. Azevedo Coste, C. Fattal, D. Guiraud, J.-R. Vignes, L. Bauchet.*Impact of direct epispinal stimulation on bladder and bowel functions in pigs: A feasibility study*, in "Neurourology and Urodynamics", January 2018, vol. 37, n^{o} 1, p. 138-147 [*DOI :* 10.1002/nau.23325], https://hal-lirmm.ccsd.cnrs.fr/lirmm-01539038

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[8] W. Tigra, B. Navarro, A. Cherubini, X. Gorron, A. Gélis, C. Fattal, D. Guiraud, C. Azevedo Coste.*A novel EMG interface for individuals with tetraplegia to pilot robot hand grasping*, in "IEEE Transactions on Neural Systems and Rehabilitation Engineering", 2018, vol. 26, n^{o} 2, p. 291-298 [*DOI :* 10.1109/TNSRE.2016.2609478], https://hal.archives-ouvertes.fr/lirmm-01373668

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[11] I. MERZOUG.*Formal validation of critical digital systems : generation of state space of Petri nets executed in synchronous*, Université Montpellier, January 2018, https://tel.archives-ouvertes.fr/tel-01704776

[12] B. SIJOBERT.*Assistive control of motion in sensorimotor impairments based on functional electrical stimulation*, Université de Montpellier, Sep 2018

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[13] C. AZEVEDO COSTE, P. WOLF.*FES-Cycling at Cybathlon 2016: Overview on Teams and Results*, in "Artificial Organs", March 2018, vol. 42, n° 3, p. 336 - 341 [*DOI :* 10.1111/AOR.13139], https://hal-lirmm.ccsd.cnrs.fr/lirmm-01737321

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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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Other Research Topics and Application Domains:

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1. Team, Visitors, External Collaborators

Research Scientists

Hervé Guillard [Inria, Senior Researcher, HDR]
Holger Heumann [Inria, Researcher, until Jun 2018]
Sebastian Minjeaud [CNRS, Researcher]
Richard Pasquetti [CNRS, Emeritus Senior Researcher, HDR]

Faculty Members

Jacques Blum [Univ Côte d'Azur, Professor, Team Leader, HDR]
Cédric Boulbe [Univ Côte d'Azur, Associate Professor]
Francesca Rapetti [Univ Côte d'Azur, Associate Professor, HDR]
Boniface Nkonga [Univ Côte d'Azur, Professor]
Afeintou Sangam [Univ Côte d'Azur, Associate Professor]

External Collaborator

Didier Auroux [Univ Côte d'Azur]

Technical Staff

Blaise Faugeras [CNRS]
Alexis Loyer [Inria, until Sep 2018]

PhD Students

Ashish Bhole [Univ Côte d'Azur]
Ali Aboudou Elarif [Inria]
Xiao Song [CEA]

Post-Doctoral Fellow

Mireille Coury [Univ Côte d'Azur, until Sep 2018]

Administrative Assistant

Montserrat Argente [Inria]

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. Application Domains

4.1. Nuclear fusion

The activity of Castor is mainly applied to nuclear fusion, in particular on the WEST, JET and ITER Tokamaks. Several tools developped in the project are used on those machines like equilibrium reconstruction, ELMs simulations...

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

- Jacques Blum has received the "Grand Prix de la Ville de Nice".
- Blaise Faugeras and Holger Heumann have been nominated as ITER Scientist Fellows.

6. New Software and Platforms

6.1. CEDRES++

KEYWORDS: 2D - Magnetic fusion - Plasma physics

FUNCTIONAL DESCRIPTION: In Tokamaks, at the slow resistive diffusion time scale, the magnetic configuration in the plasma can be described by the MHD equilibirum equations inside the plasma and the Maxwell equations outside. Moreover, the magnetic field is often supposed not to depend on the azimutal angle.

Under this assumption of axisymmetric configuration, the equilibrium in the whole space reduces to solving a 2D problem in which the magnetic field in the plasma is described by the well known Grad Shafranov equation. The unknown of this problem is the poloidal magnetic flux. The P1 finite element code CEDRES++ solves this free boundary equilibrium problem in direct and inverse mode. The direct problem consists in the computation of the magnetic configuration and of the plasma boundary, given a plasma current density profile and the total current in each poloidal field coils (PF coils). The aim of the inverse problem is to find currents in the PF coils in order to best fit a given plasma shape.

- Participants: Blaise Faugeras, Cédric Boulbe, Holger Heumann and Jacques Blum
- Partners: CNRS - CEA - Université de Nice Sophia Antipolis (UNS)
- Contact: Cédric Boulbe

6.2. Equinox

KEYWORDS: 2D - Problem inverse
FUNCTIONAL DESCRIPTION: EQUINOX is a code dedicated to the numerical reconstruction of the equilibrium of the plasma in a Tokamak. The problem solved consists in the identification of the plasma current density, a non-linear source in the 2D Grad-Shafranov equation which governs the axisymmetric equilibrium of a plasma in a Tokamak. The experimental measurements that enable this identification are the magnetics on the vacuum vessel, but also polarimetric and interferometric measures on several chords, as well as motional Stark effect measurements. The reconstruction can be obtained in real-time and the numerical method implemented involves a finite element method, a fixed-point algorithm and a least-square optimization procedure.

- Participants: Blaise Faugeras, Cédric Boulbe and Jacques Blum
- Contact: Blaise Faugeras

6.3. FBGKI

Full Braginskii
FUNCTIONAL DESCRIPTION: The Full Braginskii solver considers the equations proposed by Braginskii (1965), in order to describe the plasma turbulent transport in the edge part of tokamaks. These equations rely on a two fluid (ion - electron) description of the plasma and on the electroneutrality and electrostatic assumptions. One has then a set of 10 coupled non-linear and strongly anisotropic PDEs. FBGKI makes use in space of high order methods: Fourier in the toroidal periodic direction and spectral elements in the poloidal plane. The integration in time is based on a Strang splitting and Runge-Kutta schemes, with implicit treatment of the Lorentz terms (DIRK scheme). The spectral vanishing viscosity (SVV) technique is implemented for stabilization. Static condensation is used to reduce the computational cost. In its sequential version, a matrix free solver is used to compute the potential. The parallel version of the code is under development.

- Contact: Sebastian Minjeaud

6.4. FEEQS.M

Finite Element Equilibrium Solver in MATLAB
KEYWORDS: Finite element modelling - Optimal control - Plasma physics

FUNCTIONAL DESCRIPTION: FEEQS.M (Finite Element Equilibrium Solver in Matlab) is a MATLAB implementation of the numerical methods in [Heumann2015] to solve equilibrium problems for toroidal plasmas. Direct and inverse problems for both the static and transient formulations of plasma equilibrium can be solved. FEEQS.M exploits MATLAB's evolved sparse matrix methods and uses heavily the vectorization programming paradigm, which results in running times comparable to C/C++ implementations. FEEQS.M complements the production code CEDRES++ in being considered as fast prototyping test bed for computational methods for equilibrium problems. This includes aspects of numerics such as improved robustness of the Newton iterations or optimization algorithms for inverse problems. The latest developments aim at incorporating the resistive diffusion equation.

[Heumann2015]: Heumann, H., Blum, J., Boulbe, C., Faugeras, B., Selig, G., Ané, J.-M., Brémond, S., Grandgirard, V., Hertout, P., Nardon, E.: Quasi-static free-boundary equilibrium of toroidal plasma with CEDRES++: Computational methods and applications. In: Journal of Plasma Physics 81 (2015)

- Participant: Holger Heumann
- Contact: Holger Heumann
- URL: https://scm.gforge.inria.fr/svn/holgerheumann/Matlab/FEEQS.M

6.5. Fluidbox

FUNCTIONAL DESCRIPTION: FluidBox is a software dedicated to the simulation of inert or reactive flows. It is also able to simulate multiphase, multi-material and MDH flows. There exist 2D and 3D dimensional versions. The 2D version is used to test new ideas that are later implemented in 3D. Two classes of schemes are available : a classical finite volume scheme and the more recent residual distribution schemes. Several low Mach number preconditioning are also implemented. The code has been parallelized with and without domain overlapping.

- Participants: Boniface Nkonga, Mario Ricchiuto, Michael Papin and Rémi Abgrall
- Contact: Boniface Nkonga

6.6. Jorek-Inria

FUNCTIONAL DESCRIPTION: Jorek-Inria is a new version of the JOREK software, for MHD modeling of plasma dynamic in tokamaks geometries. The numerical approximation is derived in the context of finite elements where 3D basic functions are tensor products of 2D basis functions in the poloidal plane by 1D basis functions in the toroidal direction. More specifically, Jorek uses curved bicubic isoparametric elements in 2D and a spectral decomposition (sine, cosine) in the toroidal axis. Continuity of derivatives and mesh alignment to equilibrium surface fluxes are enforced. Resulting linear systems are solved by the PASTIX software developed at Inria-Bordeaux.

RELEASE FUNCTIONAL DESCRIPTION: The new formulation of the Jorek-Inria code extends this approximation strategy by introducing more flexibility and a variety of finite elements used in the poloidal plane and in the toroidal direction. It also proposes a sparse matrix interface SPM (Sparse Matrix Manager) that allows to develop clean code without a hard dependency on any linear solver library (i.e. PetSc, Pastix, Mumps, ...).

- Participants: Ahmed Ratnani, Boniface Nkonga, Emmanuel Franck and Hervé Guillard
- Contact: Hervé Guillard
- URL: https://gforge.inria.fr/projects/jorek/

6.7. Plato

A platform for Tokamak simulation

FUNCTIONAL DESCRIPTION: PlaTo (A platform for Tokamak simulation) is a suite of data and softwares dedicated to the geometry and physics of Tokamaks. Plato offers interfaces for reading and handling distributed unstructured meshes, numerical templates for parallel discretizations, interfaces for distributed matrices and linear and non-linear equation solvers. Plato provides meshes and solutions corresponding to equilibrium solutions that can be used as initial data for more complex computations as well as tools for visualization using Visit or Paraview.

- Participants: Afeintou Sangam, Boniface Nkonga, Elise Estibals, Giorgio Giorgiani and Hervé Guillard
- Contact: Hervé Guillard

6.8. VacTH

KEYWORD: Problem inverse
FUNCTIONAL DESCRIPTION: VacTH implements a method based on the use of toroidal harmonics and on a modelization of the poloidal field coils and divertor coils to perform the 2D interpolation and extrapolation of discrete magnetic measurements in a tokamak and the identification of the plasma boundary. The method is generic and can be used to provide the Cauchy boundary conditions needed as input by a fixed domain equilibrium reconstruction code like EQUINOX. It can also be used to extrapolate the magnetic measurements in order to compute the plasma boundary itself. The method is foreseen to be used in the real-time plasma control loop on the WEST tokamak.

- Contact: Blaise Faugeras

6.9. NICE

Newton direct and Inverse Computation for Equilibrium
KEYWORDS: 2D - C++ - Scientific computing - Finite element modelling - Plasma physics - Optimal control - Optimization - Identification
FUNCTIONAL DESCRIPTION: The NICE code is under development. Its goal is to gather in a single modern, modular and evolutionary C++ code, the different numerical methods and algorithms from VACTH, EQUINOX and CEDRES++ which share many common features. It also integrates new methods as for example the possibility to use the Stokes model for equilibrium reconstruction using polarimetry measurements.

- Contact: Blaise Faugeras

7. New Results

7.1. Block-structured meshes

Participants: Hervé Guillard, Alexis Loyer, Jalal Lakhlili [IPP Garching], Ahmed Ratnani [IPP Garching].

Due to the highly anisotropic character of strongly magnetized plasmas, a crucial point for numerical simulations is the construction of meshes that are aligned on the magnetic flux surfaces computed by Grad-Shafranov equilibrium solvers. This work has studied an original method for the construction of flux aligned grids that respect the magnetic equilibrium topology and that can be applied to block-structured meshes using C^1 finite element methods (Hermite-Bézier/Cubic spline). The method relies on the analysis of the singularities of the magnetic flux function and the construction of the Reeb graph that allows the segmentation of the physical domain into sub-domains that can be mapped to a reference square domain. Once this domain decomposition has been done, the mapping of the sub-domain to reference patches can be done using integration along the streamlines of the flux function [16]. This work was performed in the framework of the EoCoE European project (see section 8.2.1.1).

7.2. Unstructured triangular meshes for tokamaks

Participants: Hervé Guillard, Alexis Loyer, Adrien Loseille [Gamma3 team, Inria Saclay].

The construction of block-structured flux aligned grids that respect the magnetic equilibrium topology experiences difficulties in the SOL region of the tokamaks where the flux lines cross the material walls. As an alternative to the use of block structured meshes, we have studied the construction of unstructured triangular meshes using constrained anisotropic Delaunay mesh generation [16]. This work was also performed in the framework of the EoCoE European project (see section 8.2.1.1).

7.3. Simulations of hydraulic jumps with a turbulent Shallow Water model

Participants: Hervé Guillard, Argiris Delis [Technical University of Crete, Greece], Yih-Chin Tai [National Cheng Kung University, Taiwan].

We have pursued the work realized in 2017, on a new model designed for the computation of turbulent hydraulic jumps. This model is able to describe the oscillatory nature of turbulent hydraulic jumps and as such corrects the deficiency of the classical shallow water equations. The comparisons with experiments performed at Tainan University are very satisfactory given the simplicity of the model. A journal paper [3] on this subject have been published and these results have been presented at the ETAMM2018 (Emerging Trends in Applied Mathematics and Mechanics 2018) conference.

7.4. 2D C^1 triangular elements

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. In particular, we have developped the geometric tools necessary for the construction of Powell-Sabin splines and have applied these methods for the approximation of some simple hyperbolic PDE systems (namely the Euler equation of fluid dynamics [6]). The PhD thesis of Ali Elarif that has begun in october 2017 is devoted to the study of the applicability of these methods to more complex PDE models encountered in plasma physics and to an extension towards other triangular C^1 elements (Clough-Tocher elements). The work realized this year has allowed to apply these finite element spaces to the approximation of elliptic equations and to design penalization methods to enforce non-homogeneous Dirichlet boundary conditions. In particular, the use of reduced Clough-Tocher elements has been applied to obtain solution of the free-boundary non-linear Grad-Shafranov equation. The results show that the use of these C^1 elements produce results that are smoother than the ones obtained with low order P1 elements.

7.5. Equilibrium reconstruction at JET using Stokes model for polarimetry

Participant: Blaise Faugeras.

This paper presents the first application to real JET data of the new equilibrium code NICE which enables the consistent resolution of the inverse equilibrium reconstruction problem in the framework of non-linear free-boundary equilibrium coupled to the Stokes model equation for polarimetry. The conducted numerical experiments enable first of all to validate NICE by comparing it to the well-established EFIT code on 4 selected high performance shots. Secondly the results indicate that the fit to polarimetry measurements clearly benefits from the use of Stokes vector measurements compared to the classical case of Faraday measurements, and that the reconstructed p' and ff' profiles are better constrained with smaller error bars and are closer to the profiles reconstructed by EFTM, the EFIT JET code using internal MSE constraints.

7.6. Operational plasma boundary reconstruction with the NICE-VacTH code on WEST Tokamak

Participant: Blaise Faugeras.

A new regularization term has been proposed for the inverse problem of plasma boundary reconstruction using an expansion of the poloidal flux in toroidal harmonics. It has been implemented in the VacTH code and is used successfully on the WEST Tokamak.

7.7. Equilibrium reconstruction with NICE at WEST and within the framework of the European Integrated Tokamak Modelling WPCD project

Participant: Blaise Faugeras.

The adaptation of NICE to IMAS (the ITER standard using IDS as data type) has been carried on. Equilibrium reconstructions using IMAS have been performed on real JET measurements and are now performed routinely at WEST.

7.8. Equilibrium reconstruction with Equinox at JET

Participant: Blaise Faugeras.

The adaptation of NICE to IMAS the ITER standard using IDS as data type has been carried on. Equilibrium reconstructions using IMAS have been performed on real JET measurements and are now performed routineley at WEST.

7.9. Evolutive mode and iron model in NICE

Participants: Blaise Faugeras, Jacques Blum, Cédric Boulbe.

The capabilities of the equilbirum code NICE have been extended. The evolutive direct model and the iron model of the free boundary equilibrium code CEDRES++ have been ported in NICE.

7.10. Coupling CEDRES++ - WEST controller in IMAS

Participants: Cédric Boulbe, Jakub Urban [IPP Prague].

The free boundary equilibrium code has been fully adapted to IMAS and has been coupled to the magnetic controller of WEST. The code CEDRES++ simulate the plant and the controller provide the voltages applied to the PF supplies. This coupling has enabled to develop a tool in Python to interface easily Simulink controllers with IMAS. With that tool, it is possible to run a controller installed on a distant computer and to run it from IMAS. As a test case, the WEST controller has been interfaced with IMAS and coupled to CEDRES++ using an IMAS python workflow.

7.11. Spectral Element method for high order partial differential equations

Participants: Sebastian Minjeaud, Richard Pasquetti.

The Korteweg-de Vries equation has been addressed as an interesting model of high order partial differential equation. In [9] it is shown that it is possible to develop reliable and effective schemes, in terms of accuracy, computational efficiency, simplicity of implementation and, if required, conservation of the lower invariants, on the basis of a (only) H^1-conformal Galerkin approximation, namely the Spectral Element Method. The proposed approach is *a priori* easily extensible to other partial differential equations and to multidimensional problems.

7.12. Recent advances in Spectral element methods on simplicial meshes

Participants: Richard Pasquetti, Francesca Rapetti.

R. Pasquetti and F. Rapetti have investigated the cubature points based triangular spectral element method. Using cubature points, both for interpolations and quadratures, shows the advantage of yielding a diagonal mass matrix. Accuracy results are provided in [10], for elliptic problems in non polygonal domains, using various isoparametric mappings. The capabilities of the method are here again clearly confirmed.

7.13. Full-MHD with Jorek

Participants: Boniface Nkonga, Ashish Bhole.

In the context of A. Bohle PhD, we have developped a strategy to improve the formulation of finite element space in the context of iso-parametric finite elements with singular parametrization. This result in a set of constraints to be applied in the numerical formulation to fit in the well defined approximated space. Applied to interpolations, we recover the optimal order of convergence of the numerical approximation. Next step is applications to the resolution of reduced-MHD and then full-MHD.

7.14. A discontinuous Galerkin method for a two dimensional resistive MHD model

Participants: Ashish Bhole, Boniface Nkonga, Praveen Chandrashekar.

We consider the numerical approximation of two dimensional incompressible magnetohydrodynamics equations with vorticity and current as the dynamical variables. We construct a discontinuous Galerkin (DG) method for the MHD model written in symmetric form. The numerical flux is based on a Riemann solver and the scalar fluxes of velocity and magnetic field are computed using a Galerkin method. The performance of the method is demonstrated on some standard instability problems relevant to magnetically confined fusion reactors.

7.15. Fluctuation splitting Riemann solver for a non-conservative shear shallow water flow

Participants: Ashish Bhole, Boniface Nkonga, Sergey Gavrilyuk.

We propose a fluctuation splitting finite volume scheme for a non-conservative modeling of shear shallow water flow (SSWF). This model was originally proposed by Teshukov and was extended to include modeling of friction by Gavrilyuk (2018). We develop a cell-centered finite volume code to validate the proposed scheme with the help of some numerical tests. As expected, the scheme shows first order convergence. The numerical simulation of 1D roll waves shows a good agreement with the experimental results. The numerical simulations of 2D roll waves show similar transverse wave structures as observed by Gavrilyuk (Paper in revision at JCP).

7.16. Automating the design of Tokamak experiment scenarios

Participants: Jacques Blum, Holger Heumann, Xiao Song.

The real-time control of plasma position, shape and current in a tokamak has to be ensured 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 HL2M highlight the exibility and broad scope of the proposed optimal control formulation.

7.17. Multiscales scheme for the MHD model in a tokamak

Participants: Hervé Guillard, Afeintou Sangam.

Recently, in [21], it is proven that the Reduced MHD equations are a singular limit of the Full MHD system when the inverse ratio parameter goes to zero. In this limit, the toroidal dynamics is almost entirely decoupled from the incompressible poloidal dynamics. From a numerical point of view, in this limit, the propagation of fast magnetosonic waves severely constraints the time step in explicit schemes. A possible remedy is therefore to design a semi-implicit time stepping strategy allowing an implicit handling of the fast waves but retaining an explicit treatment of the slow ones. In this work, we have derived a linear simplified model in two dimensions that retains the main characteristics of the formal passage from the Full MHD equations to the Reduced MHD system. A semi-implicit numerical scheme free of time step restrictions based on the fast wave velocity has been constructed for this model. The extension of this numerical scheme to the Full MHD model is under investigation.

7.18. Asymptotic Transport Models for heat and mass transport in reactive porous media

Participants: Bruno Dubroca, Afeintou Sangam.

Charrier and *Dubroca* in [20], have suggested an approach to derive rigously a family of models of mass and heat transfer in reactive porous media. At a microscopic level they proposed a model coupling the Boltzmann equation in the gas phase, the heat equation and appropriate interface conditions, including adsorption-deposition reactions. Then an asymptotic expansion mixing homogenization and fluid limit leads to a system of coupled diffusion equations where the effective diffusion tensors are defined from the microscopic geometry of the material. Open questions paved their work. We solve one of them, consisting in setting adequate conditions on interest models that ensure the uniqueness of solutions of the first order expansion. They are based on the concept of thermodynamically closed in average system.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. Inria Project Lab: FRATRES (Fusion Reactors Research and Simulation)

- Participants : Inria project-teams : CASTOR, IPSO, TONUS,
- Partners : IRFM-CEA, Max Planck Institute-IPP Garching, LJLL-Jussieu, IMT-Toulouse

Controlled nuclear fusion can be considered as an example of grand challenge in many fields of computational sciences from physical modelling, mathematical and numerical analysis to algorithmics and software development and several Inria teams and their partners are developing mathematical and numerical tools in these areas.
Since january 2015, H. Guillard is coordinating the Inria Project Lab FRATRES (https://team.inria.fr/ipl-fratres/) to organize these developments on a collaborative basis in order to overcome the current limitations of today numerical methodologies. The ambition is to prepare the next generation of numerical modelling methodologies able to use in an optimal way the processing capabilities of modern massively parallel architectures. This objective requires close collaboration between a) applied mathematicians and physicists that develop and study mathematical models of PDE; b) numerical analysts developing approximation schemes; c) specialists of algorithmic proposing solvers and libraries using the many levels of parallelism offered by the modern architecture and d) computer scientists. This Inria Project Lab will contribute in close connection with National and European initiatives devoted to nuclear Fusion to the improvement and design of numerical simulation technologies applied to plasma physics and in particular to the ITER project for magnetic confinement fusion.

Contact : Hervé Guillard

8.1.2. Defi : Infiniti : INterFaces Interdisciplinaires NumérIque et ThéorIque

- Participants: HervéGuillard, AnnaDegioanni[LAMPEA Aix-en-Provence], SilvanaCondemi[ADES, Marseille], ZhenyuXu

In the framework of the "Defi : Infiniti : INterFaces Interdisciplinaires NumérIque et ThéorIque" of the “Mission pour l’Interdisciplinarité” of CNRS, this work has associated Hervé Guillard to Anna Degioanni of the Laboratory LAMPEA - Laboratoire Méditerranéen de Préhistoire Europe-Afrique of Aix-en-Provence and Silvana Condemi of the ADES (Anthropologie bio-culturelle, droit, éthique et santé - UMR 7268) laboratory in Marseille. The purpose of this work was to propose a numerical model and to realize a software allowing paleo-anthropologist and pre-historians to study numerically the propagation and diffusion of Homo Sapiens in Europe between 50 000 and 30 000 years BP. A 6 month internship of Ms Zhenyu Xu, 3rd year student at the polytech’Nice school of engineers has been devoted to this project and the results have been presented at the "Journée de restitution 2018 du Défi Infiniti", (http://www.cnrs.fr/mi/spip.php?article1440&lang=fr)

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. EoCoE

Title: Energy oriented Centre of Excellence for computer applications

Programm: H2020

Duration: October 2015 - October 2018

Coordinator: CEA

Partners:

- Barcelona Supercomputing Center - Centro Nacional de Supercomputacion (Spain)
- Commissariat A L Energie Atomique et Aux Energies Alternatives (France)
- Centre Europeen de Recherche et de Formation Avancee en Calcul Scientifique (France)
- Consiglio Nazionale Delle Ricerche (Italy)
- The Cyprus Institute (Cyprus)
- Agenzia Nazionale Per le Nuove Tecnologie, l'energia E Lo Sviluppo Economico Sostenibile (Italy)
- Fraunhofer Gesellschaft Zur Forderung Der Angewandten Forschung Ev (Germany)
- Instytut Chemii Bioorganicznej Polskiej Akademii Nauk (Poland)
- Forschungszentrum Julich (Germany)
- Max Planck Gesellschaft Zur Foerderung Der Wissenschaften E.V. (Germany)
- University of Bath (United Kingdom)
- Universite Libre de Bruxelles (Belgium)
- Universita Degli Studi di Trento (Italy)

Inria contact: Michel Kern

The aim of the present proposal is to establish an Energy Oriented Centre of Excellence for computing applications, (EoCoE). EoCoE (pronounce "Echo") will use the prodigious potential offered by the ever-growing computing infrastructure to foster and accelerate the European transition to a reliable and low carbon energy supply. To achieve this goal, we believe that the present revolution in hardware technology calls for a similar paradigm change in the way application codes are designed. EoCoE will assist the energy transition via targeted support to four renewable energy pillars: Meteo, Materials, Water and Fusion, each with a heavy reliance on numerical modelling. These four pillars will be anchored within a strong transversal multidisciplinary basis providing high-end expertise in applied mathematics and HPC. EoCoE is structured around a central Franco-German hub coordinating a pan-European network, gathering a total of 8 countries and 23 teams. Its partners are strongly engaged in both the HPC and energy fields; a prerequisite for the long-term sustainability of EoCoE and also ensuring that it is deeply integrated in the overall European strategy for HPC. The primary goal of EoCoE is to create a new, long lasting and sustainable community around computational energy science. At the same time, EoCoE is committed to deliver high-impact results within the first three years. It will resolve current bottlenecks in application codes, leading to new modelling capabilities and scientific advances among the four user communities; it will develop cutting-edge mathematical and numerical methods, and tools to foster the usage of Exascale computing. Dedicated services for laboratories and industries will be established to leverage this expertise and to foster an ecosystem around HPC for energy. EoCoE will give birth to new collaborations and working methods and will encourage widely spread best practices.

8.2.2. Collaborations in European Programs, Except FP7 & H2020

EuroFusion Consortium

CASTOR participates to the following EuroFusion consortium projects :

Enabling research contract 2014-2018. (B. Nkonga, H. Guillard, A. Sangam) CfP-WP15-ENR-01/IPP-05, Grant agreement No 633053. «Global non-linear MHD modeling in toroidal X-point geometry of disruptions, edge localized modes, and techniques for their mitigation and suppression »

EUROfusion WPCD (Working Package Code Development):

- ACT1: Extended equilibrium and stability chain (participation)
- ACT2: Free boundary equilibrium and control (participation and coordination)

8.3. International Initiatives

8.3.1. Inria International Partners

8.3.1.1. Informal International Partners

- The team collaborates with TUC (Technical University of Crete, Prof. Argyris Delis) on extension of the shallow water model to turbulent flows. These common works overlap with the collaboration with Taiwan in the framework of the former AMOSS associate team.
- Collaboration with TIFR-Bangalore on MHD, one month invited at Bangalore (B. Nkonga and A. Bhole) C. Praveen will have 2months as invited professor at UCA in 2019.

8.3.2. Participation in Other International Programs

ITER Contracts (B. Nkonga):

- ITER IO/17/CT/4300001505: 2017-2019, "Non-linear MHD simulations for ITER QH-mode plasma with and without 3D magnetic field perturbations from in-vessel ELM control coils". (150KE)

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

- IPL FRATRES Workshop 2018. Alsace, November 21-23 (https://team.inria.fr/ipl-fratres/2018-ipl-meetings-ipl-workshop-alsace/)
- Final Summary meeting, Inria Paris, November 19 (https://team.inria.fr/ipl-fratres/final-summary-meeting/)

9.1.2. Journal

9.1.2.1. Member of the Editorial Boards

- C. Boulbe is layout editor of the free journal SMAI-Journal of Computational Mathematics.
- J. Blum is member of
  - the editorial board of the Journal of Scientific Computing (JSC),
  - the scientific committee of the collection "Mathématiques et Statistiques" of the ISTE publications,
  - editor in chief of the ISTE Open Science journal: "Mathématiques appliquées et stochastiques".
- F. Rapetti is member of the editorial board of the Advances in Computational Mathematics (ACOM) journal by Springer

9.1.2.2. Reviewer - Reviewing Activities

- Hervé Guillard has been reviewer for the Journal of Computational physics, Computers and Fluids and International Journal for Numerical methods in Fluids.

9.1.3. Invited Talks

- Hervé Guillard, "Low Mach and multiphase flows", Workshop on numerical and physical modeling in multiphase flows: a cross-fertilisation approach, Paris, February 1-2, 2018, https://workshopmultiphase.wixsite.com/mpf2018
- Hervé Guillard, "Tokamesh : A software for mesh generation in Tokamaks", Renewable Energy meets High Performance Computing: Final Conference of the Energy-Oriented Centre of Excellence, Nicosia, Cyprus, September 17-18, 2018, https://www.eocoe.eu/events/final-eocoe-conference-cyprus
- Jacques Blum, "Algorithmes de contrôle optimal pour l'identification de l'équilibre du plasma et pour l'optimisation de scénarios dans un Tokamak", Marseille, November 29, 2018, https://plasmas2018.sciencesconf.org/resource/page/id/3

9.1.4. Leadership within the Scientific Community

- H. Guillard is coordinator of the topic "Turbulence and transport of edge plasma" within the Fédération FR-FCM

9.1.5. Scientific Expertise

- H. Guillard has acted as scientific expert for the FRS-FNRS (Fonds de la Recherche Scientifique - FNRS Fédération Wallonie-Bruxelles) and PRACE (Partnership for Advanced Computing in Europe).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Ecole d'ingénieur: D. Auroux, Optimisation, 66h, M1, Polytech Nice, Université de Nice Sophia Antipolis, France

Ecole d'ingénieur: D. Auroux, Méthodes numériques, 36h, M2, Polytech Nice Sophia, Université de Nice Sophia Antipolis, France

Ecole d'ingenieur: D. Auroux, Projet, 35h, L3, Polytech Nice Sophia Antipolis, France

Master: J. Blum, Optimisation, 36h, M1, Université de Nice Sophia Antipolis, France

Ecole d'ingénieur: C. Boulbe, Analyse Numérique, 71.5h, L3, Polytech Nice Sophia Antipolis, France

Ecole d'ingenieur: C. Boulbe, Projet, 35h, L3, Polytech Nice Sophia Antipolis, France

Licence: S. Minjeaud, module Eléments de calcul différentiel, 18 h, L3, Université de Nice Sophia Antipolis, France.

Master: S. Minjeaud, module Méthodes numériques en EDP, 62 h, M1, Université de Nice Sophia Antipolis, France.

Licence: S. Minjeaud, module Compléments de calcul différentiel, 20 h, L3, Université de Nice Sophia Antipolis, France.

Master: B. Nkonga, Analyse Numérique, 40h, M1, Université de 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

Licence: A. Sangam, Analyse, 40h, L1, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Analyse, 70h, L2, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Analyse Numérique, 86h, L3, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Projet tuteuré en laboratoire, 15h, L3 Physique, Université Nice Sophia Antipolis, France

Master: A. Sangam, Introduction to Finite Elements, 25h, M1, Université Nice Sophia Antipolis, France

9.2.2. Supervision

- PhD : Julie Llobel, "Schémas Volumes Finis à mailles décalées pour la dynamique des gaz", Université Cote d'Azur, Thierry Goudon et Sebastian Minjeaud
- PhD in progress : Ali Elarif, "Simulation numérique des instabilités magnétohydrodynamique dans les Tokamaks", since October 2017, Hervé Guillard
- PhD in progress: Xiao Song, "Model-based control-oriented scenario construction in tokamaks", since October 2016, Blaise Faugeras and Holger Heumann
- PhD in progress: Ashish Bhole, Numerical improvements and validations of the stabilized full MHD with applications to tokamaks, October 2017, Boniface Nkonga

9.2.3. Juries

- Hervé Guillard was referee in the HDR jury of Jean-Philippe BRAEUNIG, October 19, 2018, "Contributions à l'étude de schémas numériques de type Volumes Finis et de leurs applications pratiques".
- F. Rapetti was examinator in the jury of Matteo Valentinuzzi PhD defense at CEA in Cadarache on December, the 17th, 2018, "Numerical modelling of power flux densities on tokamak plasma facing components by using advanced coupling techniques for kinetic and fluid codes"

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Publications of the year

Articles in International Peer-Reviewed Journal

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[2] Q. CARMOUZE, F. FRAYSSE, R. SAUREL, B. NKONGA.*Coupling rigid bodies motion with single phase and two-phase compressible flows on unstructured meshes*, in "Journal of Computational Physics", 2018 [*DOI :* 10.1016/J.JCP.2018.08.023], https://hal.inria.fr/hal-01865705

[3] A. I. DELIS, H. GUILLARD, Y.-C. TAI.*Numerical simulations of hydraulic jumps with the Shear Shallow Water model*, in "SMAI Journal of Computational Mathematics", 2018, vol. 4, p. 319-344, https://hal.inria.fr/hal-01946806

[4] B. FAUGERAS, F. ORSITTO.*Equilibrium reconstruction at JET using Stokes model for polarimetry*, in "Nuclear Fusion", October 2018, vol. 58, n^o 10 [*DOI :* 10.1088/1741-4326/AAD751], https://hal.archives-ouvertes.fr/hal-01936062

[5] G. GIORGIANI, T. CAMMINADY, H. BUFFERAND, G. CIRAOLO, P. GHENDRIH, H. GUILLARD, H. HEUMANN, B. NKONGA, F. SCHWANDER, E. SERRE, P. TAMAIN.*A new high-order fluid solver for tokamak edge plasma transport simulations based on a magnetic-field independent discretization*, in "Contributions to Plasma Physics", January 2018, p. 1-8 [*DOI :* 10.1002/CTPP.201700172], https://hal.archives-ouvertes.fr/hal-01657680

[6] G. GIORGIANI, H. GUILLARD, B. NKONGA, E. SERRE.*A stabilized Powell–Sabin finite-element method for the 2D Euler equations in supersonic regime*, in "Computer Methods in Applied Mechanics and Engineering", 2018, vol. 340, p. 216-235 [*DOI :* 10.1016/J.CMA.2018.05.032], https://hal.inria.fr/hal-01865708

[7] H. HEUMANN, F. RAPETTI, X. SONG.*Finite element methods on composite meshes for tuning plasma equilibria in tokamaks*, in "Journal of Mathematics in Industry", December 2018, vol. 8, n^{o} 1, https://hal.archives-ouvertes.fr/hal-01948902

[8] F. LIU, G. T. A. HUIJSMANS, A. LOARTE, A. M. GAROFALO, W. M. SOLOMON, M. HOELZL, B. NKONGA, S. PAMELA, M. BECOULET, F. ORAIN, D. VAN VUGT.*Nonlinear MHD simulations of QH-mode DIII-D plasmas and implications for ITER high Q scenarios*, in "Plasma Physics and Controlled Fusion", January 2018, vol. 60, n^{o} 1, p. 1-13 [*DOI :* 10.1088/1361-6587/AA934F], https://hal.archives-ouvertes.fr/hal-01589770

[9] S. MINJEAUD, R. PASQUETTI.*High Order C0-Continuous Galerkin Schemes for High Order PDEs, Conservation of Quadratic Invariants and Application to the Korteweg-de Vries Model*, in "Journal of Scientific Computing", January 2018, vol. 74, n^{o} 1, p. 491-518, https://hal.univ-cotedazur.fr/hal-01946668

[10] R. PASQUETTI, F. RAPETTI.*Cubature Points Based Triangular Spectral Elements: an Accuracy Study*, in "JOURNAL OF MATHEMATICAL STUDY J. Math. Study", 2018, https://hal.archives-ouvertes.fr/hal-01963281

Invited Conferences

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[12] H. GUILLARD.*Fast waves and incompressible models*, in "Workshop on numerical and physical modelling in multiphase flows: a cross-fertilisation approach", Paris, France, February 2018, https://hal.inria.fr/hal-01949646

Conferences without Proceedings

[13] R. COELHO, W. ZWINGMANN, B. FAUGERAS, E. GIOVANNOZZI, P. MCCARTHY, E. P. SUCHKOV, F. S. ZAITSEV, J. HOLLOCOMBE, N. HAWKES, G. SZEPESI, L. APPEL, S. SILBURN, G. POULIPOULIS, D. TERRANOVA.*Plasma equilibrium reconstruction of jet discharges using the imas modelling infrastructure*, in "27th IAEA Fusion Energy Conference FEC 2018", Gandhinagar, India, October 2018, https://hal.archives-ouvertes.fr/hal-01947230

Research Reports

[14] J. BLUM, H. HEUMANN, E. NARDON, X. SONG.*Automating the Design of Tokamak Experiment Scenarios*, Inria, 2018, n^{o} RR-9237, https://hal.archives-ouvertes.fr/hal-01959583

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[17] A. BHOLE, B. NKONGA, S. L. GAVRILYUK, K. A. IVANOVA.*Fluctuation splitting Riemann solver for a non-conservative modeling of shear shallow water flow*, September 2018, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01877504

[18] S. GAVRILYUK, B. NKONGA, K.-M. SHYUE, L. TRUSKINOVSKY.*Generalized Riemann problem for dispersive equations*, December 2018, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01958328

[19] H. GUILLARD, J. LAKHLILI, A. LOYER, A. RATNANI, E. SONNENDRÜCKER.*Mesh generation for fusion applications*, November 2018, IPP Ringberg Theory Meeting, Poster, https://hal.inria.fr/hal-01950388

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[21] H. GUILLARD.*The mathematical theory of reduced MHD models for fusion plasmas*, Inria, April 2015, n^o RR-8715, https://hal.inria.fr/hal-01145009

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

Creation of the Team: 2013 January 01, updated into Project-Team: 2013 January 01

Keywords:

Computer Science and Digital Science:

A1.2.1. - Dynamic reconfiguration
A1.2.3. - Routing
A1.2.9. - Social Networks
A1.6. - Green Computing
A3.5.1. - Analysis of large graphs
A7.1. - Algorithms
A7.1.1. - Distributed algorithms
A7.1.3. - Graph algorithms
A8.1. - Discrete mathematics, combinatorics
A8.2. - Optimization
A8.2.1. - Operations research
A8.7. - Graph theory
A8.8. - Network science

Other Research Topics and Application Domains:

B1.1.1. - Structural biology
B6.3.3. - Network Management
B6.3.4. - Social Networks
B7.2. - Smart travel

1. Team, Visitors, External Collaborators

Research Scientists

Jean-Claude Bermond [CNRS, Emeritus, HDR]
David Coudert [Inria, Team leader, Senior Researcher, HDR]
Frédéric Giroire [CNRS, Researcher, HDR]
Frédéric Havet [CNRS, Senior Researcher, HDR]
Nicolas Nisse [Inria, Researcher, HDR]
Stéphane Pérennes [CNRS, Senior Researcher, HDR]
Bruce Reed [CNRS, Senior Researcher, on leave at McGill Univ. since Nov. 2017]

Faculty Members

Julien Bensmail [Univ Nice - Sophia Antipolis, Associate Professor]
Alexandre Caminada [Univ Nice - Sophia Antipolis, Professor, from Sep 2018]
Christelle Caillouet [Univ Nice - Sophia Antipolis, Associate Professor]
Joanna Moulierac [Univ Nice - Sophia Antipolis, Associate Professor]
Michel Syska [Univ Nice - Sophia Antipolis, Associate Professor]

External Collaborators

Nathann Cohen [CNRS]
Nicolas Huin [Concordia University, till Aug 2018]

Technical Staff

Mohammed Amine Ait Ouahmed [Univ Nice - Sophia Antipolis, from Feb 2018]

PhD Students

Ali Al Zoobi [Inria, from Oct 2018]
Adrien Gausseran [Univ Côte d'Azur, from Oct 2018]
William Lochet [Univ de Nice - Sophia Antipolis, until Aug 2018]
Fionn Mc Inerney [Inria]
Thi Viet Ha Nguyen [Inria, from Sep 2018]
Andrea Tomassilli [Univ Nice - Sophia Antipolis]

Post-Doctoral Fellow

Francois Dross [Univ Nice - Sophia Antipolis, from Sep 2018]

Visiting Scientists

Jorgen Bang-Jensen [Univ. Southern Denmark, Jun 2018]
Romuald Elie [Univ Paris-Est, from Feb 2018 until Mar 2018]
Adrien Gausseran [Univ Côte d'Azur, Sep 2018]
Takako Kodate [Tokyo's Woman's Christian University, until Mar 2018]
Kasper Szabo Lyngsie [Technical University of Denmark, from Jun 2018 until Jul 2018]
Joseph Peters [Simon Fraser University, until Jun 2018]
Leonardo Sampaio Rocha [University Federal de Ceara, from Jul 2018]
Joseph Yu [University of the Fraser Valley, Abbotsford, BC, Canada, from Mar 2018 until Apr 2018]
Tahiry Razafindralambo [Univ de La Réunion, Jul 2018, HDR]

Administrative Assistant

Patricia Lachaume [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) and UNS (Univ. Nice Sophia Antipolis). 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:

- **Energy efficiency and Software-Defined Networks (SDN)** at both the design and management levels. We study the deployment of energy-efficient routing algorithm within SDN. We developed new algorithms in order to take into account the new constraints of SDN equipments and we evaluate their performance by simulation and by experimentation on a fat-tree architecture.
- **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 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.

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 have started a collaboration with SME Instant-System on dynamic car-pooling combined with multi-modal transportation systems. This collaboration is now consolidated as an ANR project 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

Guillaume Ducoffe, former PhD student of COATI, is the recipient of the second PhD prize delivered jointly by GDR RSD and Association ACM SIGOPS France (ASF), edition 2018, for his PhD thesis entitled "Metric properties of large graphs".

5.1.2. Habilitation à Diriger des Recherches

Frédéric Giroire has defended his Habilitation à Diriger des Recherches, entitled "*Optimisation des infrastructures réseaux. Un peu de vert dans les réseaux et autres problèmes de placement et de gestion de ressources*" [1], at Univ. Côte d'Azur on October 23, 2018.

Abstract: Pushed by the new sensitivity of the society, politics, and companies to energy costs and global warming, he investigated the question of how to build green networks. He first studied some practical scenarios to answer the question: how much energy could be saved for Internet Service Providers by putting into practice energy efficient protocols? It led him to study fundamental problems of graph theory.

At the core of these energy efficient methods, there is a dynamic adaptation to the changes of demands, which is impossible to do in legacy networks which are mostly manually operated. The emergence of two new paradigms, software defined networking (SDN) and network function virtualization (NFV), leads to a finer control of networks and thus bears the promise to to put energy efficient solutions into practice. He thus studied how to use SDN to implement dynamic routing.

His approach has been to use theoretical tools to solve problems raised by the introduction of new technologies or new applications. His tools come mainly from combinatorics and in particular from graph theory, algorithmics, optimization and probabilities. When he was able to propose new methods of resolution, he then tried to evaluate their practical impact by numerical evaluation, simulation or experimentation with realistic scenarios.

5.1.3. New team members

- Alexandre Caminada has been recruited as a University Professor of Univ. Nice Sophia Antipolis since September 2018 and he is now a member of COATI. Since September 2017, he is the director of the Polytech'Nice engineering school of Univ. Nice Sophia Antipolis.
- Emanuele Natale has been recruited as a Junior researcher at CNRS in 2018. He will join COATI in January 2019.

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 BSP model) we decided to develop our own platform.

This platform is based on the existing BIGGRPH library and we are now in the phasis where we focus on the quality and the improvement 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 Bulk Synchronous Parallel 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/sage-8.4.txt
NEWS OF THE YEAR: 1) Implementation of a linear time algorithm for partitioning a graph into 3-connected components. Done in the context of Google Summer of Code 2018. 2) Main contributor for making the graph module (more than 100,000 lines of code) of SageMath compatible with Python3 (ongoing, already more than 100 patchs)

- Participant: David Coudert
- Contact: David Coudert
- URL: http://www.sagemath.org/

7. New Results

7.1. Network Design and Management

Participants: Jean-Claude Bermond, Christelle Caillouet, David Coudert, Frédéric Giroire, Frédéric Havet, Nicolas Huin, Joanna Moulierac, Nicolas Nisse, Stéphane Pérennes, 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 the new network paradigms, Software-Defined Networks (SDN) and Network Function Virtualization (NFV). On the contrary to legacy networks, in SDN, a centralized controller is in charge of the control plane and takes the routing decisions for the switches and routers based on the network conditions. This new technology brings new constraints and therefore new algorithmic problems such as the problem of limited space in the switches to store the forwarding rules. We then tackle the problem of placement of virtualized resources. We validated our algorithms on a real SDN platform [0]. Secondly, we consider different scenarios regarding wireless networks and connected Unmanned Aerial Vehicules (UAVs). Third, we tackle routing in the Internet. Last, we study live streaming in distributed systems.

7.1.1. Software Defined Networks (SDN)

Software-defined Networks (SDN) is a new networking paradigm enabling innovation through network programmability. SDN is gaining momentum with the support of major manufacturers. Over past few years, many applications have been built using SDN such as server load balancing, virtual-machine migration, traffic engineering and access control.

7.1.1.1. Bringing Energy Aware Routing Closer to Reality With SDN Hybrid Networks

Energy-aware routing aims at reducing the energy consumption of Internet service provider (ISP) networks. The idea is to adapt routing to the traffic load to turn off some hardware. However, it implies to make dynamic changes to routing configurations which is almost impossible with legacy protocols. The software defined network (SDN) paradigm bears the promise of allowing a dynamic optimization with its centralized controller. In [34], we propose smooth energy aware routing (SENAtoR), an algorithm to enable energy-aware routing in a scenario of progressive migration from legacy to SDN hardware. Since in real life, turning off network devices is a delicate task as it can lead to packet losses, SENAtoR also provides several features to safely enable energy saving services: tunneling for fast rerouting, smooth node disabling, and detection of both traffic spikes and link failures. We validate our solution by extensive simulations and by experimentation. We show that SENAtoR can be progressively deployed in a network using the SDN paradigm. It allows us to reduce the energy consumption of ISP networks by 5%–35% depending on the penetration of SDN hardware while diminishing the packet loss rate compared to legacy protocols.

7.1.1.2. Energy-Aware Routing in Software-Defined Network using Compression

Over past few years, many applications have been built using SDN such as server load balancing, virtual-machine migration, traffic engineering and access control. In [31], we focus on using SDN for energy-aware routing (EAR). Since traffic load has a small influence on the power consumption of routers, EAR allows putting unused links into sleep mode to save energy. SDN can collect traffic matrix and then computes routing solutions satisfying QoS while being minimal in energy consumption. However, prior works on EAR have assumed that the SDN forwarding table switch can hold an infinite number of rules. In practice, this assumption

[0] Testbed with SDN hardware, in particular a switch HP 5412 with 96 ports, hosted at I3S laboratory. A complete fat-tree architecture with 16 servers can be built on the testbed.

does not hold since such flow tables are implemented in Ternary Content Addressable Memory (TCAM) which is expensive and power-hungry. We consider the use of wildcard rules to compress the forwarding tables. In [31], we propose optimization methods to minimize energy consumption for a backbone network while respecting capacity constraints on links and rule space constraints on routers. In details, we present two exact formulations using Integer Linear Program (ILP) and introduce efficient heuristic algorithms. Based on simulations on realistic network topologies, we show that using this smart rule space allocation, it is possible to save almost as much power consumption as the classical EAR approach.

7.1.1.3. Complexity of Compressing Two Dimensional Routing Tables with Order

Motivated by routing in telecommunication network using Software Defined Network (SDN) technologies, we consider the following problem of finding short routing lists using aggregation rules. We are given a set of communications $\mathcal{X}$, which are distinct pairs $(s,t) \subseteq S \times T$, (typically S is the set of sources and T the set of destinations), and a port function $\pi : \mathcal{X} \to P$ where P is the set of ports. A *routing list*$\mathcal{R}$ is an ordered list of triples which are of the form (s,t,p), $(*,t,p)$, $(s,*,p)$ or $(*,*,p)$ with $s \in S$, $t \in T$ and $p \in P$. It *routes* the communication (s,t) to the port $r(s,t) = p$ which appears on the first triple in the list $\mathcal{R}$ that is of the form (s,t,p), $(*,t,p)$, $(s,*,p)$ or $(*,*,p)$. If $r(s,t) = \pi(s,t)$, then we say that (s,t) is *properly routed* by $\mathcal{R}$ and if all communications of $\mathcal{X}$ are properly routed, we say that $\mathcal{R}$*emulates*$(\mathcal{X},\pi)$. The aim is to find a shortest routing list emulating $(\mathcal{X},\pi)$. In [30], we carry out a study of the complexity of the two dual decision problems associated to it. Given a set of communication $\mathcal{X}$, a port function π and an integer k, the first one called ROUTING LIST (resp. the second one, called LIST REDUCTION) consists in deciding whether there is a routing list emulating $(\mathcal{X},\pi)$ of size at most k (resp. $|\mathcal{X}| - k$). We prove that both problems are NP-complete. We then give a 3-approximation for LIST REDUCTION, which can be generalized to higher dimensions. We also give a 4-approximation for ROUTING LIST in the fundamental case when there are only two ports (i.e. $|P| = 2$), $\mathcal{X} = S \times T$ and $|S| = |T|$.

7.1.2. Provisioning Service Function Chains

7.1.2.1. Optimal Network Service Chain Provisioning

Service chains consist of a set of network services, such as firewalls or application delivery controllers, which are interconnected through a network to support various applications. While it is not a new concept, there has been an extremely important new trend with the rise of Software-Defined Network (SDN) and Network Function Virtualization (NFV). The combination of SDN and NFV can make the service chain and application provisioning process much shorter and simpler. In [33], [48], we study the provisioning of service chains jointly with the number/location of Virtual Network Functions (VNFs). While chains are often built to support multiple applications, the question arises as how to plan the provisioning of service chains in order to avoid data passing through unnecessary network devices or servers and consuming extra bandwidth and CPU cycles. It requires choosing carefully the number and the location of the VNFs. We propose an exact mathematical model using decomposition methods whose solution is scalable in order to conduct such an investigation. We conduct extensive numerical experiments, and show we can solve exactly the routing of service chain requests in a few minutes for networks with up to 50 nodes, and traffic requests between all pairs of nodes. Detailed analysis is then made on the best compromise between minimizing the bandwidth requirement and minimizing the number of VNFs and optimizing their locations using different data sets.

7.1.2.2. Energy-Efficient Service Function Chain Provisioning

Network Function Virtualization (NFV) is a promising network architecture concept to reduce operational costs. In legacy networks, network functions, such as firewall or TCP optimization, are performed by specific hardware. In networks enabling NFV coupled with the Software Defined Network (SDN) paradigm, Virtual Network Functions (VNFs) can be implemented dynamically on generic hardware. This is of primary interest to implement energy efficient solutions, in order to adapt the resource usage dynamically to the demand. In [35], we study how to use NFV coupled with SDN to improve the energy efficiency of networks. We consider a setting in which a flow has to go through a Service Function Chain, that is several network functions in a specific order. We propose an ILP formulation, an ILP-based heuristic, as well as a decomposition model that relies on joint routing and placement configuration to solve the problem. We show that virtualization provides between 22% to 62% of energy savings for networks of different sizes.

7.1.2.3. Placement of Service Function Chains with Ordering Constraints

A Service Function Chain (SFC) is an ordered sequence of network functions, such as load balancing, content filtering, and firewall. With the Network Function Virtualization (NFV) paradigm, network functions can be deployed as pieces of software on generic hardware, leading to a flexibility of network service composition. Along with its benefits, NFV brings several challenges to network operators, such as the placement of virtual network functions. In [49], [50], [62], we study the problem of how to optimally place the network functions within the network in order to satisfy all the SFC requirements of the flows. Our optimization task is to minimize the total deployment cost. We show that the problem can be seen as an instance of the Set Cover Problem, even in the case of ordered sequences of network functions. It allows us to propose two logarithmic factor approximation algorithms which have the best possible asymptotic factor. Further, we devise an optimal algorithm for tree topologies. Finally, we evaluate the performances of our proposed algorithms through extensive simulations. We demonstrate that near-optimal solutions can be found with our approach.

7.1.2.4. Resource Requirements for Reliable Service Function Chaining

We study in [51], [49] the problem of deploying reliable Service Function Chains over a virtualized network function architecture. While there is a need for reliable service function chaining, there is a high cost to pay for it in terms of bandwidth and VNF processing requirements. We investigate two different protection mechanisms and discuss their resource requirements, as well as the latency of their paths. For each mechanism, we develop a scalable exact mathematical model using column generation.

7.1.2.5. Path protection in optical flexible networks with distance-adaptive modulation formats

Thanks to a flexible frequency grid, Elastic Optical Networks (EONs) will support a more efficient usage of the spectrum resources. On the other hand, this efficiency may lead to even more disruptive effects of a failure on the number of involved connections with respect to traditional networks. In [52], we study the problem of providing path protection to the lightpaths against a single fiber failure event in the optical layer. Our optimization task is to minimize the spectrum requirements for the protection in the network. We develop a scalable exact mathematical model using column generation for both shared and dedicated path protection schemes. The model takes into account practical constraints such as the modulation format, regenerators, and shared risk link groups. We demonstrate the effectiveness of our model through extensive simulation on two real-world topologies of different sizes. Finally, we compare the two protection schemes under different scenario assumptions, studying the impact of factors such as number of regenerators and demands on their performances.

7.1.2.6. Reconfiguring Service Functions chains with a make-before-break approach

The centralized routing model of SDN jointly with the possibility of instantiating VNFs on-demand open the way for a more efficient operation and management of networks. In [58], we consider the problem of reconfiguring network connections 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.

7.1.3. Capacity defragmentation

Optical multilayer optimization continuously reorganizes layer 0-1-2 network elements to handle both existing and dynamic traffic requirements in the most efficient manner. This delays the need to add new resources for new requests, saving CAPEX and leads to optical network defragmentation.

In [46], [47], we focus on Layer 2, i.e., on capacity defragmentation at the Optical Transport Network (OTN) layer when routes (e.g., LSPs in MPLS networks) are making unnecessarily long detours to evade congestion. Reconfiguration into optimized routes can be achieved by redefining the routes, one at a time, so that they use the vacant resources generated by the disappearance of services using part of a path that transits the congested section. For the Quality of Service, it is desirable to operate under Make-Before-Break (MBB), with the minimum number of rerouting. The challenge is to identify the rerouting order, one connection at a time, while minimizing the bandwidth requirement. We propose in [46], [47] an exact and scalable optimization model for computing a minimum bandwidth rerouting scheme subject to MBB in the OTN layer of an optical network. Numerical results show that we can successfully apply it on networks with up to 30 nodes, a very significant improvement with the state of the art. We also provide some defragmentation analysis in terms of the bandwidth requirement vs. the number of reroutings.

In [37], we focus on wavelength defragmentation in WDM networks. We propose a MBB wavelength defragmentation process which minimizes the bandwidth requirement of the resulting provisioning. Comparisons with minimum bandwidth provisioning that is not subject to MBB show that, on average, the best seamless lightpath rerouting is never more than 5% away (less than 1% on average) from an optimal lightpath provisioning.

7.1.4. 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 [16], 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.

7.1.5. Optimizing drone coverage

In the context of a collaboration with Tahiry Razafindralambo from the University of la Réunion we have studied several problems related to deployment of drones in order to collect data generated from sensors. Those problems may be seen as belonging to the category of "cover" problems and we have designed and proposed efficient formulations using linear programming models with columns generation.

Drones (Unmanned Aerial Vehicles, UAV) can be used to provide anytime and anywhere network access to targets located on the ground, using air-to-ground and air-to-air communications through directional antennas. In [43] we study how to deploy these drones to cover a set of fixed targets. It is a complex problem since each target should be covered, while minimizing (i) the deployment cost and (ii) the drones altitudes to ensure good communication quality. We also consider connectivity between the drone and a base station in order to collect and send information to the targets, which is not considered in many similar studies. We provide an efficient optimal program to solve the problem and show the trade-off analysis due to conflicting objectives. We propose a fair trade-off optimal solution and also evaluate the cost of adding connectivity to the drone deployment.

In [41], [42] we introduce a Linear Programming (LP) model for the problem of data gathering with mobile drones. The goal is to deploy a connected set of Unmanned Aerial Vehicles (UAVs) continuously monitoring mobile sensors and reporting information to a fixed base station for efficient data collection. We propose an effective optimization model reducing the number of variables of the problem and solved using column generation. Results show that our model is tractable for large topologies with several hundreds of possible 3D locations for the UAVs deployment and provides integer solutions with the generated columns very close to the optimum. Moreover, the deployment changes among time remains low in terms of number of UAVs and cost, to maintain connectivity and minimize the data collection delay to the base station.

We also have studied a problem arising when one will to recharge wireless sensor networks using drones and wireless power transfer; in [44] we consider the optimal energy replenishment problem (OERP). The goal is to operate a given number of flying drones in order to efficiently recharge wireless sensor nodes. We present a linear program that maximizes the amount of harvested energy to the sensors. We show that the model is solved to optimality in a few seconds for sensor networks with up to 50 nodes. The small number of available drones is shown to be optimally deployed at low altitude in order to efficiently recharge the batteries of at least half of the sensor nodes.

7.1.6. Other results in wireless networks

7.1.6.1. 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 [64], 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.

7.1.6.2. Gossiping with interference in radio chain networks

In [53], we study the problem of gossiping with interference constraint in radio chain networks. Gossiping (or total exchange information) is a protocol where each node in the network has a message and wants to distribute its own message to every other node in the network. The gossiping problem consists in finding the minimum running time (makespan) of a gossiping protocol and efficient algorithms that attain this makespan. The network is assumed to be synchronous, the time is slotted into steps, and each device is equipped with a half duplex interface; so, a node cannot both receive and transmit during a step. We use a binary asymmetric model of interference based on the distance in the communication digraph. We determine exactly the minimum number of rounds R needed to achieve a gossiping when transmission network is a dipath P_n on $n \geq 3$ nodes and the interference distance is $d_I = 1$.

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. Parameterized complexity of polynomial optimization problems (FPT in P)

Parameterized complexity theory has enabled a refined classification of the difficulty of NP-hard optimization problems on graphs with respect to key structural properties, and so to a better understanding of their true difficulties. More recently, hardness results for problems in P were established under reasonable complexity theoretic assumptions such as: Strong Exponential Time Hypothesis (SETH), 3SUM and All-Pairs Shortest-Paths (APSP). According to these assumptions, many graph theoretic problems do not admit truly subquadratic algorithms, nor even truly subcubic algorithms (Williams and Williams, FOCS 2010 [83] and Abboud *et al.* SODA 2015 [67]). A central technique used to tackle the difficulty of the above mentioned problems is fixed-parameter algorithms for polynomial-time problems with *polynomial dependency* in the fixed parameter (P-FPT). This technique was rigorously formalized by Giannopoulou et al. (IPEC 2015) [74], [75]. Following that, it was continued by Abboud *et al.* (SODA 2016) [68], by Husfeldt (IPEC 2016) [76] and Fomin *et al.* (SODA 2017) [73], using the treewidth as a parameter. Applying this technique to *clique-width*, another important graph parameter, remained to be done.

In [45] we study several graph theoretic problems for which hardness results exist such as *cycle problems* (triangle detection, triangle counting, girth), *distance problems* (diameter, eccentricities, Gromov hyperbolicity, betweenness centrality) and *maximum matching*. We provide hardness results and fully polynomial FPT algorithms, using clique-width and some of its upper-bounds as parameters (split-width, modular-width and P_4-sparseness). We believe that our most important result is an $\mathcal{O}(k^4 \cdot n + m)$-time algorithm for computing a maximum matching where k is either the modular-width or the P_4-sparseness. The latter generalizes many algorithms that have been introduced so far for specific subclasses such as cographs, P_4-lite graphs, P_4-extendible graphs and P_4-tidy graphs. Our algorithms are based on preprocessing methods using modular decomposition, split decomposition and primeval decomposition. Thus they can also be generalized to some graph classes with unbounded clique-width.

7.2.1.2. *Revisiting Decomposition by Clique Separators*

We study in [26] the complexity of decomposing a graph by means of clique separators. This common algorithmic tool, first introduced by Tarjan [79], allows to cut a graph into smaller pieces, and so, it can be applied to preprocess the graph in the computation of optimization problems. However, the best-known algorithms for computing a decomposition have respective $\mathcal{O}(nm)$-time and $\mathcal{O}(n^{(3+\alpha)/2}) = o(n^{2.69})$-time complexity, with $\alpha < 2.3729$ being the exponent for matrix multiplication. Such running times are prohibitive for large graphs. In [26], we prove that for every graph G, a decomposition can be computed in $\mathcal{O}(T(G) + \min\{n^\alpha, \omega^2 n\})$-time with $T(G)$ and ω being respectively the time needed to compute a minimal triangulation of G and the clique-number of G. In particular, it implies that every graph can be decomposed by clique separators in $\mathcal{O}(n^\alpha \log n)$-time. Based on prior work from Kratsch and Spinrad [77], we prove in addition that decomposing a graph by clique-separators is as least as hard as triangle detection. Therefore, the existence of any $o(n^\alpha)$-time algorithm for this problem would be a significant breakthrough in the field of algorithmic. Finally, our main result implies that planar graphs, bounded-treewidth graphs and bounded-degree graphs can be decomposed by clique separators in linear or quasi-linear time.

7.2.1.3. *Distance-preserving elimination orderings in graphs*

For every connected graph G, a subgraph H of G is *isometric* if the distance between any two vertices in H is the same in H as in G. A *distance-preserving elimination ordering* of G is a total ordering of its vertex-set $V(G)$, denoted $(v_1, v_2, ..., v_n)$, such that any subgraph $G_i = G \setminus (v_1, v_2, ..., v_i)$ with $1 \leq i < n$ is isometric. This kind of ordering has been introduced by Chepoi in his study on weakly modular graphs [71]. In [27], we prove that it is NP-complete to decide whether such ordering exists for a given graph | even if it has diameter at most 2. Then, we prove on the positive side that the problem of computing a distance-preserving ordering when there exists one is fixed-parameter-tractable in the treewidth. Lastly, we describe a heuristic in order to compute a distance-preserving ordering when there exists one that we compare to an exact exponential time algorithm and to an ILP formulation for the problem.

7.2.1.4. *Complexity of computing strong pathbreadth*

The strong pathbreadth of a given graph G is the minimum ρ such that G admits a Robertson and Seymour's path decomposition where every bag is the complete ρ-neighbourhood of some vertex in G. In [29] [0], we prove that deciding whether a given graph has strong pathbreadth at most one is NP-complete. This answers negatively to a conjecture of Leitert and Dragan [78].

7.2.1.5. *Improving matchings in trees, via bounded-length augmentations*

In [13] Due to a classical result of Berge, it is known that a matching of any graph can be turned into a maximum matching by repeatedly augmenting alternating paths whose ends are not covered. In a recent work, Nisse, Salch and Weber considered the influence, on this process, of augmenting paths with length at most k only. Given a graph G, an initial matching $M \subseteq E(G)$ and an odd integer k, the problem is to find a longest sequence of augmenting paths of length at most k that can be augmented sequentially from M. They proved that, when only paths of length at most $k = 3$ can be augmented, computing such a longest sequence can be done in polynomial time for any graph, while the same problem for any $k \geq 5$ is *NP*-hard. Although the latter result remains true for bipartite graphs, the status of the complexity of the same problem for trees is not known.

[0] Work done while G. Ducoffe was a member of COATI and published this year.

This work is dedicated to the complexity of this problem for trees. On the positive side, we first show that it can be solved in polynomial time for more classes of trees, namely bounded-degree trees (via a dynamic programming approach), caterpillars and trees where the nodes with degree at least 3 are sufficiently far apart. On the negative side, we show that, when only paths of length *exactly*k can be augmented, the problem becomes *NP*-hard already for $k = 3$, in the class of planar bipartite graphs with maximum degree 3 and arbitrary large girth. We also show that the latter problem is *NP*-hard in trees when k is part of the input.

7.2.2. Dynamics of formation of communities in social networks

We consider in [40] 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 $k \le 2$ and $O(|V|^3)$ 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 $k \le 2$ the tight upper-bound $O(|V| \min \alpha(G^-), \sqrt{|V|})$ 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 $k \ge 4$, was conjectured to be polynomial. In [40], we disprove this. Specifically, we prove that for any $k \ge 4$, the maximum time of convergence is an $\Omega(|V|^{\Theta(\log |V|)})$.

7.2.3. Application to bioinformatics

For a (possibly infinite) fixed family of graphs $\mathcal{F}$, we say that a graph *G*overlays$\mathcal{F}$ on a hypergraph H if $V(H)$ is equal to $V(G)$ and the subgraph of G induced by every hyperedge of H contains some member of $\mathcal{F}$ as a spanning subgraph. While it is easy to see that the complete graph on $|V(H)|$ overlays $\mathcal{F}$ on a hypergraph H whenever the problem admits a solution, the MINIMUM $\mathcal{F}$-OVERLAY problem asks for such a graph with at most k edges, for some given $k \in \mathbb{N}$. This problem allows to generalize some natural problems which may arise in practice. For instance, if the family $\mathcal{F}$ contains all connected graphs, then MINIMUM $\mathcal{F}$-OVERLAY corresponds to the MINIMUM CONNECTIVITY INFERENCE problem (also known as SUBSET INTERCONNECTION DESIGN problem) introduced for the low-resolution reconstruction of macro-molecular assembly in structural biology, or for the design of networks.

In [23], we prove a strong dichotomy result regarding the polynomial vs. NP-complete status with respect to the considered family $\mathcal{F}$. Roughly speaking, we show that the easy cases one can think of (e.g. when edgeless graphs of the right sizes are in $\mathcal{F}$, or if $\mathcal{F}$ contains only cliques) are the only families giving rise to a polynomial problem: all others are $\mathcal{NP}$-complete. We then investigate the parameterized complexity of the problem and give similar sufficient conditions on $\mathcal{F}$ that give rise to W[1]-hard, W[2]-hard or FPT problems when the parameter is the size of the solution. This yields an FPT/W[1]-hard dichotomy for a relaxed problem, where every hyperedge of H must contain some member of $\mathcal{F}$ as a (non necessarily spanning) subgraph.

7.3. Games on Graphs

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We study several two-player games on graphs. Some of these games allow to model real-life applications. In the case of the Spy-game presented below, we propose a successful new approach by studying fractional relaxation of such games.

7.3.1. Spy-game on graphs and eternal domination

In [24] we define and study the following two-player game on a graph G. Let $k \in \mathbf{N}^*$. A set of k guards is occupying some vertices of G while one spy is standing at some node. At each turn, first the spy may move along at most s edges, where $s \in \mathbf{N}^*$ is his speed. Then, each guard may move along one edge. The spy and the guards may occupy the same vertices. The spy has to escape the surveillance of the guards, i.e., must reach a vertex at distance more than $d \in \mathbf{N}$ (a predefined distance) from every guard. Can the spy win against k guards? Similarly, what is the minimum distance d such that k guards may ensure that at least one of them remains at distance at most d from the spy? This game generalizes two well-studied games: Cops and robber games (when $s = 1$) and Eternal Dominating Set (when s is unbounded).

In [24], we consider the computational complexity of the problem, showing that it is NP-hard (for every speed s and distance d) and that some variant of it is PSPACE-hard in DAGs. Then, we establish tight tradeoffs between the number of guards, the speed s of the spy and the required distance d when G is a path or a cycle.

In order to determine the smallest number of guards necessary for this task, we analyze in [25] the game through a Linear Programming formulation and the fractional strategies it yields for the guards. We then show the equivalence of fractional and integral strategies in trees. This allows us to design a polynomial-time algorithm for computing an optimal strategy in this class of graphs. Using duality in Linear Programming, we also provide non-trivial bounds on the fractional guard-number of grids and torus. We believe that the approach using fractional relaxation and Linear Programming is promising to obtain new results in the field of combinatorial games.

In [60] we pursue the study of the eternal domination game (which is equivalent to the spy game when s is unbounded and $d = 0$) on strong grids $P_n \Box P_m$. Cartesian grids $P_n \Box P_m$ 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 $\gamma^{\infty}_{all}(P_n \Box P_m) = \gamma(P_n \Box P_m) + O(n + m)$ where $\gamma(P_n \Box P_m)$ is the domination number of $P_n \Box P_m$ which lower bounds the eternal domination number. We prove that, for all $n, m \in \mathbb{N}^*$ such that $m \geq n$, $\lceil \frac{nm}{9} \rceil + \Omega(n + m) = \gamma^{\infty}_{all}(P_n \boxtimes P_m) = \lceil \frac{nm}{9} \rceil + O(m\sqrt{n})$ (note that $\lceil \frac{nm}{9} \rceil$ is the domination number of $P_n \boxtimes P_m$).

7.3.2. Metric dimension & localization

The questions that we study there are variant of the usual *Metric Dimension* problem in which one wishes to identify the vertices of a graph from the knowledge of the distances to a few points. This is motivated by localization problems, e.g., in cellular networks. few anchors.

In [19] we introduce a generalization of metric dimension based on a pursuit graph game that resembles the famous Cops and Robbers game. In this game, an invisible target is hidden at some vertex of a graph (at each turn, it may move to a neighbor). At every step, $k \geq 1$ vertices of G can be probed which results in the knowledge of the distances between each of these vertices and the secret location of the target. We provide upper bounds on the related graph invariant $\zeta(G)$, defined as the least number of probes per turn needed to localize the robber on a graph G, for several classes of graphs (trees, bipartite graphs, etc). Our main result is that, surprisingly, there exists planar graphs of treewidth 2 and unbounded $\zeta(G)$. On a positive side, we prove that $\zeta(G)$ is bounded by the pathwidth of G. We then show that the algorithmic problem of determining $\zeta(G)$ is NP-hard in graphs with diameter at most 2. Finally, we show that at most one cop can approximate (arbitrary close) the location of the robber in the Euclidean plane. We further study this problem in [18] where, in particular, we prove that $\zeta(G) \leq 3$ in outer-planar graphs.

In [39], [56], [38], we address the sequential metric dimension when the invisible target is immobile. The objective of the game is to minimize the number of steps needed to locate the target whatever be its location. Precisely, given a graph G and two integers $k, \ell \geq 1$, the LOCALIZATION problem asks whether there exists a strategy to locate a target hidden in G in at most ℓ steps and probing at most k vertices per step. We first show that, in general, this problem is *NP*-complete for every fixed $k \geq 1$ (resp., $\ell \geq 1$). We then focus on the class of trees. On the negative side, we prove that the LOCALIZATION PROBLEM is *NP*-complete in trees when k and ℓ are part of the input. On the positive side, we design a $(+1)$-approximation for the problem in n-node trees, *i.e.*, an algorithm that computes in time $O(n \log n)$ (independent of k) a strategy to locate the target in at most one more step than an optimal strategy. This algorithm can be used to solve the LOCALIZATION PROBLEM in trees in polynomial time if k is fixed.

In [57] we try to understand the phenomena when one choose an orientation of an (undirected) graphs. Namely, 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 $\frac{nm}{2}$.

7.3.3. Orienting edges to fight fire in graphs

In [12], we investigate a new oriented variant of the Firefighter Problem. In the traditional Firefighter Problem, a fire breaks out at a given vertex of a graph, and at each time interval spreads to neighbouring vertices that have not been protected, while a constant number of vertices are protected at each time interval. In our version of the problem, the firefighters are able to orient the edges of the graph before the fire breaks out, but the fire could start at any vertex. We consider this problem when played on a graph in one of several graph classes, and give upper and lower bounds on the number of vertices that can be saved. In particular, when one firefighter is available at each time interval, and the given graph is a complete graph, or a complete bipartite graph, we present firefighting strategies that are provably optimal. We also provide lower bounds on the number of vertices that can be saved as a function of the chromatic number, of the maximum degree, and of the treewidth of a graph. For a sub-cubic graph, we show that the firefighters can save all but two vertices, and this is best possible.

7.3.4. Network decontamination

The Network Decontamination problem consists in 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. In this Chapter, we focus on networks modeled by graphs. Many different objectives have been studied in this context, the main one being the minimization of the number of mobile agents necessary to clean a contaminated network. Another important aspect is that this optimization problem 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). Our chapter [61] consists of an overview of algorithmic results on graph decontamination and graph searching.

7.3.5. Hyperopic Cops and Robbers

We introduce in [17] a new variant of the game of Cops and Robbers played on graphs, where the robber is invisible unless outside the neighbor set of a cop. The hyperopic cop number is the corresponding analogue of the cop number, and we investigate bounds and other properties of this parameter. We characterize the cop-win graphs for this variant, along with graphs with the largest possible hyperopic cop number. We analyze the cases of graphs with diameter 2 or at least 3, focusing on when the hyperopic cop number is at most one greater than the cop number. We show that for planar graphs, as with the usual cop number, the hyperopic cop number is at most 3. The hyperopic cop number is considered for countable graphs, and it is shown that for connected chains of graphs, the hyperopic cop density can be any real number in $[0, 1/2]$.

7.4. Graph theory

Participants: Julien Bensmail, Frédéric Havet, William Lochet, Nicolas Nisse, Fionn Mc Inerney, Stéphane Pérennes, Bruce Reed.

COATI studies theoretical problems in graph theory. If some of them are directly motivated by applications, others are more fundamental.

7.4.1. Interval number in cycle convexity

Recently, Araujo et al. [Manuscript in preparation, 2017] introduced the notion of Cycle Convexity of graphs. In their seminal work, they studied the graph convexity parameter called hull number for this new graph convexity they proposed, and they presented some of its applications in Knot theory. Roughly, the *tunnel number* of a knot embedded in a plane is upper bounded by the hull number of a corresponding planar 4-regular graph in cycle convexity. In [4], we go further in the study of this new graph convexity and we study the interval number of a graph in cycle convexity. This parameter is, alongside the hull number, one of the most studied parameters in the literature about graph convexities. Precisely, given a graph G, its *interval number* in cycle convexity, denoted by $CCIHN(G)$, is the minimum cardinality of a set $S \subseteq V(G)$ such that every vertex $w \in V(G) \setminus S$ has two distinct neighbors $u, v \in S$ such that u and v lie in same connected component of $G[S]$, i.e. the subgraph of G induced by the vertices in S.

In [4] we provide bounds on $CCIHN(G)$ and its relations to other graph convexity parameters, and explore its behaviour on grids. Then, we present some hardness results by showing that deciding whether $CCIHN(G) \leq k$ is NP-complete, even if G is a split graph or a bounded-degree planar graph, and that the problem is W[2]-hard in bipartite graphs when k is the parameter. As a consequence, we obtain that $CCIHN(G)$ cannot be approximated up to a constant factor in the classes of split graphs and bipartite graphs (unless $P = NP$).

On the positive side, we present polynomial-time algorithms to compute $CCIHN(G)$ for outerplanar graphs, cobipartite graphs and interval graphs. We also present fixed-parameter tractable (FPT) algorithms to compute it for $(q, q-4)$-graphs when q is the parameter and for general graphs G when parameterized either by the treewidth or the neighborhood diversity of G.

Some of our hardness results and positive results are not known to hold for related graph convexities and domination problems. We hope that the design of our new reductions and polynomial-time algorithms can be helpful in order to advance in the study of related graph problems.

7.4.2. Steinberg-like theorems for backbone colouring

A function $f : V(G) \to \{1, ..., k\}$ is a (proper) k-colouring of G if $|f(u) - f(v)| \geq 1$, for every edge $uv \in E(G)$. The *chromatic number*$\chi(G)$ is the smallest integer k for which there exists a proper k-colouring of G. Given a graph G and a subgraph H of G, a circular q-backbone k-colouring f of (G, H) is a k-colouring of G such that $q \leq |c(u) - c(v)| \leq k - q$, for each edge $uv \in E(H)$. The *circular q-backbone chromatic number* of a graph pair (G, H), denoted $\mathrm{CBC}_q(G, H)$, is the minimum k such that (G, H) admits a circular q-backbone k-colouring. Steinberg conjectured that if G is planar and G contains no cycles on 4 or 5 vertices, then $\chi(G) \leq 3$. If this conjecture is correct, then one could deduce that $\mathrm{CBC}_2(G, H) \leq 6$, for any $H \subseteq G$. In [5], we first show that if G is a planar graph containing no cycle on 4 or 5 vertices and $H \subseteq G$ is a forest, then $\mathrm{CBC}_2(G, H) \leq 7$. Then, we prove that if $H \subseteq G$ is a forest whose connected components are paths, then $\mathrm{CBC}_2(G, H) \leq 6$.

7.4.3. Homomorphisms of planar signed graphs and absolute cliques

Homomorphisms are an important topic in graph theory, as example the chromatic number of a graph G is the minimum k such that G maps onto the complete graph K_k. A signed graph (G, Σ) is a (simple) graph with sign function $\Sigma E(G) \to \{-1, 1\}$. A closed-walk is unbalanced if it has an odd number of negative edges, it is balanced otherwise. Homomorphisms of signed graphs are mapping that preserve adjacency and balance of cycles. Naserasr, Rollova and Sopena (Journal of Graph Theory 2015) posed the important question of finding out the minimum size k such that any planar signed graph (G, Σ) admits a homomorphism to a signed graph with k vertices. The question can be seen as the counterpart of the 4 color theorem which implies that any palnar graph maps onto K_4. It is known that if this minimum value is equal to 10, then every planar signed graph maps to a particular unique signed graph (P^+9, Γ^+) with 10 vertices. A graph G is an underlying absolute signed clique if there exists a signed graph (G, Σ) which does not admit any homomorphism to any signed graph (H, Π) with $|V(H)| < |V(G)|$. In [66] we characterize all underlying absolute signed planar cliques up to spanning subgraph inclusion. Furthermore, we show that every signed planar graph having underlying graphs obtained by (repeated, finite) k-clique sums ($k \leq 3$) of underlying absolute signed planar cliques admits a homomorphism to $(P^{+}9, \Gamma^{+})$. Based on this evidence, we conjecture that every planar signed graph admits a homomorphism to $(P+9, \Gamma^{+})$.

7.4.4. Edge-partitioning a graph into paths: 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. We recently proved this conjecture with Merker [69].

The path case of the Barát-Thomassen conjecture (i.e $\forall k, m = |E| \, mod \, k = 0$ there exists $f(k)$ such that if the connectivity of G is larger than $f(k)$ then G can be partitionned into P_k) has also been studied, notably by Thomassen [80], [81], [82], and had been solved by Botler, Mota, Oshiro and Wakabayashi [70]. In [15] we 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 $f(k)$ has an edge-partition into paths of length k. We also show that 24 can be dropped to 4 when the graph is Eulerian.

7.4.5. Some Aspects of Arbitrarily Partitionable Graphs

An n-graph G is arbitrarily partitionable (AP) if, for every partition of n as $n = n_1 + ... + n_p$, there is a partition $(V_1, ..., V_p)$ of $V(G)$ such that for $i = 1, ..., pG[V_i]$ is connected and $|V_i| = n_i$. The property of being AP is related to other well-known graph notions, such as perfect matchings and Hamiltonian cycles (obviously Hamiltonian graph is AP), with which it shares several properties. In [65] This work we studying two aspects of AP graphs.

On the one hand, we consider the algorithmic aspects. We first establish the *NP*-hardness of the problem of partitioning a graph into connected subgraphs following a given sequence, for various new graph classes of interest. We then prove that the problem of deciding whether a graph is AP is *NP*-hard for several classes of graphs, confirming a conjecture of Barth and Fournier.

On the other hand, we consider the weakening of APness to sufficient conditions for Hamiltonicity. While previous works have suggested that such conditions can sometimes indeed be weakened, we point out cases for which this is not true. This is done by considering conditions for Hamiltonicity involving squares of graphs, and claw- and net-free graphs.

7.4.6. Incident Sum problems and the 1-2-3 Conjecture

How can one distinguish the adjacent vertices of a graph through an edge-weighting? In the last decades, this question has been attracting increasing attention, which resulted in the active field of distinguishing labelings. One of its most popular problems is the one where neighbours must be distinguishable via their incident sums of weights. An edge-weighting verifying this is said to be *proper*. The popularity of this notion arises mainly due to the influence of the famous 1-2-3 Conjecture (posed by Karoński, Łuczak and Thomason), which claims that proper weightings with weights in $\{1, 2, 3\}$ exist for graphs with no isolated edge.

The questions that we study aim at solving or at progressing toward the solution of the 1-2-3 conjecture and similar problems.

In [8] we study locally irregular decompositions of sub-cubic graphs. A graph G is locally irregular if every two adjacent vertices of G have different degrees (this corresponds to a uniform weight). A locally irregular decomposition of G is a partition $E_1, \cdots, E_k$ of the edge set $E(G)$ such that each $G[E_i]$ is locally irregular. Not all graphs admit locally irregular decompositions, but for those who are decomposable, it was conjectured by Baudon, Bensmail, Przybyło and Woźniak that the decomposition uses at most 3 locally irregular graphs. Towards that conjecture, it was recently proved by Bensmail, Merker and Thomassen that every decomposable graph decomposes into at most 328 locally irregular graphs. Our work focuses on the case of sub-cubic graphs, which form an important family of graphs in this context, as all non-decomposable graphs are sub-cubic. As a main result, we prove that decomposable sub-cubic graphs decompose into at most 5 locally irregular graphs, and at most 4 when the maximum average degree is less than $\frac{12}{5}$. We then consider weaker decomposition, where subgraphs can also include regular connected components, and prove the relaxations of the conjecture above for sub-cubic graphs.

In [9] we pursue recent works generalizing "Neighbour Sum problems" (e.g. the well-known 1-2-3 Conjecture, or the notion of locally irregular decomposition) to digraphs. We introduce and study several variants of the 1-2 Conjecture for digraphs and for every such variant, we state conjectures concerning the number of weights necessary to obtain a desired total-weighting in any digraph. We verify some of these conjectures, while we obtain close results towards the solution of the ones that are still open.

In [10] we study a variant of the classical 1-2-3 Conjecture. This conjecture asks whether every graph but K_2 can be 3-edge-weighted so that every two adjacent vertices u and v can be distinguished via the sum of their incident weights, that is the incident sums of u and v differ by at least 1. In this work we investigate the consequences on the 1-2-3 Conjecture of requiring a stronger distinction condition, that is requiring the incident sums to differ by at least 2. Our conjecture is that every graph but K_2 admits a 5-edge-weighting permitting to distinguish the adjacent vertices in this stronger way. We prove this conjecture for several classes of graphs, including bipartite graphs and cubic graphs. We then consider algorithmic aspects, and show that it is *NP*-complete to determine the smallest k such that a given bipartite graph admits such a k-edge-weighting. In contrast, we show that the same problem can be solved in polynomial time when the graph is a tree.

In [11] we prove a 1-2-3-4 result for the 1-2-3 Conjecture in 5-regular graphs. Currently the best-known result toward te 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 (.i.e in our context total means that both the vertices and the edges are assigned weights). Our work, 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 adjacent vertices.

In [63] we investigate another aspect of edge weighting that allow to distinguish adjacent vertices (we shall call them *proper*). Namely we study the minimum number of distinct neighbourhood sums we can produce using such proper weightings. Clearly, this minimum number is bounded below by the chromatic number $\chi(G)$ of G. When using weights in Z, we show that we can always produce proper edge-weightings generating $\chi(G)$ distinct sums but in the peculiar case where G is a balanced bipartite graph, in which case exactly $\chi(G) + 1$ distinct sums have to be generated. 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.

The 1-2-3 Conjecture has recently been investigated from a decompositional angle, via so-called locally irregular decompositions, which are edge-partitions into locally irregular subgraphs. Through several recent studies, it was shown that this concept is quite related to the 1-2-3 Conjecture. However, the full connection between all those concepts was not clear. In [55], we propose an approach that generalizes all concepts above, involving coloured weights and sums. As a consequence, we get another interpretation of several existing results related to the 1-2-3 Conjecture. We also propose new related conjectures, to which we give some support.

7.4.7. Identifying codes

For G a graph or a digraph, let $\mathrm{id}(G)$ be the minimum size of an identifying code of G if one exists, and $\mathrm{id}(G) = +\infty$ otherwise. For a graph G, let $\mathrm{idor}(G)$ be the minimum of $\mathrm{id}(D)$ overall orientations D of G. In [20], we give some lower and upper bounds on $\mathrm{idor}(G)$. In particular, we show that $\mathrm{idor}(G) \leq 3/2\mathrm{id}(G)$ for every graph G. We also show that computing $\mathrm{idor}(G)$ is NP-hard, while deciding whether $\mathrm{idor}(G) \leq |V(G)| - k$ is polynomial-time solvable for every fixed integer k.

7.5. Digraph theory

Participants: Julien Bensmail, Frédéric Havet, Nicolas Nisse, William Lochet.

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.

7.5.1. 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 [59], 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 is polynomial-time solvable for all fixed positive integer. On the other hand, deciding whether a graph admits an ear decomposition without ears of length in F is NP-complete for any finite set 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 is polynomial-time solvable for all positive integer ; deciding whether a digraph admits a handle decomposition without handles of length in F is NP-complete for any finite set F of positive integers (and minimizing the number of handles of length in F is not approximable up to $n(1-\varepsilon)$); 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 A of integers, deciding whether a digraph has a handle decomposition with all handles of length in A is NP-complete, unless there exists $h \in \mathbf{N}$ such that $A = \{1, \cdots, h\}$.

7.5.2. Substructures in digraphs

We study substructures in digraphs. We study all kind of substructures: subdigraphs (induced or not), subdivision, immersion, minors, etc. We are both interested in the algorithmic point of view, that is determining the complexity of finding a (fixed or given) substructure in a given graph, and the structural point of view, that is finding sufficient conditions to guarantee the existence of a substructure.

In [32], we study the algorithmic complexity of the problem of deciding if a digraph contains a subdivision of a fixed digraph F. Up to 5 exceptions, we completely classify for which 4-vertex digraphs F, the F-subdivision problem is polynomial-time solvable and for which it is NP-complete. While all NP-hardness proofs are made by reduction from some version of the 2-linkage problem in digraphs, some of the polynomial-time solvable cases involve relatively complicated algorithms.

In [25], [22] we study conditions under which a digraph contain a subdivision of an oriented cycle. An oriented cycle is an orientation of a undirected cycle. We first show that for any oriented cycle C, there are digraphs containing no subdivision of C (as a subdigraph) and arbitrarily large chromatic number. In contrast, we show that for any C a cycle with two blocks, every strongly connected digraph with sufficiently large chromatic number contains a subdivision of C. We prove a similar result for the antidirected cycle on four vertices (in which two vertices have out-degree 2 and two vertices have in-degree 2). We study the existence of more general structures than cycles. A $(k_1 + k_2)$-bispindle is the union of $k_1 (x, y)$-dipaths and $k_2 (y, x)$-dipaths, all these dipaths being pairwise internally disjoint. The above-mentioned results on cycle with two blocks [25] can be restated as follows: for every $(1, 1)$-bispindle B, there exists an integer k such that every strongly connected digraph with chromatic number greater than k contains a subdivision of B. In [21], we investigate generalizations of this result by first showing constructions of strongly connected digraphs with large chromatic number without any $(3, 0)$-bispindle or $(2, 2)$-bispindle. We then consider $(2, 1)$-bispindles. Let $B(k_1, k_2; k_3)$ denote the $(2, 1)$-bispindle formed by three internally disjoint dipaths between two vertices x, y, two (x, y)-dipaths, one of length k_1 and the other of length k_2, and one (y, x)-dipath of length k_3. We conjecture that for any positive integers k_1, k_2, k_3, there is an integer $g(k_1, k_2, k_3)$ such that every strongly connected digraph with chromatic number greater than $g(k_1, k_2, k_3)$ contains a subdivision of $B(k_1, k_2; k_3)$. As evidence, we prove this conjecture for $k_2 = 1$ (and k_1, k_3 arbitrary).

In [36], we prove the existence of a function $h(k)$ such that every simple digraph with minimum outdegree greater than $h(k)$ contains an immersion of the transitive tournament on k vertices. This solves a conjecture of Devos, McDonald, Mohar and Scheide [72].

In [3], we study χ-bounded families of oriented graphs. A famous conjecture of Gyárfás and Sumner states for any tree T and integer k, if the chromatic number of a graph is large enough, either the graph contains a clique of size k or it contains T as an induced subgraph. We present some results and open problems about extensions of this conjecture to oriented graphs. In particular, we conjecture that for every oriented star S and integer k, if the chromatic number of a digraph is large enough, either the digraph contains a clique of size k or it contains S as an induced subgraph. As an evidence, we prove that for any oriented star S, every oriented graph with sufficiently large chromatic number contains either a transitive tournament of order 3 or S as an induced subdigraph. We then study for which sets $\mathcal{P}$ of orientations of P_4 (the path on four vertices) similar statements hold. We establish some positive and negative results.

7.5.3. *Partitions of digraphs*

We also study partitions of digraphs. Again we are interested in the algorithmic point of view, that is determining the complexity of finding a partition satisfying some properties in a digraph, and the structural point of view, that is finding sufficient conditions to guarantee the existence of such a partition.

For a given 2-partition (V_1, V_2) of the vertices of a (di)graph G, we study in [7] properties of the spanning bipartite subdigraph $B_G(V_1, V_2)$ of G induced by those arcs/edges that have one end in each V_i, $i \in \{1, 2\}$. 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 $\mathcal{NP}$-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 $B_D(V_1, V_2)$ is strongly connected. This holds even if we require the input to be a highly connected Eulerian digraph.

The dichromatic number $\overrightarrow{\chi}(D)$ of a digraph D is the least number k such that the vertex set of D can be partitioned into k parts each of which induces an acyclic subdigraph. Introduced by Neumann-Lara in 1982, this digraph invariant shares many properties with the usual chromatic number of graphs and can be seen as the natural analog of the graph chromatic number. In [14], we study the list dichromatic number of digraphs, giving evidence that this notion generalizes the list chromatic number of graphs. We first prove that the list dichromatic number and the dichromatic number behave the same in many contexts, such as in small digraphs (by proving a directed version of Ohba's Conjecture), tournaments, and random digraphs. We then consider bipartite digraphs, and show that their list dichromatic number can be as large as $\Omega(\log_2 n)$. We finally give a Brooks-type upper bound on the list dichromatic number of digon-free digraphs.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. *COSIT, 2018-2019*

Participants: Mohammed Amine Ait Ouahmed, Ali Al Zoobi, David Coudert, Nicolas Nisse.

Program: Innovation project, Centre de reference "Smart City" of IDEX UCA$^{\mathrm{JEDI}}$.

Project acronym: COSIT

Project title: Convergent Service for Intermodal Transportation

Duration: February 2018 - January 2019

Coordinator: David Coudert

Other partners: UMR ESPACE (France) and SME Instant-System

Abstract: On-demand transportation is a highly flexible mode of transportation that aims at optimizing transit operator service by reducing operational cost while increasing the number of passengers per vehicles, and to increase customer satisfaction. We are considering a service where a fleet of vehicles (minibuses with a limited number of seats) is used to answer user requests. Vehicle trajectories need to be recalculated dynamically as new queries arrive. It is a complementary offer to existing public transport services (bus, tram, metro, etc.) and intermediate in terms of cost and quality of service between public transport and individual transport (taxi, VTC).

In the COSIT project, we studied different aspects of the problem including static and dynamic algorithms for the assignment of users to vehicles, the study of user flows in the city, and the prediction of users queries. We will developed a graphical interface to visualize the evolution of vehicle itineraries as the demands of users arrive.

8.1.2. 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.

8.2. National Initiatives

8.2.1. ANR-17-CE22-0016 MultiMod, 2018-2021

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 2021

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/

8.2.2. PEPS POCODIS

Program PEPS

Project Acronym: POCODIS

Project Title: POndérations et COlorations DIStinguantes de graphes

Duration: Février-Décembre 2018

Coordinator: Julien Bensmail

Others Partners: None

Abstract: This project is about two conjectures on *proper* weightings of a graph, namely the 1-2-3 conjecture and a conjecture about localy irregular decompositions. A weighting is proper whenever the coloring obtained by taking as color for a vertex v the sum of the weight in the neighbourhood of v is a proper coloring, more concisely adjacent vertices have different sums. The main objective of the project is to address several open questions around (i.e. motivated by) these conjectures since we believe that this could lead to significant progress toward the solution of the two main conjectures. To that aim we will make use of several recent and innovative tools and technique in the field, such as the probabilistic method and the polynomial method. In order to use and understand these techniques to their best we shall strengthen several international collaborations with experts from the field.

8.2.3. 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: organisme, labo (pays) 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 is 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.

8.2.4. GDR Actions

8.2.4.1. GDR RSD, ongoing (since 2006)

Members of COATI are involved in the working group RESCOM (*Réseaux de communications*) of GDR RSD, CNRS (http://rescom.asr.cnrs.fr/). In particular, David Coudert is co-chair of this working group since 2017 and has organized its annual summer school, RESCOM'18. Christelle Caillouet was co-chair of the programme committee of the annual conference AlgoTel'18.

We are also involved in the working group "Energy" of GDR RSD. In particular, Frédéric Giroire is co-hair of this working group.

8.2.4.2. 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.

8.2.4.3. GDR MADICS, ongoing (since 2017)

Members of COATI are involed 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/).

The annual summer school RESCOM'18 of GDR RSD has been co-organized with GDR MADICS.

8.3. International Initiatives

8.3.1. IFCAM Program, Applications of Graph homomorphisms

Program: IFCAM 2018-2020 (http://math.iisc.ac.in/~ifcam/)

Project acronym: –

Project title: Applications of graph homomorphisms on graph database

Duration: Janvier 2018 - Décembre 2020

Coordinator: Reza Naserasr (for France) - Sagnik Sen (for India)

Other partners: complete list of participants on the project website.

Abstract: In this project, we are going to study the graph homomorphism problems from a very general point of view. Apart from studying the usual graph homomorphism on undirected graphs, we will study it for different types of graphs such as, signed graphs, oriented graphs, edge-colored graphs, colored mixed graphs etc. We will apply the theories and techniques associated with graph homomorphism to solve practical problems. Our main application oriented work is studying graph homomorphism in the context of graph database, a type of database now a days used even by popular social medias. Graph homomorphism is equivalent to the query evaluation problem in graph database, and thus have exciting intersection with the theory. In our group we have experts of graph homomorphisms as well as graph database making this project a potential case for Indo-French interdisciplinary collaboration. We want to organize a workshop by the end of this project. We also consider a few other application oriented topics as auxiliary research tracks inside this project.

8.3.2. Inria International Labs

Inria Chile

Associate Team involved in the International Lab:

8.3.2.1. ALDYNET

Title: distributed ALgorithms for DYnamic NETworks

International Partner (Institution - Laboratory - Researcher):

Universidad Adolfo Ibañez (Chile) - Facultad de Ingeniería y Ciencias - Karol SUCHAN

Start year: 2016

See also: https://team.inria.fr/coati/projects/aldynet/

This associated team would be the natural continuation of the fruitful EA AlDyNet (2013-2015, https://team.inria.fr/coati/projects/aldynet/)

The main goal of this Associate Team is to design and implement practical algorithms for computing graph structural properties. We will then use these algorithms on a concrete case of study which concerns the transportation network of the Santiago agglomeration. We are both interested in theoretical results concerning the feasibility of computing graph properties, and by their practical implementation (using Sagemath) for our application and their diffusion in the scientific community. There are three main objectives:

1) Design efficient algorithms to compute important graph properties (hyperbolicity, treelength, centrality, treewidth...) in real networks. We are not only interested by the worst-case time-complexity of these algorithms but by their performance in practice.

2) Implement and document our algorithms using the open-source framework SageMath. One advantage of using SageMath is that it has interfaces with other graph libraries (igraph, Boost...) and with Linear Programming solver (GLPK, Cplex...). Moreover, the success of SageMath (which has accumulated thousands of users over the last 10 years) will participate to the diffusion of our algorithms.

3) Apply our algorithms on the Santiago transportation network that have been collected by our Chilean partner during the last year of AlDyNet (2013-2015). Based on the results, propose tools for decision support in designing bus routes, timetables, etc. More precisely, we have collected information about the use of public transport (data of smart cards for automatic fare collection -BIP-, bus routes and bus schedules, etc.), urban infrastructure information, schools' addresses, and approximate locations where students live. We have started to clean and consolidate these data. We will then develop decision support tools, for example, for improving quality education accessibility.

8.3.3. Inria International Partners

8.3.3.1. 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;

RWTH Aachen Univ., Lehrstuhl II für Mathematik (Aachen, Germany), Prof. Arie M.C.A. Koster;

Concordia Univ. (Montréal, Québec, Canada), Prof. Brigitte Jaumard.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

- Jørgen Bang-Jensen

  University of Southern Denmark, Odense, Denmark. June 2018.
- Romuald Elie

  Paris-Est University. February 3 - March 2 2018.

- Gwenael Joret
  Université Libre de Bruxelles, Belgique. March 2018.
- Takako Kodate
  Tokyo's Woman's Christian University. December 15 2017 till March 31 2018.
- Kasper Szabo Lyngsie
  Technical University of Denmark, Lyngby, Denmark. June 27 - July 8.
- Joseph Peters
  Simon Fraser University, Vancouver, BC, Canada. October 1 2017 till March 31 2018.
- Tahiry Razafindralambo
  Université de la Réunion. July 8-28 2018.
- Leonardo Sampaio Rocha
  University Federal de Ceara, Fortaleza, Brazil. July 1 2018 till June 30 2019.
- Karol Suchan
  Universidad Adolfo Ibañez, Santiago, Chile. September 9-23 2018.
- Robert E. Tarjan
  Princetown University, Princetown, NJ, USA. July 2018.
- Min-Li (Joseph) Yu
  University of the Fraser Valley, Abbotsford, BC, Canada. March 1 till April 15 2018.

8.4.2. Visits to International Teams

8.4.2.1. Research Stays Abroad

- Julien Bensmail :
  Northwestern Polytechnical University, Xi'an, China. 22 Avril-13 Mai.
  LaBRI, Bordeaux, France. 23 Mai-12 Juin.
  Technical University of Denmark, Lyngby, Denmark. 22 Août-2 Septembre.
  AGH University, Krakow, Poland. 24 Novembre-2 Décembre.
- David Coudert :
  Universidad Adolfo Ibañez, Santiago, Chile, December 1-14, 2018.
- Frédéric Havet :
  University of Southern Denmark, Odense, Denmark. April 2018.
  Ecole Normale Supérieure de Lyon, France, January and September 2018.
- Nicolas Nisse :
  Xidian University, Xi'an, China, September 1-15, 2018
  Univ. Adolfo Ibañez, Santiago, Chile, December 1-15, 2018

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

- David Coudert :

RESCOM'18 : school of the *pôle ResCom of GDR ASR of CNRS* on "Apprentissage et fouille de données dans les réseaux", Porquerolles, France, June 18-22, 2018. This edition was organized in collaboration with GDR MADICS.

- Frédéric Havet :

  School on Graph Theory (SGT 2018), Séve, France, June 11-15 2018.

  Journées Combinatoire et Algorithmes du Littoral Méditerranéen (JCALM).

- Nicolas Nisse

  GRASTA'18 : 9th workshop on GRAph Searching, Theory & Applications, Berlin, Germany, 24-27 September 2018.

9.1.2. Scientific Events Selection

9.1.2.1. Chair of Conference Program Committees

- Christelle Caillouet :

  Program Committee Chair of AlgoTel'18 (20e Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications): conférence of the *pôle ResCom of GDR ASR of CNRS* Roscoff, France, May 29-June 1, 2018.

9.1.2.2. Member of the Conference Program Committees

- David Coudert :

  ONDM'18: 22nd Conference on Optical Network Design and Management, Dublin, Ireland, May 14-17, 2018.

  IEEE ICC'18 : IEEE International Conference on Communications, Kansas City, MO, USA, May 20-24, 2018.

  SEA'18: 17th International Symposium on Experimental Algorithms, L'Aquila, Italy, June 27-29, 2018.

  IPEC'18: 13th International Symposium on Parameterized and Exact Computation, Helsinki, Finland, August 20–24, 2018.

  IEEE Globecom'18: IEEE Global Communications Conference, Abu Dhabi, UAE, December 9-13, 2018.

- Frédéric Havet :

  10th International Colloquium on Graph Theory (ICGT 2018), Lyon, France, July 9-13, 2018.

  Journées Graphes et Algorithmes (JGA 2018), Grenoble, France, 14-16 November, 2018.

- Nicolas Nisse

  SEA'18: 17th int. Symposium on Experimental Algorithms, L'Aquila, Italy, 27-29 June 2018.

  CoRes'18: 3rd conférence francophone centrée les réseaux et protocoles de communicatio. Roscoff, France, 29 May- 1st June 2018

9.1.3. Journal

9.1.3.1. 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.

David Coudert

Discrete Applied Mathematics (Elsevier); Networks (Wiley).

Frédéric Giroire

Journal of Interconnection Networks (World Scientific).

Frédéric Havet

Discrete Mathematics and Theoretical Computer Science.

Bruce Reed

Journal of Graph Theory, Electronic Journal of Combinatorics.

9.1.3.2. Reviewer - Reviewing Activities

Members of COATI have reviewed numerous manuscripts submitted to international journals, including:

ACM Journal of Experimental Algorithmics, Ad Hoc Networks, Ars Combinatorica, Computer Networks (COMNET) Discrete Applied Mathematics (DAM), Discrete Mathematics, Discrete Mathematics and Theoretical Computer Science (DMTCS), European Journal of Combinatorics, IEEE/OSA Journal of Lightwave Technology (JLT), IEEE/ACM Transactions on Networking (ToN), IEEE Transactions on Parallel and Distributed Systems (TPDS), Journal of Computer and System Sciences (JCSS), Theoretical Computer Science (TCS) Theory of Computing Systems (TOCS), Utilitas Mathematica.

9.1.4. Invited Talks

- Julien Bensmail

  Sequential Metric Dimension (in trees). Graph Theory 2018 (GT'18), Nyborg, Denmark. August 2018.

  Augmenting matchings in trees, via bounded-length augmentations. 3rd International Symposium on the Frontier of Graph Theory, Qinghai Normal University, Xining, China. April 2018.

  Sequential Metric Dimension (in trees). Seminarium Matematyka Dyskretna, AGH university, Kraków, Poland. November 2018.

  A Decompositional Approach to the 1-2-3 Conjecture. Seminar of the Department of Applied Mathematics, Northwestern Polytechnical University, Xi'an, China. May 2018.

  On partitioning graphs into connected subgraphs. Seminar of the School of Mathematical Sciences, Anhui University, Hefei, China. May 2018.

- Christelle Caillouet

  Optimization of mobile sensor coverage with UAVs. Workshop "L'Internet des Objets Industriels" (IIoT) of GDR RSD / ResCom and GDR MACS, Strasbourg, France, July 3, 2018.

- Frédéric Giroire

  Optimization of Network Infrastructures. Seminar of ETIS, University Cergy-Pontoise, France. November 2018.

- Frédéric Havet :

  Bispindles in strongly connected digraphs with large chromatic number. Graph Theory Meeting (GT 2018), Nyborg, Denmark, August 29 - September 1, 2018.

  Trees in tournaments. Journées Combinatoire Graphes et Algorithmes, Lyon, December 10-11, 2018.

- Nicolas Nisse

  When treewidth and treelength are equivalent: Seminar Xidian University, Xi'an, China, September 2018.

- Stéphane Pérennes, Luc Hogie, Michel Syska

  Parallel & Distributed Graph algorithms for large graphs, practical challenges: Atelier de programmation GRAMINEES in ANF APSEM2018 (Apprentissage et sémantique). November 2018.

9.1.5. Leadership within the Scientific Community

David Coudert

Member of the steering committee of *Pôle ResCom du GDR RSD du CNRS* since 2005, and co-chair since June 2017.

Frédéric Giroire

Member of the steering committee of *GT Energy of the GDR RSD du CNRS*.

Frédéric Havet :

Member of the steering committee of *GT Graphes of the GDR IM of CNRS*.

9.1.6. Scientific Expertise

- Jean-Claude Bermond

  Expert for DRTT-MESR Crédit impôt recherche (CIR et agréments).
- Frédéric Havet :

  Expert for ANR and NSERC (Canada)
- Nicolas Nisse

  Expert for ANR

  Expert for ODP (OPUS, Poland) 2018

  Expert for Millennium Science Initiative (Programme de financement chilien) (2018).

  Expert for ESF (European Science Foundation) 2018.

9.1.7. Research Administration

- Jean-Claude Bermond

  Responsible fo the cooperation between Inria and Greece (obtention of join grants and of 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;

  Member of "Comité de Sélection" MCF 0403, Grenoble INP, 2018.
- David Coudert :

  Nominated member for Inria at the doctoral school STIC since September 2017;

  Member of the "Comité de Suivi Doctoral" of Inria (since 2009);

  Member of the scientific council of Academy RISE (Networks, Information, Digital Society) of UCA$^{\text{JEDI}}$ till January 2018;

  Nominated member for Inria at the steering committee of Academy RISE (Networks, Information, Digital Society) of UCA$^{\text{JEDI}}$ and EUR DS4H since Février 2018;

  Member of "Comité de Sélection" 4109 - 0074 - PR 27 STS, Université d'Avignon et des Pays de Vaucluse, 2018.

  Member of "Comité de Sélection" 27 Pr 519, Université Nice - Sophia Antipolis, 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.
- Nicolas Nisse

  Elected member of Comité de Centre, Inria Sophia Antipolis since 2016

  Membre du CS Académie 1 UCA
- Michel Syska

  Elected member of CPRH (Comité Permanent de Ressources Humaines) University of Nice-Sophia Antipolis;

9.2. Teaching - Supervision - Juries

9.2.1. Teaching responsibilities

- Julien Bensmail

  In charge of the internships of first year students of QLIO département of IUT Nice Côte d'Azur.
- Joanna Moulierac

  "Directrice d'études" for the 1st-year students du 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).

9.2.2. Teaching

- Julien Bensmail

  Sécurité des systèmes d'information, 36h ETD, Level LP, IUT Nice Côte d'Azur, UNS;

  Recherche opérationnelle, 82h ETD, Level L2, IUT Nice Côte d'Azur, UNS;

  Systèmes de gestion de bases de données, 86h ETD, Level L2, IUT Nice Côte d'Azur, UNS.
- Christelle Caillouet

  Programmation Orientée Objet, 96h ETD, Level L1, IUT Nice Côte d'Azur, UNS;
- David Coudert

  Algorithms for Telecoms, 32h ETD, stream UbiNet of Master 2 IFI and Master RIF, UNS.
- Frédéric Giroire

  Algorithmics of Telecommunications, 18h ETD, stream UbiNet of Master 2 IFI, UNS;

  Data Mining for Networks, 18h ETD, stream UbiNet of Master 2 IFI, UNS;

  Introduction to probability and statistics, 15h ETD, International Master 1, UNS.
- Joanna Moulierac

  Introduction à l'algorithmique, 30h ETD, Level L1, IUT Nice Côte d'Azur, UNS;

  Introduction aux Réseaux, 60h ETD, Level L1, IUT Nice Côte d'Azur, UNS;

  Programmation répartie, 40h ETD, Level L1, IUT Nice Côte d'Azur, UNS.

  Réseaux avancés, 60h ETD, Level L2, IUT Nice Côte d'Azur, UNS;

  Compléments d'algorithmique, 30h ETD, Level L2, IUT Nice Côte d'Azur, UNS.
- Nicolas Nisse

  Graph Algorithms and Combinatorial Optimization, 18 ETD, Master 2, parcours Ubinet master IFI, UNS;

  Informatique théorique, 24 ETD, MPSI, classe préparatoire, CIV, Valbonne;

- Stéphane Pérennes

  Java pour le Calcul Ditribué et Concurrent, 60 h ETD Level : Master MIAGE Univ. Nice Côte d'Azur, UNS;

- Michel Syska

  Operating Systems: Advanced Programming, 28h ETD, Level L2, IUT Nice Côte d'Azur, UNS;

  Data Structures and Algorithms, 40h ETD, Level L2, IUT Nice Côte d'Azur, UNS;

  Algorithmics, 52h ETD, Level L2, IUT Nice Côte d'Azur, UNS;

  Distributed Programming, 58h ETD, Level L2, IUT Nice Côte d'Azur, UNS;

9.2.3. Supervision

9.2.3.1. PhD thesis

PhD: William Lochet, *Substructures in digraphs* [2], Université Côte d'Azur, July 19, 2018. Co-supervisors: Frédéric Havet and Stéphan Thomassé (ÉNS Lyon).

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: Brieuc Berruet, *Application des techniques de Machine Learning à la géolocalisation des objets connectés dans le contexte de la future 5G*, doctorale school SPIM, Université de Belfort Franche Comté, since November 2016. Supervisor: Alexandre Caminada and Oumaya Baala (Orange).

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.

PhD in progress: Adrien Gausseran, *Optimization Algorithms for Network Slicing for 5G*, since October 2018. Supervisors: Joanna Moulierac and Nicolas Nisse.

PhD in progress: 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, since September 2016. Supervisor: Alexandre Caminada and Fouad Hadjselem (Orange).

PhD in progress: Fionn McInerney, *Combinatorial Games in Graphs*, since October 2016. Supervisor: Nicolas Nisse.

PhD in progress: Andrea Tomassilli, *Diffusion of information on large dynamic graphs*, since October 2016. Supervisors: Stéphane Pérennes and Frédéric Giroire.

PhD in progress: Thibaud Trolliet, *Exploring Trust on Twitter*, since October 2017. Co-supervisors: Arnaud Legout (DIANA) and Frédéric Giroire.

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).

9.2.3.2. Internships

- Eleni Batziou

  Date: from November 2017 until May 2018

  Institution: Master 2, National Technical University of Athens (Greece)

  Supervisors: David Coudert and Nicolas Nisse

  Subject: Enhancing urban mobility with shared on-demand services

- Florent Cabret

  Date: from April 2018 until June 2018

  Institution: DUT 2, IUT, Université Nice Sophia Antipolis

Supervisors: Luc Hogie and Michel Syska

Subject: Evaluation of Jmaxgraph, a distributed computing framework on large graphs

- Théo Frasquet

  Date: from July 2018 until August 2018

  Institution: SI4, Polytech'Nice, France

  Supervisors: David Coudert

  Subject: Decomposing a digraph into k-strongly connected components

- Adrien Gausseran

  Date: from March 2018 until september 2018

  Institution: Master 2 RIF, Université Nice Sophia Antipolis

  Supervisors: Frédéric Giroire and Joanna Moulierac

  Subject: Optimization Algorithms for Network Slicing for 5G

- Thibault Hilaire

  Date: from June-July 2018

  Institution: L3, ENS Saclay

  Supervisor: Nicolas Nisse

  Subject: Polynomial algorithm for connected graph searching.

- Allen Passos Ibiapina

  Date: from October 15 until December 14 2018

  Institution: Master 2, UFC Fortaleza, Brazil

  Supervisor: Frédéric Havet

  Subject: Constrained ear decompositions in graphs and digraphs.

- Badr Jouhar

  Date: from March 2018 until August 2018

  Institution: stream UbiNet of Master 2 IFI

  Supervisors: Frédéric Giroire and Andrea Tomassilli

  Subject: Joint optimization of network and data centers

- Thi-Viet-Ha Nguyen

  Date: from January 2018 until June 2018

  Institution: Master 2, ENS Lyon.

  Supervisors: Frédéric Havet, Dorian Mazauric (ABS) and Rémi Watrigant (ENS Lyon)

  Subject: Overlaying a hypergraph by graph families with bonded maximum degree.

- Meghana M. Reddy

  Date: from May 2018 until August 2018

  Institution: Master at IIIT-Bangalore, India

  Supervisors: David Coudert

  Subject: implementation of a linear time algorithms for decomposing a graph into 3-connected components in Sagemath. In the context of the Google Summer of Code (GSoC).

- Alexandre Simon

  Date: from June-July 2018

  Institution: L3, INSA Lyon

Supervisor: Nicolas Nisse

Subject: Treelength des graphes planaires.

- Sai Harsh Tondomker

  Date: from May 2018 until August 2018

  Institution: Master at IIIT-Hyderabad, India

  Supervisors: David Coudert

  Subject: implementation of algorithms for decomposing a graph into 3-connected components and organizing these components as a SPQR-tree in Sagemath. In the context of the Google Summer of Code (GSoC).

- Xuchun Zhang

  Date: from July 2018 until September 2018

  Institution: Master 1 MAM, Université de Nice Sophia Antipolis

  Supervisors: Jean-Baptiste Caillau, Enzo Giusti (Oui!Greens startup), Dorian Mazauric and Joanna Moulierac

  Subject: Optimal Assignment Problem for Oui!Greens

- Yin Zhuochao

  Date: from March 2018 until August 2018

  Institution: stream UbiNet of Master 2 IFI, UNS

  Supervisors: David Coudert and Nicolas Nisse

  Subject: On the pickup-and-delivery problem with time window

- Mykhailo Zima

  Date: from March 2018 until August 2018

  Institution: stream UbiNet of Master 2 IFI, UNS

  Supervisors: David Coudert and Nicolas Nisse

  Subject: Routing in multimodal networks with bicycles

9.2.4. Juries

- Jean-Claude Bermond :

  Member of the HDR jury of Ignasi Sau Valls, LIRMM, Montpellier, June 25 2018;

  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 the PhD jury of Alassanne Samba, IMT Atlantique, October 29, 2018;

- David Coudert :

  President of the PhD jury of Jianding Guo, Université de Technologie de Belfort-Montbéliard, June 6, 2018;

  President of the PhD jury of Mohammed Amine Ait Ouahmed, Université d'Avignon et des Pays de Vaucluse, October 15, 2018;

  Referee and member of HDR committee of Fen Zhou, Université d'Avignon et des Pays de Vaucluse, September 28, 2018;

  External referee in the PhD thesis monitoring committee of Karyna Gogunska, Université Côte d'Azur, March 19, 2018;

- Frédéric Giroire :

Invited member of the PhD jury of Marwa Dammak, ENSEA, Cergy-Pontoise, November 20, 2018;

- Frédéric Havet :

  Referee and member of PhD committee of Antoine Dailly, Université Lyon 1, September 2018.

  Referee and member of PhD committee of Tien-Nam Le, ENS Lyon, November 2018.

  Member of PhD committee of Leo Planche, Université Paris Descartes, November 2018.

  Referee and member of HDR committee of Laurent Beaudou, Université Clermont-Auvergne, December 2018.

  Referee and member of PhD committee of Tilde Nielsen, Southern Denmark University, Odense, Denmark, December 2018.

9.3. Popularization

9.3.1. Internal or external Inria responsibilities

- Frédéric Havet :

  Vice-president and member of the scientific committee of the association Institut Esope 21 (http://www.esope21.eu).

- Nicolas Nisse:

  Membre de Mastic (Médiation et Animation scientifiques Inria Sophia Antipolis - Méditerranée).

9.3.2. Education

- Frédéric Havet, Joanna Moulierac and Nicolas Nisse : Participation to Galejade projet.

  Design of pedagogical resources introducing graphs and algorithms to primary school students.

  Training of primary school teachers, ESPE April 9-10 2018.

9.3.3. Interventions

- Fête de la Science (Frédéric Havet, Nicolas Nisse, Fionn Mc Inerney, Ali Al Zoobi)

  Journée portes ouvertes, Inria Sophia Antipolis, Sunday October 7, 2018.

  Palais des Congrès de Juan-Les-Pins, October 20-21, 2018.

  Collège de Vinon-sur-Verdon (83), October 9-12, 2018.

- Frédéric Havet, Joanna Moulierac, and Nicolas Nisse

  Participation to the supervision of the internships of 12 pupils of 3eme, December 17-21, 2018.

- Frédéric Havet

  L'élégance des Mathématiques. Conference at Lycée Janetti, St Maximin, February 16, 2018. Audience: 3 classes (1e S and ES).

  La magie des graphes et du binaire. Conference at collège Alphonse Daudet, Nice, April 17, 2018. Audience: 2 classes of 4e and 1 of 6e.

  L'élégance des mathématiques. General audience conference, Rians, Var, France, April 28, 2018.

- Nicolas Nisse

  Training and awareness of school teachers (Cycle 2, CP-CE2) to scientific mediation. Le Cannet, November 21 and Mandelieu, November 28, 2018.

Training and awareness of future teachers to scientific mediation, Ecole Supérieure du Professorat et de l'Education (ESPE, ex IUFM) of Académie de Nice. March 19-20 and April 9-10, 2018.

Liens entre médiation numérique et recherche, Maison méditerranéenne des Sciences de l'homme (MMSH), Aix en Provence, March 14, 2018.

Mediation for the Master en science de l'éducation, Nice, October 18, 2018.

- Fionn Mc Inerney :

  Presentation at Collège Victor Hugo, Nevers, France, March 23, 2018.

  Participation in the day "*L'informatique, c'est pas génétique, filles ou garçons, les clics sont identiques!*", Lycée Raoul Follereau, Nevers, France, March 22, 2018.

  Presentation at Ecole Primaire Romain Rolland, Varennes-Vauzelles, France, March 21, 2018.

  Supervised internship of a school girl in 2nd, Inria Sophia-Antipolis - Méditerranée, France, June 18-22, 2018.

- Michel Syska :

  Organisation and supervision of the code competition "*La nuit de l'info*", December 6-7, 2018.

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Publications of the year

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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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Computer Science and Digital Science:

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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
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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]

Faculty Members

Florent Berthelin [Univ de Nice - Sophia Antipolis, Associate Professor, HDR]
Konstantin Brenner [Univ de Nice - Sophia Antipolis, Associate Professor]
Stéphane Junca [Univ de Nice - Sophia Antipolis, Associate Professor, HDR]
Stella Krell [Univ de Nice - Sophia Antipolis, Associate Professor]
Roland Masson [Univ de Nice - Sophia Antipolis, Professor, HDR]

PhD Students

Kevin Atsou [Inria]
Laurence Beaude [Univ. Côte d'Azur, until Dec. 2018]
Nadine Dirani [Inria, from Nov 2018]
Billel Guelmame [Univ. Côte d'Azur]
Giulia Lissoni [Univ. Côte d'Azur]
Julie Llobell [Univ. Côte d'Azur, until Sep 2018]
Leo Vivion [Univ. Côte d'Azur]

Post-Doctoral Fellows

Joubine Aghili [Inria]
Laurence Beaude [Univ de Nice - Sophia Antipolis, since Dec. 2018]
Nabil Birgle [Inria, until Mar 2018]

Administrative Assistant

Marie-Cécile Lafont [Inria]

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
  - Finite Volume Schemes for Conservation Laws
  - Well-Balanced and Asymptotic-Preserving Methods
- Modeling and Analysis of PDEs
  - Kinetic equations and hyperbolic systems
  - PDEs in random media
  - Interface problems

4. Application Domains

4.1. Multiphase flows in porous media

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.

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. Biological degradation, biofilms formation and algae proliferation

Members of the team have started an original research program devoted to biofilms formation and algae proliferation. We started working on this subject through a collaboration with Roberto Natalini and a group of experts in Firenze interested in preventing damages on historical monuments. It is also motivated by Ostreopsis proliferation in the Mediterranean Sea. The multidisciplinary character of this research relies on discussions with researchers of the Oceanography Laboratory in Villefranche-sur-Mer, a leading marine research unit, and the Inria team BIOCORE, led by J-L Gouzé. This research was supported by a ANR-project, led by M. Ribot, and it was the main topic of the PhD thesis of B. Polizzi. It continues through a collaboration with INRA (Jouy-en-Josas), dealing with the modeling of flows in the gut and with the aim of describing the formation and stability of mucus layers.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

- Stéphane Junca received an invitation at the LMA (Laboratory of Mechanics and Acoustics, Marseille, France), 6 months, from February to July 2018.
- Florent Berthelin had a Inria delegation from January to June 2018 to work with teams ACUMES and TOSCA. In particular he worked with P. Goatin on models for traffic flows.

6. New Software and Platforms

6.1. 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

6.2. 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/

6.3. 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

6.4. 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-Zotto
- URL: https://wikis.univ-lille1.fr/painleve/ns2ddv

6.5. 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

6.6. 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/

7. New Results

7.1. A few words on the results of the year

- Face based discretization of two-phase Darcy flows in fractured porous medium with matrix fracture interface local nonlinear solver. Application to the simulation of the desaturation by suction in nuclear waster storages [20], [17].
- Convergence analysis of the gradient discretization of a two-phase Darcy flow model in fractured porous media with nonlinear transmission conditions [10].
- Numerical method for non-isothermal compositional Darcy flows combining face based and nodal based discretizations on hybrid meshes [22].
- We introduced and analyzed a novel Hybrid High-Order method for the steady incompressible Navier-Stokes equations. We showed under general assumptions the existence of a discrete solution, we proved convergence of the sequence of discrete solutions to minimal regularity exact solutions for general data and we proved optimal convergence rates for the velocity and the pressure [9].
- We proposed a nonlinear Discrete Duality Finite Volume scheme to approximate the solutions of drift diffusion equations. The scheme is built to preserve at the discrete level even on severely distorted meshes the energy / energy dissipation relation [7].
- We studied a Discrete Duality Finite Volume scheme for the unsteady incompressible Navier-Stokes problem with outflow boundary conditions [24].
- We introduced a new non-overlapping optimized Schwarz method for anisotropic diffusion problems. We studied the new method at the continuous level, proved its convergence using energy estimates, and also derived convergence factors to determine the optimal choice of parameters in the transmission conditions, and presented a discretization of the algorithm using discrete duality finite volumes [23].
- We consider a non-local traffic model involving a convolution product. Unlike other studies, the considered kernel is discontinuous on $\mathbb{R}$. We prove Sobolev estimates and prove the convergence of approximate solutions solving a viscous and regularized non-local equation. It leads to weak, $C([0,T],L^2(\mathbb{R}))$ and $C([0,T],L^2(\mathbb{R}))$, and smooth, $W^{2,2N}([0,T]\times\mathbb{R})$ and $W^{2,2N}([0,T]\times\mathbb{R})$, solutions for the non-local traffic model [4].
- We proposed a new closure for Geometrical Shock Dynamics taking into account the effect of transverse Mach variation for the fast propagation of shocks. The model has been tested using a Lagrangian solver [28].
- We proposed a new explicit pseudo-energy conserving time-integration scheme for separated Hamiltonian systems. We proved the second-order accuracy and conditional stability of the scheme. In addition, the scheme can be adapted into an asynchronous version while retaining its properties, which is adapted to slow-fast splitting strategies [14].
- We proposed a well-balanced scheme for the modified Lifschitz-Slyozov-Wagner system with diffusion, which models Ostwald ripening. The scheme outperforms a standard advection-diffusion scheme for long time dynamics [25].
- We investigate several models describing interacting particles, either motivated form physics or population dynamics.

8. Bilateral Contracts and Grants with Industry

8.1. 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.

9. Partnerships and Cooperations

9.1. Regional Initiatives

The team is involved in the IDEX project UCA-JEDI.

- PhD of Laurence Beaude (october 2015 - december 2018) co-funded by BRGM and Region PACA and dealing with the simulation of geothermal systems, supervised by Roland Masson, Konstantin Brenner from LJAD-Inria and by Simon Lopez, Farid Smai from BRGM.

9.2. National Initiatives

9.2.1. 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.

9.2.2. 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.

9.3. International Research Visitors

9.3.1. Visits of International Scientists

- Martin Gander (Genève), UCA invited professor 18/06 – 18/07, collaboration on reduced fracture models and DDM for coupling liquid gas Darcy and free gas flows. Co-organisation with Martin Gander, Stella Krell, Victorita Dolean, Roland Masson of the summer school on DDM: 19,20,21/06 https://math.unice.fr/~krell/ColloqueDD/index.php
- Felix Kwok (Hong Kong): 11/06 – 25/06 on nonlinear domain decomposition for the Richards equation.

10. Dissemination

10.1. Promoting Scientific Activities

We do not keep track of such activities.

10.1.1. Journal

10.1.1.1. Member of the Editorial Boards

T. Goudon is the founding editor and co-Editor in chief of SMAI Journal of Computational Mathematics.

10.1.2. Scientific Expertise

Thierry Goudon is member of the scientific board of CIRM and of FSMP.

10.1.3. Research Administration

- Roland Masson is the head of the team PDE and Numerical Analysis of the laboratory J.A. Dieudonné.
- Roland Masson is a member of the scientific committee of CERFACS.
- Roland Masson is scientific advisor at the scientific direction of Total.
- Thierry Goudon is member of the Evaluation Committee of Inria.
- Thierry Goudon is Scientific Officer at the French Ministry of Education and Research.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Members of the team are faculties of Université Côte d'Azur and they teach in all degrees of the University.

Florent Berthelin, Master 2 Mathématiques fondamentales, Université Côte d'Azur.

Florent Berthelin, Chair of the Master 2 Mathématiques fondamentales, Université Côte d'Azur.

Florent Berthelin, Analysis, L2, Université Nice Sophia Antipolis, 60h.

Thierry Goudon is President of the national competition to hire teachers (agregation de mathematiques).

Stella Krell, Linear Algebra, Master 1 enseignement, ESPE Nice, 23h.

Stella Krell, Didactics of mathematics, Master 1 EEF, Université Nice Sophia Antipolis, 43h.

Stella Krell, Theses and placement supervision, Master 2 EEF, Université Nice Sophia Antipolis, 12h.

Stella Krell, Preparation to mathematics agrégation interne, Université Nice Sophia Antipolis, 18h.

Stella Krell, Intervention, Master 2 enseignement, Université Nice Sophia Antipolis, 3h.

Stéphane Junca, Hyperbolic PDEs and mechanics, Master 2 MPA, Université Nice Sophia Antipolis, 36h.

Roland Masson, Numerical methods for PDEs, Master 2 MPA, Université Nice Sophia Antipolis, 36h.

Laurent Monasse, Introduction to dynamical systems, Ecole des Ponts ParisTech, 10h.

Laurent Monasse, Numerical analysis, L3, Université Nice Sophia Antipolis, 40h.

10.2.2. Supervision

PhD: Julie Llobell, Numerical schemes on staggered grids for conservation laws, Univ Nice Sophia Antipolis, 24 October 2018, Thierry Goudon and Sebastian Minjeaud

PhD: Laurence Beaude, Discretization of high energy geothermal systems in faulted porous media, Univ Nice Sophia Antipolis, 10 December 2018, Roland Masson, Konstantin Brenner, Simon Lopez and Farid Smai

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: Giulia Lissonni, DDFV methods and domain decomposition: applications in fluid mechanics, 01 September 2016, Stella Krell and Thierry Goudon.

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.

10.2.3. Juries

- Roland Masson:
  - Referee of the PhD of Florent Chave, 12/11/2018, Montpellier, “Méthodes Hybrides d’Ordre Elevé pour les problèmes d’interface”.
  - Referee of the PhD of El Houssaine Quenjel, 15/12/2018, Meknes, Maroc “Volumes finis/Eléments finis pour des écoulements diphasiques compressibles en milieux poreux hétérogènes et anisotropes”.
  - Referee of the PhD of Thibaut Lunet, 09/01/2018, Toulouse, “Stratégies de parallélisation espace-temps pour la simulation numérique des écoulements turbulents”.

11. Bibliography

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[28] J. RIDOUX, N. LARDJANE, L. MONASSE, F. COULOUVRAT.*Beyond the limitation of Geometrical Shock Dynamics for diffraction over wedges*, September 2018, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01880213

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
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Other Research Topics and Application Domains:

B6.2. - Network technologies
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B9.10. - Privacy

1. Team, Visitors, External Collaborators

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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. Awards

Karyna Gogunska's paper on "On the Cost of Measuring Traffic in a Virtualized Environment" [20] got the Best Student Paper Award at the IEEE Cloudnet 2018 in Japan.

4.1.2. ANR JCJC DET4ALL

Damien Saucez's project titled DET4ALL was accepted in the JCJC programme (2019-2021). The goal of this project is to apply the concept of network programmability to the world of industrial communicating systems.

4.1.3. ACM SIGCOMM Artefact Evaluation Committee

Our team organized the Reproducibility'17@SIGCOMM workshop (proposed and co-chaired by Damien Saucez). Based on the results of the workshop, we put in place the ACM SIGCOMM *Artefact Evaluation Committee* (AEC). The role of the AEC is to assess the reproducibility level of papers accepted to any ACM SIGCOMM sponsored conferences and journals during the year 2018. The reproducibility quality is awarded by ACM reproducibility badges [0]. Authors volunteered to be evaluated and we received 33 demands. In parallel to this effort, the organisers of the ACM CoNEXT'18 conference asked us to assess the reproducibility level of CoNEXT papers in 2018 as part of the publication process. We accepted and out of the 32 CoNEXT papers, 14 volunteered to be evaluated and 12 received an award. The result is that ACM CoNEXT'18 is the first ever ACM SIGCOMM sponsored conference to award reproducibility. Based on that the main ACM SIGCOMM conference has decided to make a trial in 2019 and integrate reproducibility evaluation as part of the publication process for 2019.

5. New Software and Platforms

5.1. ACQUAmobile

KEYWORDS: Android - Internet access - Performance measure - Quality of Experience

[0] http://www.acm.org/publications/policies/artifact-review-badging

FUNCTIONAL DESCRIPTION: ACQUA is an Application for prediCting QUality of Experience (QoE) at Internet Access. 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 [22], [21] 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.

- 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 13th July 2018 we have 84 000 downloads in Google Play, an average score of 4.4/5, 30 000 active users, 850 millions measured signals.

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. OpenLISP

KEYWORDS: LISP - Routing - Control-plane
FUNCTIONAL DESCRIPTION: Among many options tackling the scalability issues of the current Internet routing architecture, the Locator/Identifier Separation Protocol (LISP) appears as a viable solution. LISP improves a network's scalability, flexibility, and traffic engineering, enabling mobility with limited overhead. As for any new technology, implementation and deployment are essential to gather and master the real benefits that it provides. We propose a complete open source implementation of the LISP control plane. Our implementation is deployed in the worldwide LISP Beta Network and the French LISP-Lab testbed, and includes the key standardized control plane features. Our control plane software is the companion of the existing OpenLISP dataplane implementation, allowing the deployment of a fully functional open source LISP network compatible with any implementation respecting the standards.

- Contact: Damien Saucez
- URL: http://www.openlisp.org/downloads

5.4. 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
- Contact: Thierry Parmentelat
- URL: http://nepi-ng.inria.fr

5.5. Platforms

5.5.1. Reproducible research Lab - R2lab

Scientific evaluation of network protocols requires for experiments to be reproducible before they can be deemed valid. This is particularly difficult to obtain in the wireless networking area, where characteristics of wireless channels are known to be variable, unpredictable and hardly controllable.

The R2lab wireless testbed is built around an isolated and anechoic chamber, featuring RF absorbers preventing radio waves reflections and a Faraday cage blocking external interferences. This lab, named R2lab, represents an ideal environment for experiments reproducibility.

It represents a perfect facility for making wireless experiments reproducible. It has been operated for 3 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. This testbed is for the long-haul, and is scheduled to remain operational until at least 2020.

During 2018, our focus regarding R2lab has been set on enhancing the `nepi-ng` software toolkit, extending the set of tutorials and on deploying more network devices such as LoRa and Ettus USRP devices. The chamber now offers 19 USRP devices, as well as a couple of lime-sdr devices and a couple of E3372 LTE dongles. Moreover, two remotely controllable iphone are available. All these additions aim at widening even further the spectrum of experiments that the testbed can support.

Access to R2lab is open 24/7. We currently have around 150 active users from all over the world among them 45 new users registered in 2018. 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. An Intelligent Sampling Framework for Controlled Experimentation and QoE Modeling

Participants: Muhammad Jawad Khokhar, Nawfal Abbasi Saber, Thierry Spetebroot, Chadi Barakat.

For internet applications, measuring, modeling and predicting the quality experienced by end users as a function of network conditions is challenging. A common approach for building application specific Quality of Experience (QoE) models is to rely on controlled experimentation. For accurate QoE modeling, this approach can result in a large number of experiments to carry out because of the multiplicity of the network features, their large span (e.g., bandwidth, delay) and the time needed to setup the experiments themselves. However, most often, the space of network features in which experimentations are carried out shows a high degree of similarity in the training labels of QoE. This similarity, difficult to predict beforehand, amplifies the training cost with little or no improvement in QoE modeling accuracy. So, in this work, funded by ANR BottleNet and IPL BetterNet, we aim to exploit this similarity, and propose a methodology based on active learning, to sample the experimental space intelligently, so that the training cost of experimentation is reduced. We validate our approach for the case of YouTube video streaming QoE modeling from out-of-band network performance measurements, and perform a rigorous analysis of our approach to quantify the gain of active sampling over uniform sampling. We first develop the methodology for an offline case where a pool of scenarios to experiment with is available. Then, we present an online variant that does not require a pool of scenarios, but finds automatically and in an online manner the best scenarios to experiment with. This latter variant outperforms the offline variant both in terms of accuracy and computation complexity. It is published in [22]. The overall methodology and its specification to both the offline and the online cases are published in [15].

6.1.2. A Methodology for Performance Benchmarking of Mobile Networks for Internet Video Streaming

Participants: Muhammad Khokhar, Thierry Spetebroot, Chadi Barakat.

Video streaming is a dominant contributor to the global Internet traffic. Consequently, gauging network performance w.r.t. the video Quality of Experience (QoE) is of paramount importance to both telecom operators and regulators. Modern video streaming systems, e.g. YouTube, have huge catalogs of billions of different videos that vary significantly in content type. Owing to this difference, the QoE of different videos as perceived by end users can vary for the same network Quality of Service (QoS). In this work, funded by ANR BottleNet and IPL BetterNet, we present a methodology for benchmarking performance of mobile operators w.r.t Internet video that considers this variation in QoE. We take a data-driven approach to build a predictive model using supervised machine learning (ML) that takes into account a wide range of videos and network conditions. To that end, we first build and analyze a large catalog of YouTube videos. We then propose and demonstrate a framework of controlled experimentation based on active learning to build the training data for the targeted ML model. Using this model, we then devise YouScore, an estimate of the percentage of YouTube videos that may play out smoothly under a given network condition. Finally, to demonstrate the benchmarking utility of YouScore, we apply it on an open dataset of real user mobile network measurements to compare performance of mobile operators for video streaming. This work is published in [21] and its extension to more sophisticated QoE models that consider other factors than interruptions is ongoing.

6.1.3. On the Cost of Measuring Traffic in a Virtualized Environment

Participants: Karyna Gogunska, Chadi Barakat.

The current trend in application development and deployment is to package applications and services within containers or virtual machines. This results in a blend of virtual and physical resources with complex network interconnection schemas mixing virtual and physical switches along with specific protocols to build virtual networks spanning over several servers. While the complexity of this setup is hidden by private/public cloud management solutions, e.g. OpenStack, this new environment constitutes a challenge when it comes to monitor and debug performance related issues. In this work carried out in collaboration with the Signet team of I3S with the support of the UCN@Sophia Labex, we introduce the problem of measuring traffic in a virtualized environment and focus on one typical scenario, namely virtual machines interconnected with a virtual switch. For this scenario, we assess the cost of continuously measuring the network traffic activity of the machines. Specifically, we seek to estimate the competition that exists to access the physical resources (e.g., CPU) of the physical server between the measurement task and the legacy application activity. This work was published in the IEEE Cloudnet 2018 conference [20] where it was awarded the Best Student Award. The collaboration with I3S is pursued towards a controlled configuration and deployment of measurements tools in a way to limit their impact on the legacy data plane of virtualized environments.

6.1.4. 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 2019. 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) are following the Digital Startup training from Inria/EM Lyon. This training helped formalize and improve the product market fit and the business model. We are also preparing the iLab competition.

The business model of ElectroSmart is to create an affiliation strategy to help companies selling product to reduce EMF exposure to find potential clients. Indeed, ElectroSmart users represent a highly qualified database of people concerned by EMF exposure. This database is invaluable to these companies as it is an emerging market and it is hard for these companies to make efficient marketing campaigns. The benefit for the ElectroSmart users is to have access to negotiated and validated solutions to reduce their EMF exposure. We are currently validating this market. We started our first affiliation campaign in December 2018 with the Spartan company that sells radiation blocking boxers. We already have two more planned campaigns in 2019, with a goal of 5 campaigns in 2019.

6.2. Open Network Architecture

6.2.1. Controller load in SDN networks

Participant: Damien Saucez.

In OpenFlow, a centralized programmable controller installs forwarding rules into switches to implement policies. However, this flexibility comes at the expense of extra overhead in signalling and number of rules to install. The community considered that it was essential to install all rules and strictly respect routing requirements, hence working on making extra fast and large memory switches and controllers. Instead we took an opposite direction and came with a new vision that leverages the SDN concept and considers the network as a black box where tailored rules should be used only for network traffic that really matters while for the rest a good-enough (sub-optimal but cheap) default behaviour should be enough. In the past, we applied this vision to limit the needed memory on network switches in [7]. Lately, we proposed solutions to limit the number of exchanged messages between the switches and the controller. More precisely, in [19], we developed a distributed sampling adaptive algorithm that allows switches to locally decide if they can contact the controller or if instead they should make their own decision locally. Numerical evaluation and emulation in Mininet demonstrate the benefit of the approach. The results were published in IEEE INFOCOM 2018, April 2018.

6.2.2. Resilient Service Function Chains in virtual networks

Participants: Ghada Moualla, Damien Saucez, Thierry Turletti.

Virtualization of network functions has led to the whole new concept of Service Function Chaining (SFC) that aims at building on the fly network services by deploying them in the Cloud. A vast literature proposes techniques to build virtual service chains and map them into physical infrastructure to maximize performance while reducing costs. However, the resiliency of chains is not investigated. However, such service chains are used for critical services like e-health or autonomous transportation systems and thus require high availability. Respecting some availability level is hard in general, but it becomes even harder if the operator of the service is not aware of the physical infrastructure that will support the service, which is the case when SFCs are deployed in multi-tenant data centers. With this work, we propose algorithms to solve the placement of topology-oblivious SFC demands such that placed SFCs respect availability constraints imposed by the tenant. In order to be practically usable, i.e., without knowledge on future demands, we leverage the structural properties of multi-tier data-center topologies such as Fat-Tree or Sine and Leaf topologies to build fast yet efficient online algorithms. We explored two radically different approaches: a deterministic one and a stochastic one and results show that both can be used in very large scale data-centers (i.e., 40k nodes or more) and our simulation results show that the algorithms are able to satisfy as many demands as possible by spreading the load between the replicas and enhancing the network resources utilization [23].

Initial results were published in IEEE International Conference on Cloud Networking 2018, October 2018.

6.2.3. Privacy preserving distributed services

Participants: Damien Saucez, Yevhenii Semenko, Alberto Zirondelli.

Blockchains are expected to help in reducing dependency on centralized platforms (e.g., Uber, Airbnb). With this internship, we have designed a protocol to make a fully distributed, secured, and privacy protecting taxi service – a distributed version of Uber. The analytical study shows that in such system the privacy protection comes with an important overhead in network communications which raises reasonable doubt on the feasibility of actually using fully distributed platforms in an “internet-scale environment” even though our implementation on Android phones shows that it is technically possible to build such systems. This work is done in collaboration with the GREDEG [0], that is evaluating the incentives for users to move to fully distributed platforms that are privacy preserving but that require the users to play an active role in the system.

6.2.4. P4Bricks: Enabling multiprocessing using Linker-based network data plane architecture

Participants: Hardik Soni, Thierry Turletti, Walid Dabbous.

[0] Groupe de Recherche en Droit, Economie, Gestion, a research center related to both the CNRS and the University of Nice-Sophia Antipolis and dealing with economic, managerial and legal aspects. See http://unice.fr/laboratoires/gredeg in French.

Packet-level programming languages such as P4 usually require to describe all packet processing functionalities for a given programmable network device within a single program. However, this approach monopolizes the device by a single large network application program, which prevents possible addition of new functionalities by other independently written network applications. We propose P4Bricks, a system which aims to deploy and execute multiple independently developed and compiled P4 programs on the same reconfigurable hardware device. P4Bricks is based on a Linker component that merges the programmable parsers/deparsers and restructures the logical pipeline of P4 programs by refactoring, decomposing and scheduling the pipelines' tables. It merges P4 programs according to packet processing semantics (parallel or sequential) specified by the network operator and runs the programs on the stages of the same hardware pipeline, thereby enabling multiprocessing. We present the initial design of our system with an ongoing implementation and study P4 language's fundamental constructs facilitating merging of independently written programs [34], [12].

6.2.5. Applications in ITS Message Dissemination

Participants: Thierry Turletti.

We build upon our prior work on D2-ITS, a flexible and extensible framework to dynamically distribute network control to enable message dissemination in Intelligent Transport Systems (ITS), and extend it with handover and load balancing capabilities. More specifically, D2-ITS' new handover feature allows a controller to automatically "delegate" control of a vehicle to another controller as the vehicle moves. Control delegation can also be used as a way to balance load among controllers and ensure that required application quality of service is maintained. We showcase D2-ITS' handover and load-balancing features using the Mininet-Wifi network simulator/emulator. Our preliminary experiments show D2-ITS' ability to seamlessly handover control of vehicles as they move. This work has been presented at the 27th International Conference on Computer Communications and Networks (ICCCN 2018), Jul 2018, Hangzhou, China [17].

6.2.6. 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 IEEE Transactions on Mobile Computing [16]. The part specifying the framework to a chunk-based scenario by accounting for partial storage of videos in vehicles was published in [25].

6.2.7. Cost Optimization of Cloud-RAN Planning and Provisioning for 5G Networks

Participants: Osama Arouk, Thierry Turletti.

We propose a network planning and provisioning framework that optimizes the deployment cost in C-RAN based 5G networks. Our framework is based on a Mixed Integer Quadratically Constrained Programming (MIQCP) model that optimizes "virtualized" 5G service chain deployment cost while performing adequate provisioning to address user demand and performance requirements. We use two realistic scenarios to showcase that our framework can be applied to different types of deployments and discuss the computational cost and scalability of our solution. This work has been presented at the IEEE International Conference on Communications, in May 2018, at Kansas City, MO, United States [18].

6.2.8. Slice Orchestration for Multi-Service Disaggregated Ultra Dense RANs

Participants: Osama Arouk, Thierry Turletti.

Ultra Dense Networks (UDNs) are a natural deployment evolution for handling the tremendous traffic increase related to the emerging 5G services, especially in urban environments. However, the associated infrastructure cost may become prohibitive. The evolving paradigm of network slicing can tackle such a challenge while optimizing the network resource usage, enabling multi-tenancy and facilitating resource sharing and efficient service-oriented communications. Indeed, network slicing in UDN deployments can offer the desired degree of customization in both vanilla Radio Access Network (RAN) designs, but also in the case of disaggregated multi-service RANs. We propose a novel multi-service RAN environment, i.e., RAN runtime, capable to support slice orchestration procedures and to enable flexible customization of slices as per tenant needs. Each network slice can exploit a number of services, which can either be dedicated or shared between multiple slices over a common RAN. The novel architecture we present concentrates on the orchestration and management systems. It interacts with the RAN modules, through the RAN runtime, via a number of new interfaces enabling a customized dedicated orchestration logic for each slice. We present results for a disaggregated UDN deployment where the RAN runtime is used to support slice-based multi-service chain creation and chain placement, with an auto-scaling mechanism to increase the performance. This work has been published in IEEE Communications Magazine [13].

6.3. Experimental Evaluation

6.3.1. nepi-ng: an efficient experiment control tool in R2lab

Participants: Thierry Parmentelat, Thierry Turletti, Walid Dabbous, Mohamed Naoufal Mahfoudi.

Experimentation is an essential step for realistic evaluation of wireless network protocols. The evaluation methodology entails controllable environment conditions and a rigorous and efficient experiment control and orchestration for a variety of scenarios. Existing experiment control tools such as OMF often lack in efficiency in terms of resource management and rely on abstractions that hide the details about the wireless setup. We propose `nepi-ng`, an efficient experiment control tool that leverages job oriented programming model and efficient single-thread execution of parallel programs using asyncio. `nepi-ng` provides an efficient and modular fine grain synchronization mechanism for networking experiments with light software dependency footprint. This work has been presented at the 12th ACM International Workshop on Wireless Network Testbeds, Experimental evaluation & CHaracterization (WINTECH) in November 2018 at New Delhi, India [24].

6.3.2. Using nepi-ng for Mesh Networks Experiments

Participants: Thierry Parmentelat, Thierry Turletti, Mohamed Naoufal Mahfoudi, Walid Dabbous.

We describe a demonstration run on R2lab, an open wireless testbed located in an anechoic chamber at Inria Sophia Antipolis. The demonstration consists in easily deploying a Wi-Fi mesh network. The nodes provisioning, configuration and the scenario orchestration and control are automatically done using the `nepi-ng` experiment orchestration tool. A performance comparison of two wireless mesh routing protocols in presence of controlled interference is shown. This demo has been presented at the 12th ACM International Workshop on Wireless Network Testbeds, Experimental evaluation & CHaracterization (WINTECH) in November 2018 at New Delhi, India [32].

6.3.3. R2Lab Testbed Evaluation for Wireless Mesh Network Experiments

Participants: Farzaneh Pakzad, Thierry Turletti, Thierry Parmentelat Mohamed Naoufal Mahfoudi, Walid Dabbous.

We have provided critical evaluations of new potential testbeds for the evaluation of SDN-based WMNs. We evaluated the R2Lab wireless testbed platform at Inria Sophia Antipolis, France. This testbed has 37 customisable wireless devices in an anechoic chamber for reproducible research in wireless WiFi and 4G/5G networks. Our work presents the first initial evaluation of the testbed for wireless multi-hop experiments, using traditional WMN routing protocols. Our results demonstrate the potential for SDN experiments. We believe this is an important contribution in its own right, since experimental validation is a key research methodology in this context, and trust in the validity of experimental results is absolutely critical.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. SAFRAN

Participants: Damien Saucez.

We have a bilateral contract covering 2017 and 2018 with Safran Electrical and Power in order to build a network simulator specialised for aeronautical networks.

7.2. Bilateral Grants with Industry

7.2.1. QWANT

Participants: 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. ADT ACQUA

Participants: Chadi Barakat.

In the context of the Inria ADT call, we have a funding for a two year engineering position on the ACQUA project for the 2015-2017 period. Thierry Spetebroot is hired on this position. In 2017, this ADT got extended by six months beyond the two years period to therefore end on March 2018.

8.1.2. IPL BetterNet

Participants: Chadi Barakat.

The DIANA team is part of the Inria Project Lab BetterNet (http://project.inria.fr/betternet/). Within this lab, Inria has funded two PhD students in 2017 co-supervised by Chadi Barakat from the DIANA project-team. The first PhD student is Thibaut Ehlinger hosted within the DIANA team and co-supervised by Vassilis Christophides from the MiMove team in Paris. The second PhD student is Imane Taibi hosted by the Dionysos team in Rennes and co-supervied by Gerardo Rubino and Yassine Hadjadj-Aoul. Both PhDs 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 is 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)

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 will target a solution based on algorithms previously developed in the DIANA project-team (BitHoc and HBSD). The project got a funding for one year engineer from the Labex. Zeineb Guizani has been working on this project since July 2018.

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 Partner (Institution - Laboratory - Researcher):

Ericsson Research, Indaiatuba-SP, BRAZIL (Brazil) Mateus Augusto Silva Santos

Start year: 2018

See also: https://team.inria.fr/diana/drive-associated-team/

Abstract: 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).

8.5.2. Inria Associate Teams Not Involved in an Inria International Labs

8.5.2.1. UHD-on-5G

Title: Ultra High Definition video streaming on future 5G networks

International Partner (Institution - Laboratory - Researcher):

National Institute of Information and Communications Technology (NICT) (Japan) - Hitoshi Asaeda

Start year: 2016

See also: https://team.inria.fr/diana/uhd-on-5g/

The aim of this collaboration is to design and develop efficient mechanisms for streaming UHD video on 5G networks and to evaluate them in a realistic and reproducible way by using novel experimental testbeds.

Our approach leverages and extends when necessary ICN and SDN technologies to allow very high quality video streaming at large scale. We also plan to use Virtual Network Functions (VNF) in order to place easily and dynamically different functions (e.g. transcoding, caching) at strategic locations within the network. Specifically, the placement of these functions will be decided by SDN controllers to optimize the quality of experience (QoE) of users. Moreover, we plan to integrate ICN functionalities (e.g., name-based forwarding and multipath transport using in-network caching) with SDN/NFV to provide better QoE and mobility services support to users than traditional IP architectures. Monitoring mechanisms such as the Contrace tool we developed in the SIMULBED associated team will be helpful to provide an accurate view of the network at the SDN controllers side. In addition, we will build a large-scale testbed to evaluate our solutions through reproducible experimentations based on two testbeds: the ICN wired CUTEi tesbed developed by NICT and the wireless R2lab testbed developed by Inria.

8.6. International Research Visitors

8.6.1. Visits of International Scientists

Katia Obraczka is Professor of Computer Engineering and Graduate Director at Department of Computer Engineering, UC Santa Cruz where she leads the Internetworking Research Group (i-NRG). She has visited us for four weeks in July 2018. The Labex UCN@Sophia has supported two one-month visits at the DIANA project-team, in July 2017 and during summer 2018 to work in particular on the decentralization of the SDN control plane applied to Intelligent Transport Systems (ITS). These two visits were very fruitful as they resulted in common publications [18], [17] and contributed to the start of the DrIVE Associated team.

8.6.2. Internships

Yevhenii Semenko and Alberto Zirondelli

Date: from from Apr 2018 until Sep 2018

Institution: Ubinet Master intern, University of Nice Sophia Antipolis

Supervisor: Damien Saucez

Subject: Privacy preserving taxi service with blockain

Laila Daanoun

Date: from Apr 2018 until Aug 2018

Institution: Ubinet Master intern, University of Nice Sophia Antipolis

Supervisor: Damien Saucez

Subject: The Network of the Future in Industry 4.0: Solving the Reachability problem

Gayatri Sivadoss

Date: from Apr 2018 until Aug 2018

Institution: Ubinet Master intern, University of Nice Sophia Antipolis

Supervisor: Mohamed Naoufal Mahfoudi, Thierry Turletti and Walid Dabbous

Subject: LoRa: Characterization and Range Extension in campus environment

Ohtmane Bensouda Korachi

Date: from Apr 2018 until Aug 2018

Institution: Ubinet Master intern, University of Nice Sophia Antipolis

Supervisor: Mohamed Naoufal Mahfoudi, Thierry Turletti and Walid Dabbous

Subject: Geolocation for LoRa Low Power Wide Area Network

Othmane Belmoukadam

Date: from Mar 2018 until Aug 2018

Institution: Ubinet Master intern, University of Nice Sophia Antipolis

Supervisor: Chadi Barakat

Subject: ACQUA - A data-driven approach for network and Quality of Experience monitoring

Yonathan Bleyfuesz

Date: from Feb 2018 to Aug 2018

Institution: International Master programme M1, University of Nice Sophia Antipolis

Supervisor: Thierry Parmentelat

Subject: Using `nepi-ng` to evaluate MANET routing protocols.

Indukala Naladala

Date: from May 2018 until Jul 2018
Institution: National Institute of Technology Karnataka, Surathkal, India
Supervisor: Thierry Turletti and Walid Dabbous
Subject: Integration of R2LAB with ns-3

Janati Idrissi

Date: from Mar 2018 until Aug 2018
Institution: Ubinet Master intern, University of Nice Sophia Antipolis
Supervisor: Arnaud Legout
Subject: Étude de la précision de la localisation dans ElectroSmart sous Android.

8.6.3. Visits to International Teams

Thierry Turletti visited NICT in Tokyo Japan in the context of the UHD-on-5G associated team in october 2018.

Thierry Turletti also visited UNICAMP in Campinas Bresil in the context of the UHD-on-5G associated team in october 2018.

9. Dissemination

9.1. Promoting Scientific Activities

Chadi Barakat is on the editorial board of the Computer Networks journal, and is on the Technical Program Committee for the ACM MECOMM Workshop held in conjunction with the ACM SIGCOMM 2018 conference, and for the Network Traffic Measurement and Analysis Conference (TMA 2019). He co-chaired the workshops at the ACM CoNext 2018 conference and will co-chair the Technical Program Committee for the CCDWN workshop 2019 to be held in conjunction with the WiOpt 2019 conference. He is currently the scientific referee for international affairs at Inria Sophia Antipolis and member of the Conseil d'Orientation Scientifique et Technologique at Inria within the working group of international affairs (COST-GTRI).

Walid Dabbous is chair of the scientific committee of the User Centric Networking (UCN@Sophia) Laroratory of Excellence, and member of the scientific committee of the Academy 1 of the UCAJedi Idex. He is also member of the Ubinet International Master program steering committee. He is chair of the Inria admissibility jury for the young graduate scientist ("CRCN") competitive selection.

Arnaud Legout is on the editorial board of the Computer Networks journal. Arnaud Legout is the president of the Commission of the users of IT resources of Sophia Antipolis Inria research center.

Damien Saucez has co-organised the ACM SIGCOMM Reproducilbity workshop. He is co-chair of 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 2018 ACM Workshop on ns-3. He was member of the TPCs of IEEE ICC 2018, DRCN 2018, ACM WNS3 2018 and is regular reviewer for IEEE, ACM, Elsevier, and Springer journals. Damien Saucez and Walid Dabbous participated to the organization of the first Grid'5000-FIT school in Sophia Antipolis in April 3-6 2018. See https://www.silecs.net/1st-grid5000-fit-school/ for more information.

Thierry Turletti, Senior ACM and IEEE member, served in 2018 in the program committees of the following international workshops and conferences: the 3rd CoRes Workshop at Roscoff, France in May 28-29, the 9th Workshop on ns-3 at Mangalore, India in June 13-14, the 13rd Workshop on Challenged Networks (CHANTS) at New Delhi, India in October 29 and IEEE Globecom at Abu Dabi, UAE in December 9-13. He 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. 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.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master 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 started his PhD on "QoE aware content management in the Internet: caching and transport" in October 2018. He is supervised by Chadi Barakat and funded by the doctoral school EDSTIC of Université Côte d'Azur (UCA).

PhD in progress: Yanis Boussad started his PhD on "Large scale characterization of the exposition to microwaves" in October 2017. He is co-supervised with Leonardo Lizzi, LEAT.

PhD in progress: Giuseppe Di Lena started his PhD on "Building a resilience methodology for NFV/SDN " in Apr 2018. His PhD is co-supervised by Thierry Turletti and Damien Saucez.

PhD in progress: Thibaut Ehlinger: started his PhD on "Mapping Quality of Service metrics to user Quality of Experience in the Internet" in November 2017. He is co-supervised by Chadi Barakat and Vassilis Christophides (EPI MiMove, Inria Paris).

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 in progress: Karyna Gogunska works on "Empowering Virtualized Networks with Measurement As a Service (MaaS)". Her thesis is co-supervised by Chadi Barakat and Guillaume Urvoy-Keller (I3S).

PhD in progress: Muhammad Jawad Khokhar works on "From Network Level Measurements to Expected Quality of User Experience". His PhD is supervised by Chadi Barakat.

PhD in progress: Mohamed Naoufal Mahfoudi works on cross-layer optimization techniques for next generation MIMO-based networks since November 2015. His thesis is co-supervised by Walid Dabbous and Robert Staraj (LEAT).

PhD in progress: Ghada Moualla works on "the problem of network faults and how to circumvent them by the means of Software Defined Networking, virtualization, and service function chaining" since November 2015. Her thesis is co-supervised by Thierry Turletti and Damien Saucez.

PhD: Vitalii Poliakov defended his PhD on "the application of Software Defined Networking on 5G networks in order to optimise the Quality of Experience of network services" in December 2018. His thesis was co-supervised by Damien Saucez and Lucile Sassatelli (I3S).

PhD: Hardik Soni defended his PhD on "Software Defined Networking in challenged environments" in April 2018. His thesis was co-supervised by Thierry Turletti and Walid Dabbous.

PhD in progress: Imane Taibi started his PhD in the Dionysos project-team on "Big data analysis for network monitoring and troubleshooting" in November 2017. She is co-supervised by Gerardo Rubino, Yassine Hadjadj-Aoul and Chadi Barakat.

PhD in progress: Mathieu Thiery started his PhD in the Privatics project-team on "Data protection of connected objects and smartphones" in April 2017. He is co-supervised by Vincent Roca and Arnaud Legout.

PhD in progress: Thibaud Trolliet started his PhD on "Exploring trust on Twitter" in octobre 2017. He is co-supervised with Frederic Giroire.

9.2.3. Juries

Chadi Barakat served as reviewer of Muhammad Ikram thesis, "Analysis and Design of Secure and Privacy Preserving Systems" defended in April 2018 at the University of New South Wales and Data61, Australia.

Walid Dabbous served as reviewer of Cédric Baudoin HDR thesis “Optimisation et intégration des réseaux de télécommunication par satellite” in INP Toulouse, defended in january 17, 2018.

Walid Dabbous served as a jury member for the mid-term review of the Ph.D. thesis of Sumit Kumar (Eurecom) for his thesis entitled "Simultaneous multi-standard SDR platform" in january 18, 2018.

Walid Dabbous served as a jury chair person for the Ph.D. thesis defense of Dolière Francis Somé on "Web Applications Security and Privacy" on october 29, 2018 (Inria, Indes project-team).

Damien Saucez served as jury member of Chi Dung Phung PhD defence, UPMC, Paris. The thesis on "Enriching the Internet control-plane for improved traffic engineering" was defended on March 30, 2018.

Damien Saucez served as jury member of Yue Li PhD defense, Telecom ParisTech, Paris. The thesis on "Future Internet Services based on LISP Technology" was defended on April 26, 2018.

Thierry Turletti served as a jury member for the mid-term review of the Ph.D. thesis of Andrea Tomassilli on "the integration of Network Functions Virtualization (NFV) techniques with Software-Defined Networking (SDN)." on May 24, 2018 (Inria, COATI project-team).

Thierry Turletti served as a jury member for the mid-term review of the Ph.D. thesis of Chia-Yu Chang on "Cloudification and Slicing in 5G Radio Access Network" on June 28, 2018 (Eurecom).

Thierry Turletti served as reviewer of Elie Bouttier PhD thesis, "Livraison de contenus sur un réseau hybride satellite / terrestre", defended on July 5, 2018 at INP Toulouse, France.

Thierry Turletti served as reviewer of Raphael Naves PhD thesis, "Apport de la gestion des interférences aux réseaux sans-fil multi-sauts: Le cas du Physical-Layer Network Coding” defended on November 19, 2018 at INP Toulouse, France.

Thierry Turletti served as reviewer and president of Imad Alawe PhD thesis “Architectures evaluation and dynamic scaling for 5G mobile core networks”, defended on November 21, 2018 at Université de Rennes 1, France.

9.3. Popularization

9.3.1. Interventions

Chadi Barakat keeps participating to the organization of the Mediterranean Students Days @ Campus SophiaTech. The sixth edition took place on Feb 12 - 14, 2018. All details on this event can be found at http://univ-cotedazur.fr/events/meddays. He also participated to the organization of the French-American Doctoral Exchange Seminar (FADEx) 2018 held in June 2018 on the three French sites Sophia Antipolis, Grenoble, and Paris.

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. Within the team, we gave a 3h game-based class to 12 collège interns that made an internship at Inria in December to introduce them to the fundamental algorithms used in the Internet (shortest-path, longest prefix matching, distance-vector, AIMD). Damien Saucez was involved in the organization of the “Journée portes-ouvertes” of the Inria Sophia Antipolis premises. Specifically, DIANA presented R2LAB and Electrosmart.

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Major publications by the team in recent years

[1] M. Gabielkov, A. Ramachandran, A. Chaintreau, A. Legout.*Social Clicks: What and Who Gets Read on Twitter?*, in "ACM SIGMETRICS / IFIP Performance 2016", Antibes Juan-les-Pins, France, June 2016, https://hal.inria.fr/hal-01281190

[2] M. Gabielkov, A. Rao, A. Legout.*Studying Social Networks at Scale: Macroscopic Anatomy of the Twitter Social Graph*, in "ACM Sigmetrics 2014", Austin, United States, June 2014, https://hal.inria.fr/hal-00948889

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[4] Y.-H. Kim, A. Quereilhac, M. A. Larabi, J. Tribino, T. Parmentelat, T. Turletti, W. Dabbous.*Enabling Iterative Development and Reproducible Evaluation of Network Protocols*, in "Computer Networks", January 2014, vol. 63, p. 238-250, https://hal.inria.fr/hal-00861002

[5] M. N. Mahfoudi, T. Parmentelat, T. Turletti, W. Dabbous, R. Knopp.*Deploy a 5G network in less than 5 minutes: Demo Abstract*, August 2017, ACM SIGCOMM Posters and Demos, Poster, https://hal.inria.fr/hal-01580065

[6] M. N. Mahfoudi, T. Turletti, T. Parmentelat, F. Ferrero, L. Lizzi, R. Staraj, W. Dabbous.*ORION: Orientation Estimation Using Commodity Wi-Fi*, in " Workshop on Advances in Network Localization and Navigation (ANLN)", Paris, France, May 2017, p. 1033-1038, https://hal.archives-ouvertes.fr/hal-01424239

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[10] L. VIGNERI, T. SPYROPOULOS, C. BARAKAT.*Low Cost Video Streaming through Mobile Edge Caching: Modelling and Optimization*, in "IEEE Transactions on Mobile Computing", 2018 [*DOI :* 10.1109/TMC.2018.2861005], https://hal.inria.fr/hal-01855304

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[11] V. POLIAKOV.*Combining in-network caching, HTTP Adaptive Streaming and Multipath to improve video Quality Of Experience*, Université Côte d'Azur, December 2018, https://hal.archives-ouvertes.fr/tel-01968837

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[13] C.-Y. CHANG, N. NIKAEIN, O. AROUK, K. KATSALIS, A. KSENTINI, T. TURLETTI, K. SAMDANIS.*Slice Orchestration for Multi-Service Disaggregated Ultra Dense RANs*, in "IEEE Communications Magazine", 2018, vol. 56, n° 8, 8 [*DOI :* 10.1109/MCOM.2018.1701044], https://hal.inria.fr/hal-01730597

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[18] O. AROUK, T. TURLETTI, N. NIKAEIN, K. OBRACZKA.*Cost Optimization of Cloud-RAN Planning and Provisioning for 5G Networks*, in "ICC 2018 - IEEE International Conference on Communications", Kansa City, MO, United States, May 2018, https://hal.inria.fr/hal-01707682

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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 Collaborators
Emmanuelle Itam [CNAM]
Bruno Koobus [Univ Montpellier II (sciences et techniques du Languedoc)]
Stephen Wornom [LEMMA]

PhD Student
Eléonore Gauci [Education Nationale]

Visiting Scientist
Olivier Allain [LEMMA]

Administrative Assistant
Christine Claux [Inria]

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 want 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 now.

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 [2].

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$\times$vector products are cheaper than matrix$\times$matrix products. This is the *adjoint mode* of AD, most effective for optimization, data assimilation [28], adjoint problems [21], or inverse problems.

Adjoint AD builds a very efficient program [24], 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 [17], [25], [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* [18] 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 [31], [19] 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 derivative come into play. Similarly *Uncertainty Quantification* can use second derivatives to evaluate how uncertainty on the simulation inputs imply uncertainty on its outputs.

We investigate several approaches to obtain the gradient, between two extremes:

- One can write an *adjoint system* of mathematical equations, then discretize it and program it by hand. This is time consuming. Although this looks mathematically sound [21], this does not provide the gradient of the discretized function itself, thus degrading the final convergence of gradient-descent optimization.
- One can apply adjoint AD (*cf*3.1) on the program that discretizes and solves the direct system. This gives exactly the adjoint of the discrete function computed by the program. Theoretical results [20] guarantee convergence of these derivatives when the direct program converges. This approach is highly mechanizable, but leads to massive use of storage and may require code transformation by hand [26], [29] to reduce memory usage.

If for instance the model is steady, or when the computation uses a Fixed-Point iteration, tradeoffs exist between these two extremes [22], [16] that combine low storage consumption with possible automated adjoint generation. We advocate incorporating them into the AD model and into the AD tools.

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 [27]) and its AD-adjoint produced by Tapenade.

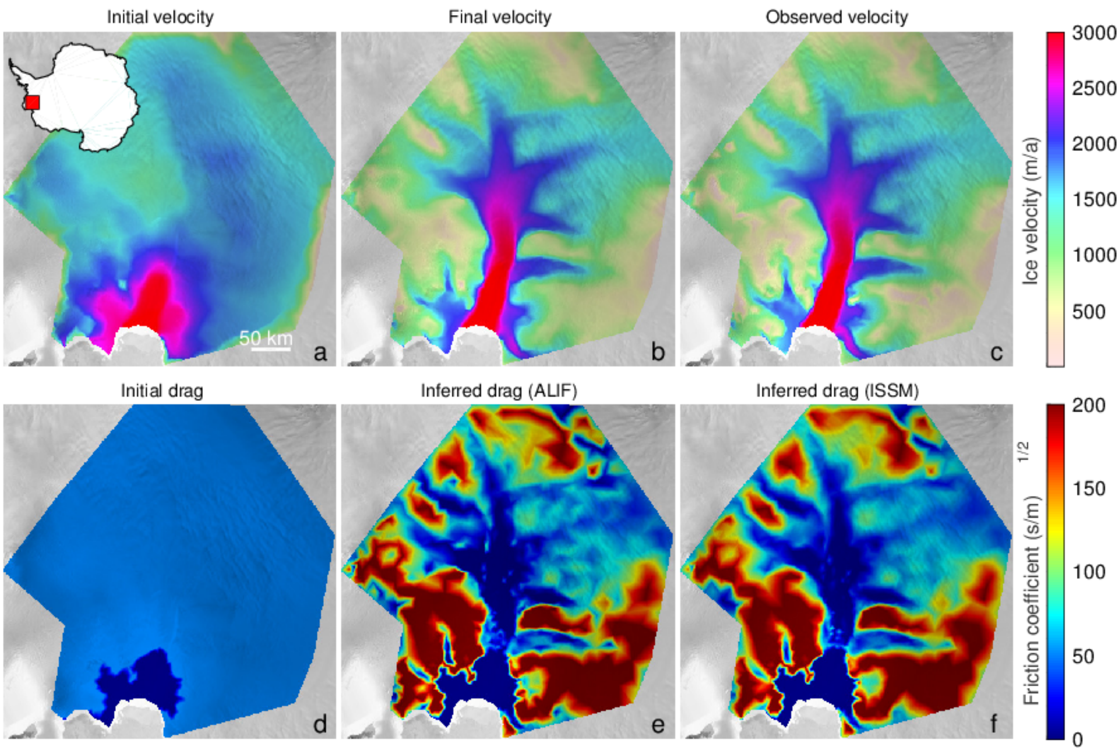

Figure 1. Assimilation of the basal friction under Pine Island glacier, West Antarctica. The final simulated surface velocity (b) is made to match the observed surface velocity (c), by estimation of the basal friction (e). A reference basal friction (f) is obtained by another data assimilation using the hand=written adjoint of ISSM

One particular case of inverse problems is *data assimilation* [28] 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 [30]. The special case of *4Dvar* data assimilation is particularly challenging. The 4$^{\text{th}}$ 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.

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:

Activity analysis: Detects variables whose derivative is either null or useless, to reduce the number of derivative instructions.

Adjoint Liveness analysis: Detects the source statements that are dead code for the computation of derivatives.

TBR analysis: In adjoint-mode AD, reduces the set of source variables that need to be recovered.
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++ based on Clang - Experimental support for building Abs-Normal Form tangent of non-smooth codes

- 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].

We made progress towards the extension of Tapenade for C++. Last year, an external parser for C++ was built on top of Clang-LLVM https://clang.llvm.org/ and connected to the input formalism "IL" of Tapenade, but the internals of Tapenade were not able to handle the new constructs present in this input. This year, integration of C++ was pushed further by taking into account many of the new constructs (namespaces, classes, constructors and destructors) in the Internal Representation(IR) of Tapenade. Not surprisingly, this implied deep changes in several areas of Tapenade code. The IR of Tapenade now contains classes, constructors and destructors, and also has a faithful representation for namespaces. The textual nested structure and the control-flow parts of the IR are correct. The symbol tables and the representation for memory locations are still under development.

As a result, Tapenade is now able to input its first C++ files and is able to output them, but without transformation. Although not advertised nor documented, the functionality is present in the latest release 3.14. Data-Flow analysis and code transformation (e.g. AD) will not be possible until we have a correct IR about variables and their memory locations. This work is going on.

This work benefited from the expertise in C++ of Frederic Cazals (Inria ABS team). The ABS team provided a large test application code (SBL, https://sbl.inria.fr/) for Molecular Dynamics, which will be our first C++ target.

6.2. AD of mixed-language codes

Participants: Valérie Pascual, Laurent Hascoët.

Last year Tapenade was extended to differentiate codes that mix different languages, beginning with the tangent mode of AD. Our motivating application here is Calculix, a 3-D Structural Finite Element code that mixes Fortran and C. This year, we continued development towards Adjoint Differentiation. Although more complete testing is needed, we now have a first correct adjoint of Calculix.

Tapenade can now routinely differentiate Fortran+C codes, and accepts and takes advantage of the interoperability directives provided by the Fortran 2003 standard. It can handle not only procedure parameters correspondence, but also interoperability between C `struct` and Fortran `COMMON` blocks. Laurent Hascoët presented the advancement of this work at the ISMP 2018 congress in Bordeaux https://ismp2018.sciencesconf.org/.

C files (aka "translation units") and Fortran modules are two instances of the more general notion of "package" for which we are looking for a unified representation in Tapenade. It appears that this common representation could also handle C++ namespaces.

6.3. Differentiation of non-smooth programs

Participants: Laurent Hascoët, Sri Hari Krishna Narayanan [Argonne National Lab. (Illinois, USA)].

Algorithmic Differentiation can be used to derive tangent models that cope with a certain class of non-smoothness, through the use of the so-called Abs-Normal Form (ANF) [23]. These tangent models incorporate some knowledge of the nearby discontinuities of the derivatives. These models bring some additional power to processes that use tangent approximations, such as simulation, optimization, or solution of differential equations.

The mechanics to derive these special tangent models can be built as an extension of standard tangent linear Algorithmic Differentiation. This has been first demonstrated by the AD tool AdolC which, being based on Operator Overloading, is more flexible and seems a natural choice for implementation. Together with Krishna Narayanan, we recently tried a similar adaption on Source-Transformation AD tools. It appears that very little development is needed in the AD-tool. Specifically for Tapenade, it appears that no development at all is needed in the tool itself. Any end-user can already produce ANF tangent without needing any access to the tool source. All it requires is a customized derivative of the absolute-value function (ABS), which is currently less than 40 lines of code.

Building the ANF of a given program introduces one new variable per run-time execution of the ABS function. As the number of rows and columns of the constructed extended Jacobian both grow like the number of variables, it may become unreasonably large for large codes. To overcome this issue, we explore the possibility of finding at run-time the "important" ABS calls that deserve this treatment, and those that don't. We base this decision on a notion of distance to the kink induced by this ABS call as illustrated by Figure 2. We presented these experiments at a Shonan meeting on this question (Shonan, Japan, June 25-29) and at a workshop of ISMP 2018 (Bordeaux, July 2-6)

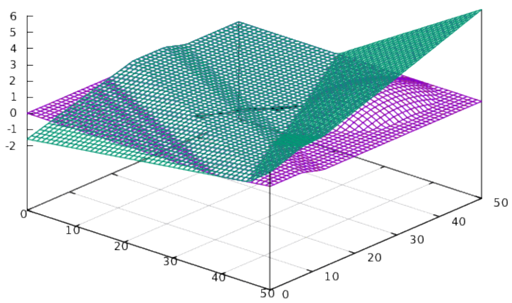

Figure 2. Abs-Normal Form of a non-smooth function: purple:original function, green ANF computed at (30,30). The ANF is linearized around the point of interest, and at the same time captures the non-smooth behavior. Notice the ANF divergence from the original function on the left, due to neglecting the leftmost kink which was decided "far" enough from the point of interest. The ANF divergence on the right is the natural effect of linearization

6.4. AD-adjoints and C dynamic memory management

Participants: Laurent Hascoët, Sri Hari Krishna Narayanan [Argonne National Lab. (Illinois, USA)].

One of the current frontiers of AD research is the definition of an adjoint AD model that can cope with dynamic memory management. This research is central to provide reliable adjoint differentiation of C, and for our distant goal of AD of C++. This research is conducted in collaboration with the MCS department of Argonne National Lab. Our partnership is formalized by joint participation in the Inria joint lab JLESC, and partly funded by the Partner University Fund (PUF) of the French embassy in the USA.

Adjoint AD must reproduce in reverse order the control decisions of the original code. In languages such as C, allocation of dynamic memory and pointer management form a significant part of these control decisions. Reproducing memory allocation in reverse means reallocating memory, possibly receiving a different memory chunk. Reproducing pointer addresses in reverse thus requires to convert addresses in the former memory chunks into equivalent addresses in the new reallocated chunks. Together with Krishna Narayanan from Argonne, we experiment on real applications to find the most efficient solution to this address conversion problem. We jointly develop a library (called ADMM, ADjoint Memory Management) whose primitives are used in AD adjoint code to handle this address conversion. Both our AD tool Tapenade and Argonne's tool OpenAD use ADMM in the adjoint code they produce.

This year, trying to prove correctness of our current address conversion, we discovered some limitations that indeed made the proof impossible. To solve these issues, it seems necessary to assign at run-time a unique identifier to each chunk of memory used by the code, and to carry this identifier along with every pointer. This results in a code transformation which, although more complex than expected, can still be described by a small set of rewrite rules. Moreover, this alternative method should reduce the run-time overhead that we observed previously. Implementation and measurements are still under way. We presented this recent research in the form of a catalogue of alternatives for Data-Flow reversal of memory addresses, at the 21$^{\text{st}}$ EuroAD workshop (Jena, Germany, November 19-20).

6.5. Application to large industrial codes

Participants: Valérie Pascual, Laurent Hascoët, Bruno Maugars [ONERA], Sébastien Bourasseau [ONERA], Bérenger Berthoul [ONERA].

We support industrial users with their first experiments of Algorithmic Differentiation of large in-house codes.

This year's main application is with ONERA on their ElsA CFD platform (Fortran 90). Both tangent and adjoint models of the kernel of ElsA were built successfully by Tapenade. It is worth noticing that this application was performed inside ONERA by ONERA engineers (Bruno Maugars, Sébastien Bourasseau, Bérenger Berthoul) with no need for installation of ElsA inside Inria. We take this as a sign of maturity of Tapenade. Apart from a few minor corrections, our contributon was essentially during development meetings, to point out some strategies and tool options to obtain efficient differentiated code. One emphasis was on adjoint of vectorized code, which was produced as vectorized code too by means of a seldom-used Tapenade option that stores intermediate values statically, i.e. not on a global stack. Sébastien Bourasseau presented the first results at the 21$^{\text{st}}$ EuroAD workshop (Jena, Germany, November 19-20), with convincing performance on industrial-size test cases. A joint article is in preparation.

6.6. Multirate methods

Participants: Alain Dervieux, Bruno Koobus, Emmanuelle Itam, Stephen Wornom.

This study is performed in collaboration with IMAG-Montpellier. It addresses an important complexity issue in unsteady mesh adaptation and took place in the work done in the ANR Maidesc (ended 2017). Unsteady high-Reynolds computations are strongly penalized by the very small time step imposed by accuracy requirements on regions involving small space-time scales. Unfortunately, this is also true for sophisticated unsteady mesh adaptive calculations. This small time step is an important computational penalty for mesh adaptive methods of AMR type. This is also the case for the Unsteady Fixed-Point mesh adaptive methods developed by Ecuador in cooperation with the Gamma3 team of Inria-Saclay. In the latter method, the loss of efficiency is even more crucial when the anisotropic mesh is locally strongly stretched since only very few cells are in the regions of small time-step constraint. This loss is evaluated as limiting the numerical convergence order for discontinuities to 8/5 instead of second-order convergence. An obvious remedy is to design time-consistent methods using different time steps on different parts of the mesh, as far as they are efficient and not too complex. The family of time-advancing methods in which unsteady phenomena are computed with different time steps in different regions is referred to as the multirate methods. In our collaboration with university of Montpellier, a novel multirate method using cell agglomeration has been designed and developed in our AIRONUM CFD platform. A series of large-scale test cases show that the new method is much more efficient than an explicit method, while retaining a similar time accuracy over the whole computational domain. A novel analysis shows that the proposed multirate algorithm indeed solves the unsteady mesh adaptation barrier identified in previous works. This work is being published in a journal [13].

6.7. Control of approximation errors

Participants: Eléonore Gauci, Alain Dervieux, Adrien Loseille [Gamma3 team, Inria-Rocquencourt], Frédéric Alauzet [Gamma3 team, Inria-Rocquencourt], Anca Belme [university of Paris 6], Gautier Brèthes [university of Montreal], 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, two conference papers were written on the methods of the team, including new analyses in [11],[10], a work on correctors in CFD in an AIAA paper. A detailed study of adjoint-based mesh adaptation for Navier-Stokes flows has been completed and published in a journal [9].

Following participation of Gamma3 and Ecuador to the European project UMRIDA (ended 2017), we wrote chapters 20, 21, 45, and 48 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).

6.8. Turbulence models

Participants: Alain Dervieux, Bruno Koobus, Stephen Wornom, Maria-Vittoria Salvetti [University of Pisa].

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 (Reynolds averaged Navier-Stokes) models. These are mainly vortical separated regions as assumed in one of the most popular hybrid models, the hybrid Detached Eddy Simulation 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.

This year, we have developed a new model relying on the hybridation of a DDES model based on a k-ϵ closure with our dynamic VMS model. This model shows improvement in most situations and in particular for laminar flows.

We have also addressed this year a challenging test case, the flow around tandem cylinders with a distance between the cylinders of 12 diameters. The accurate capture of the vortices traveling along this path of 12 diameters requires that the LES filter does not accumulate any dissipation along this trajectory. This is a noticeable property or our DVMS model. Further, the numerics need be as accurate as possible. We use a superconvergent approximation, up to fifth order accurate on Cartesian regions of the computational domain. This combination allowed for an accurate prediction of the drag of the second cylinder. This result has been presented at the workshop ETMM12 [12]

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- Ecuador and Lemma have a bilateral contract to share the results of Stephen Wornom, Lemma engineer provided to Inria and hosted by Inria under a Inria-Lemma contract.

8. Partnerships and Cooperations

8.1. International Initiatives

8.1.1. Inria International Labs

Ecuador participates in the Joint Laboratory for Exascale Computing (JLESC) together with colleagues at Argonne National Laboratory.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific events organisation

9.1.1.1. Member of the organizing committees

Laurent Hascoët is on the organizing commitee of the EuroAD Workshops on Algorithmic Differentiation (http://www.autodiff.org).

9.1.2. Scientific Expertise

Alain Dervieux is Scientific Director for the LEMMA company.

9.2. Teaching - Supervision - Juries

9.2.1. Supervision

PhD : Éléonore Gauci, “Goal-oriented metric-based mesh adaptation for unsteady CFD simulations involving moving geometries”, defended december 12, co-advisor A. Dervieux

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Articles in International Peer-Reviewed Journal

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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
A5.9. - Signal processing
A6.1. - Methods in mathematical modeling
A6.2. - Scientific computing, Numerical Analysis & Optimization
A6.3. - Computation-data interaction
A8.3. - Geometry, Topology
A9. - Artificial intelligence
A9.2. - Machine learning
A9.3. - Signal analysis
A9.6. - Decision support
A9.7. - AI algorithmics

Other Research Topics and Application Domains:

B2.2. - Physiology and diseases
B2.3. - Epidemiology
B2.4. - Therapies
B2.6. - Biological and medical imaging
B2.6.1. - Brain imaging
B2.6.2. - Cardiac imaging
B2.6.3. - Biological Imaging

1. Team, Visitors, External Collaborators

Research Scientists

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Hervé Delingette [Inria, Senior Researcher, HDR]
Marco Lorenzi [Inria, Researcher]
Xavier Pennec [Inria, Senior Researcher, HDR]
Maxime Sermesant [Inria, Researcher, HDR]

Faculty Member

Charles Bouveyron [Univ Côte d'Azur, Inria Chair, HDR]

External Collaborators

Thomas Demarcy [Oticon Medical]
Elena Erosheva [Univ Côte d'Azur, from Aug 2018]

Alan Garny [Univ. of Auckland, NZ]
Marco Milanesio [Univ de Nice - Sophia Antipolis]
Philippe Robert [Univ Côte d'Azur, from Jan 2018]
Clair Vandersteen [Centre hospitalier universitaire de Nice]
Wilhelm Wimmer [University of Bern, from Nov 2018]
Nicolas Duchateau [Univ Claude Bernard Lyon]
Hervé Lombaert [ETS Montreal, Canada]
Valeria Manera [Univ Côte d'Azur, from Apr 2018]

PhD Students

Clement Abi Nader [Univ de Nice - Sophia Antipolis, until 2020]
Luigi Antelmi [Univ de Nice - Sophia Antipolis, until 2020]
Benoît Audelan [Univ Côte d'Azur, from Feb 2018]
Tania Marina Bacoyannis [Inria, until 2020]
Nicolas Cedilnik [Inria, until 2020]
Jaume Banus Cobo [Univ de Nice - Sophia Antipolis, until 2020]
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Nicolas Guigui [Inria, from Oct 2018]
Shuman Jia [Inria, until 2020]
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Pamela Moceri [Univ de Nice - Sophia Antipolis, until Jan. 2018]
Roch-Philippe Molléro [Inria, until Jan 2018]
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Wen Wei [Inria, until 2020]
Qiao Zheng [Inria, until 2019]

Post-Doctoral Fellows

Sara Garbarino [Univ Côte d'Azur, from Apr 2018]
Nina Miolane [Inria, until Dec 2018]
Fanny Orlhac [Inria, until 2019]

Visiting Scientists

Svenja Huning [TU Graz, from Nov 2018]
Federica Ribaldi [IRCCS San Giovanni di Dio Fatebenefratelli, from May 2018 to June 2018]

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.

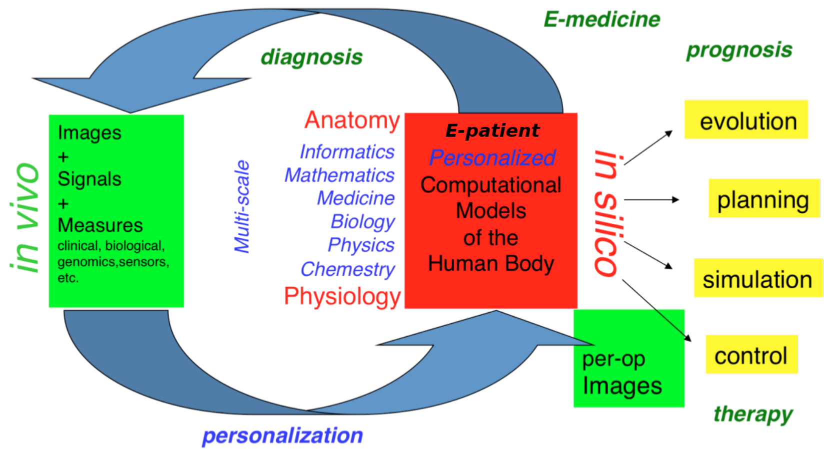

Figure 1. The e-patient for e-medicine

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

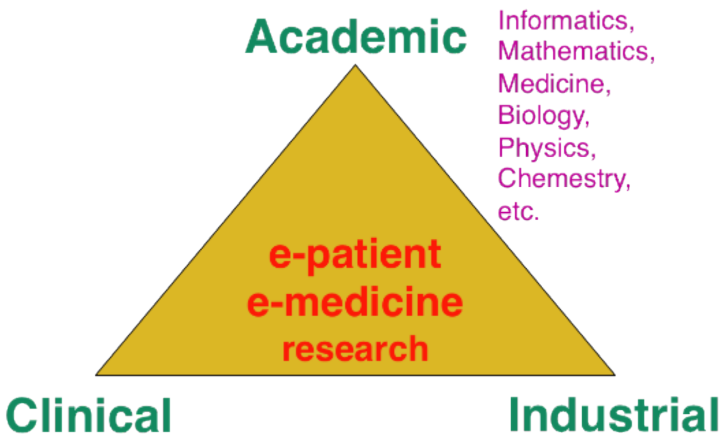

Figure 2. A pluridisciplinary research triangle

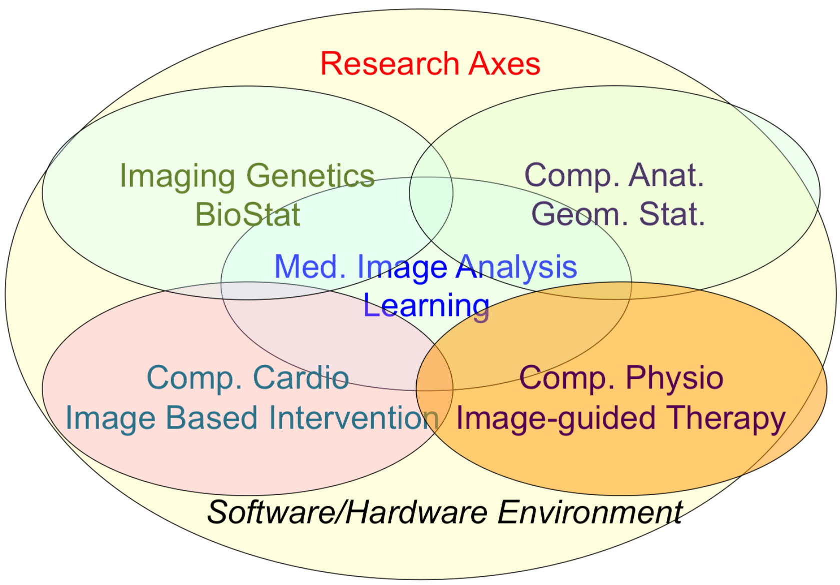

Figure 3. Epione's five main research axes

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 *online* 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 (ongoing collaboration with the Data Science team of EURECOM (France)).

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

- Xavier Pennec received an ERC advanced grant on geometric statistics for life sciences.
- Shuman Jia ranked 2nd in the AI Data Challenge organized by the French Society of Radiology.
- Shuman Jia earned 2nd prize at the Pierre Lafitte PhD competition.
- Fanny Orlhac was awarded for the L'Oréal-UNESCO grant for women in science 2018.
- Wen Wei received a travel award at the MICCAI conference.
- Wen Wei received a travel award from the SFRMBM (french society of magnetic resonance in biology and medicine) for the Joint Annual Meeting ISMRM-ESMRMB 2018.
- Nina Miolane received the second prize (special mention) for the AFRIF (french association for shape interpretation and recognition) PhD prize for her PhD entitled "Geometric Statistics for Computational Anatomy" realized in the context of the associated team GeomStats under the direction of Xavier Pennec (Inria Sophia Antipolis) and Susan Holmes (Stanford University).

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: hal-01753086, version 1

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 Visages 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: http://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. 2017 Oct 24. pii: S1053-8119(17)30706-1. doi: 10.1016/j.neuroimage.2017.08.059. HAL Id : hal-01617750 https://hal.archives-ouvertes.fr/hal-01617750/

- Authors: Marco Lorenzi and Maurizio Filippone
- Contact: Marco Lorenzi
- 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: Stéphane Cotin
- 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/

6. New Results

6.1. Medical Image Analysis

6.1.1. Learning a Probabilistic Model for Diffeomorphic Registration

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 modeling, deep learning, latent variable model, deformation transport, disease clustering

We developed a probabilistic approach for deformable image registration in 3-D using deep learning methods [30]. This method includes:

- A probabilistic formulation of the registration problem through unsupervised learning of an encoded deformation model (Fig. 4).
- A differentiable exponentiation layer and an user-adjustable smoothness layer that ensure the outputs of neural networks to be regular and diffeomorphic.
- An analysis of size and structure of a latent variable space for registration.
- Experiments on deformation transport and disease clustering.

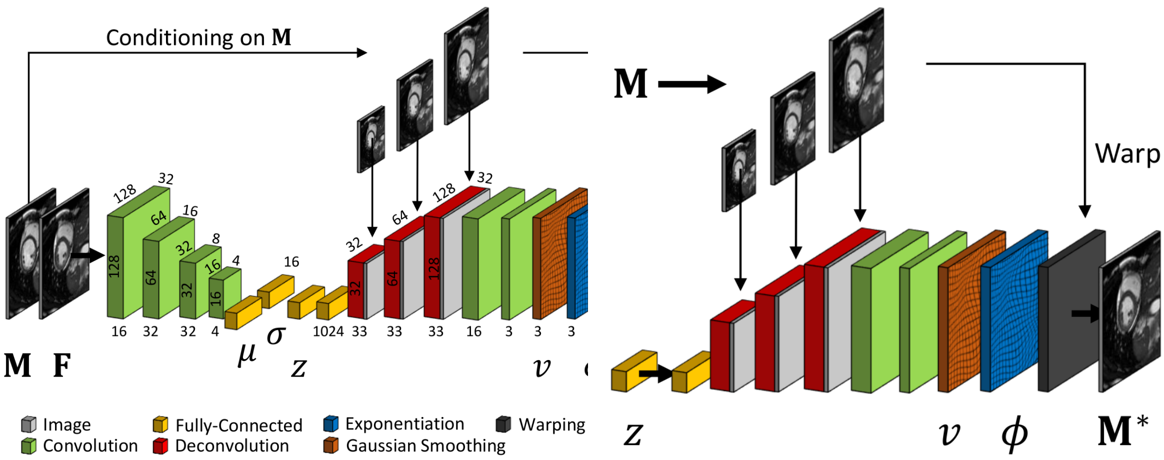

Figure 4. (Left) Probabilistic registration network including a diffeomorphic layer (exponentiation). Deformations are encoded in z from which velocities are decoded while being conditioned on the moving image. (Right) Decoder network for sampling and deformation transport: Apply z-code conditioned on any new image $\mathbf{M}$.

6.1.2. Learning Myelin Content in Multiple Sclerosis from Multimodal MRI

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

- We predict myelin content from multiparametric MRI [36].
- We design an adaptive loss and a sketch-refinement process for GANs, decomposing the problem into anatomy/physiology and myelin content prediction (Fig. 5).
- We show similar results to the PET-derived gold standard.

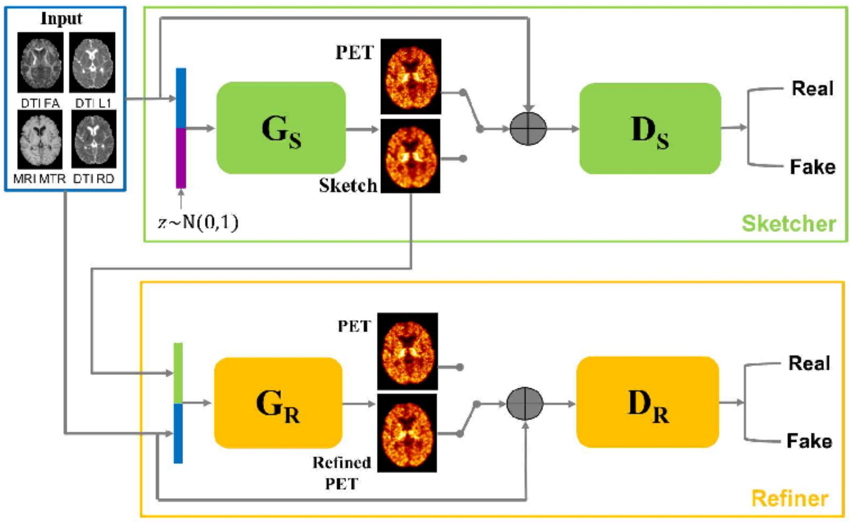

Figure 5. The sketcher receives MR images and generates the preliminary anatomy and physiology information. The refiner receives MR images IM and the sketch IS. Then it refines and generates PET images.

6.1.3. Consistent and Robust Segmentation of Cardiac Images with Propagation

Participants: Qiao Zheng [Correspondant], Hervé Delingette, Nicolas Duchateau, Nicholas Ayache.

This project is funded by European Research Council (MedYMA ERC-AdG-2011-291080).

Cardiac segmentation, deep learning, neural network, 3D consistency, spatial propagation

We propose a method based on deep learning to perform cardiac segmentation on short axis MRI image stacks iteratively from the top slice (around the base) to the bottom slice (around the apex) [26][62]. At each iteration, a novel variant of U-net is applied to propagate the segmentation of a slice to the adjacent slice below it (Fig. 6).

- 3D-consistency is hence explicitly enforced.
- Robustness and generalization ability to unseen cases are demonstrated.
- Results comparable or even better than the state-of-the-art are achieved.

The corresponding open source software, CardiacSegmentationPropagation, is available in https://team.inria.fr/epione/en/software/.

6.1.4. Deep Learning for Tumor Segmentation

Participants: Pawel Mlynarski [Correspondant], Nicholas Ayache, Hervé Delingette, Antonio Criminisi [MSR].

This work is funded by Inria-Microsoft Joint Center and is done in cooperation with Microsoft Research in Cambridge.

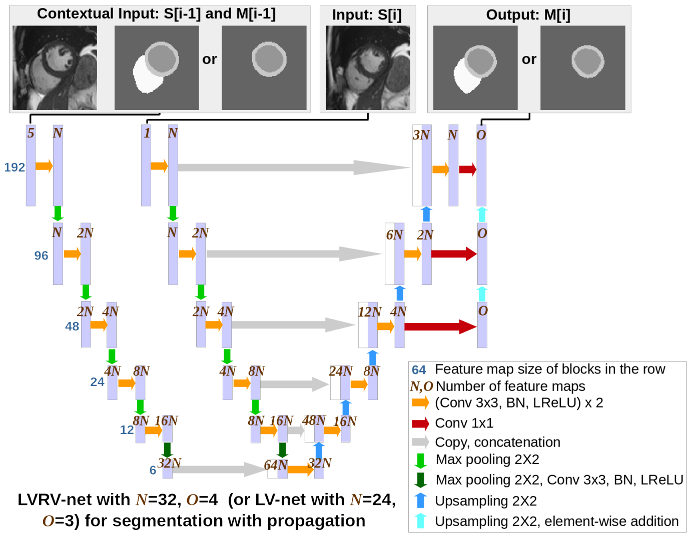

Figure 6. Propagation of cardiac segmentation by a neural network.

deep learning, semi-supervised learning, segmentation, MRI, tumors

- We proposed a model for tumor segmentation which is able to analyze a very large spatial context by combining 2D and 3D CNNs [56] (Fig. 7). Top-3 performance was obtained on BRATS 2017 challenge.
- We proposed an approach to train CNNs for tumor segmentation with a mixed level of supervision [55]. Our approach significantly improves segmentation accuracy compared to standard supervised learning.
- We designed a system for segmentation of organs at risk for protontherapy. Promising preliminary results were obtained.

6.2. Imaging & Phenomics, Biostatistics

6.2.1. Radiomic analysis to improve diagnosis and therapy in oncology

Participants: Fanny Orlhac [Correspondant], Nicholas Ayache, Charles Bouveyron, Jacques Darcourt [CAL], Hervé Delingette, Olivier Humbert [CAL], Pierre-Alexandre Mattei [Copenhague University], Thierry Pourcher [CEA], Fanny Vandenbos [CHU Nice].

Inria postdoctoral fellowship for 16 months

Radiomics, Statistical learning, Metabolomics

- We proposed a modeling which extends the High-Dimensional Discriminant Analysis (HDDA) model by incorporating a sparsity pattern for each class, called sparse HDDA (sHDDA) [21].
- We demonstrated its efficacy in identifying lung lesions based on CT radiomic features (see Figure 8) [21] or triple-negative breast lesions from PET radiomic features and metabolomic data [34], [32], [33]. Thanks to the class-specific variable selection, the final model can be easily interpreted by physicians.
- We also demonstrated the capacity of the ComBat method to harmonize radiomic features extracted from PET images acquired with different imaging protocols [40], [39].

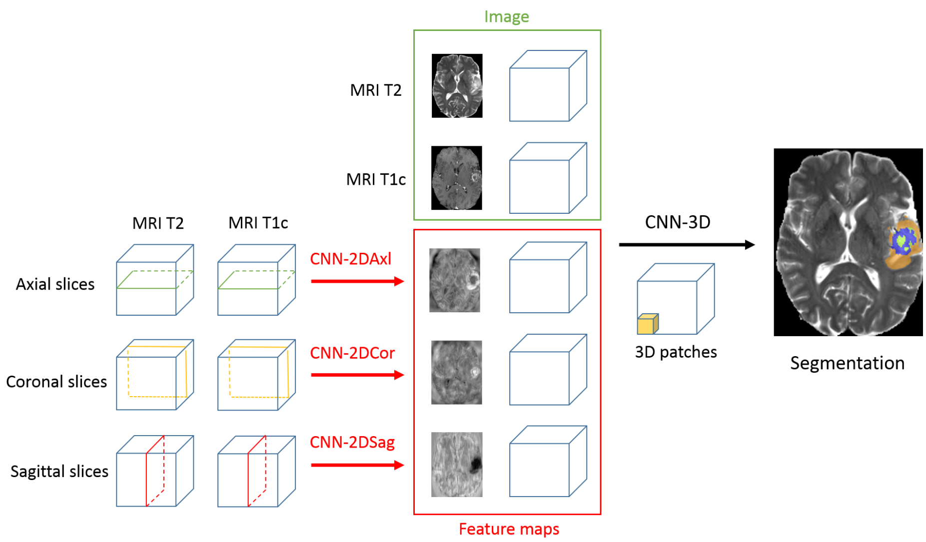

Figure 7. Illustration of our 2D-3D model for brain tumor segmentation.

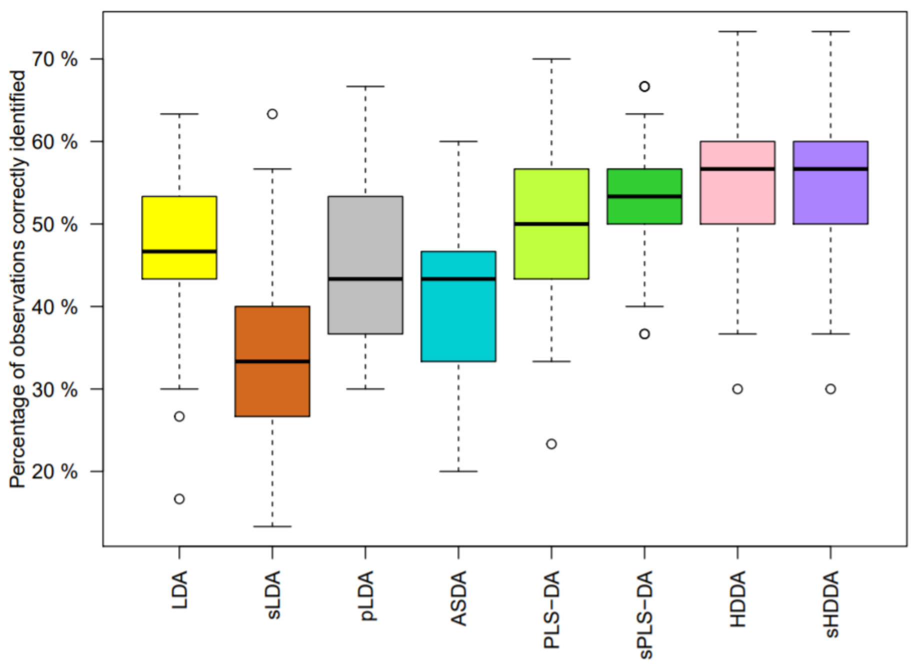

Figure 8. Classification accuracy of the eight statistical methods, including HDDA in pink and sHDDA in purple, to identifying lung lesions based on radiomic features extracted from CT images.

6.2.2. Statistical learning on large databases of heterogeneous imaging, cognitive and behavioral data

Participants: Luigi Antelmi [Correspondent], Marco Lorenzi, Valeria Manera, Philippe Robert, Nicholas Ayache.

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.

We developed a computationally efficient formulation of probabilistic latent variable models [37]. This approach is capable to highlight meaningful relationships among biomarkers in the context of Alzheimer's disease (Figure 9) that can be used to develop optimal strategies for disease quantification and prediction.

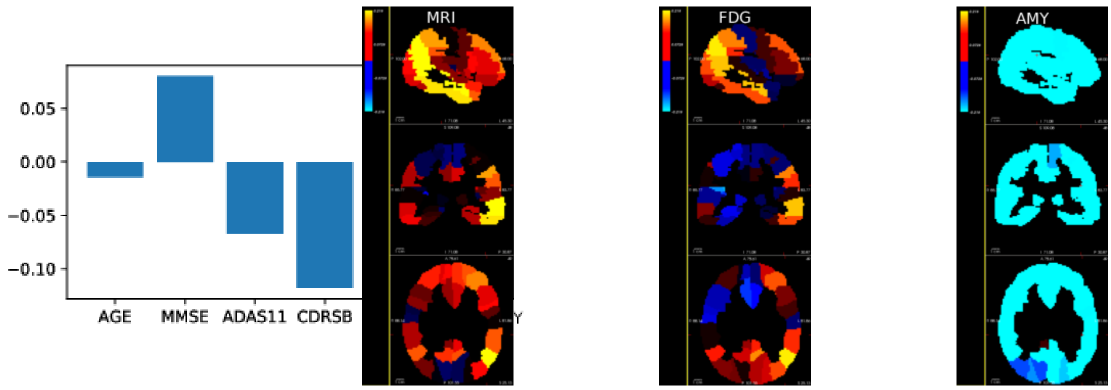

Figure 9. Joint relationships among Alzheimer's disease biomarkers discovered by our multi-channel model in the ADNI dataset. Relationships in line with the current literature discoveries. Clinical biomarkers on the left; brain imaging biomarkers on the right: gray matter density (MRI), glucose uptake (FDG), amyloid uptake (AMY).

6.2.3. Joint Biological & Imaging markers for the Diagnosis of severe lung diseases

Participants: Benoît Audelan [Correspondant], Hervé Delingette, Nicholas Ayache.

Lung cancer, Early detection, Sparse Bayesian Learning

Lung cancer is among the most common cancer and is considered to be one of the most important public health problem. The aim of this work is to improve the detection of lung cancer by combining imaging and biological markers. Exploratory analysis have been conducted to discriminate cancer patients versus controls from circulating miRNAs data using sparse Bayesian learning and to automatically pre-process lung CT images (Fig. 10).

[0] http://adni.loni.usc.edu/

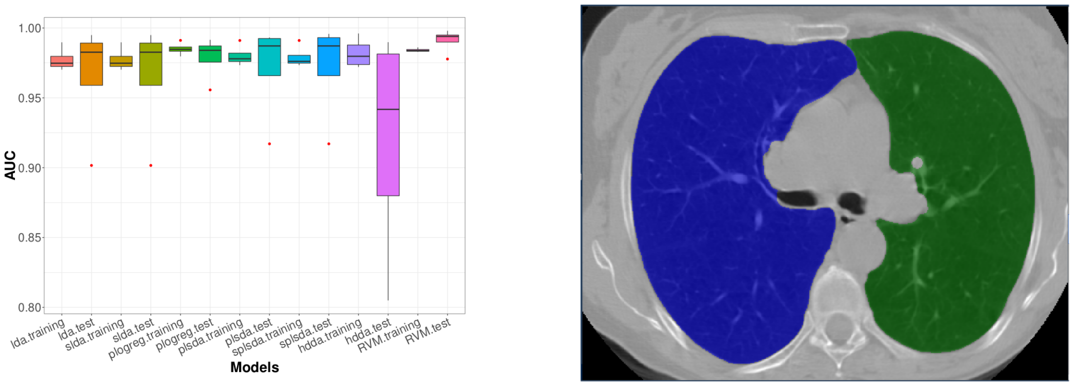

Figure 10. Comparison of statistical methods for classifying lung cancer patient from miRNAs data and lung segmentation

6.2.4. A data-driven model of mechanistic brain atrophy propagation in dementia

Participants: Sara Garbarino [Correspondant], Marco Lorenzi.

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 "AtroProDem: A data-driven model of mechanistic brain Atrophy Propagation in Dementia".

Gaussian Processes, Bayesian non–parametric modelling, neuroimaging data, protein dynamics, brain network

Models of misfolded proteins aim at discovering the bio-mechanical properties of neurological diseases by identifying plausible associated dynamical systems. Solving these systems along the full disease trajectory is usually challenging, due to the lack of a well defined time axis for the pathology. This issue is solved by disease progression models where long-term progression trajectories are estimated via time reparametrization of individual observations. However, due to their loose assumptions on the dynamics, they do not provide insights on the bio-mechanical properties of protein propagation.

In this project we propose a unified model of spatio-temporal protein dynamics based on the joint estimation of long-term protein dynamics and time reparameterization of individuals observations (Figure 11). The model is expressed within a Gaussian Process regression setting, where constraints on the dynamics are imposed through non–linear dynamical systems.

6.2.5. Federated Learning in Distributed Medical Databases: Meta-Analysis of Large-Scale Subcortical Brain Data

Participants: Santiago Silva [Correspondant], Marco Lorenzi, Boris Gutman, Andre Altman, Eduardo Romero, Paul M. Thompson.

This work was supported by the French government, through the UCAJEDI Investments in the Future project managed by the National Research Agency (ANR) with the reference number ANR-15-IDEX-01 (project Meta-ImaGen).

Federated learning, distributed databases, PCA, SVD, meta-analysis, brain disease.

We proposed a federated learning framework for securely accessing and meta-analyzing any biomedical data without sharing individual information.

- A frontend pipeline for preprocessing and analyzing data was proposed, including: standardization, confounders correction, and variability analysis via federated PCA.

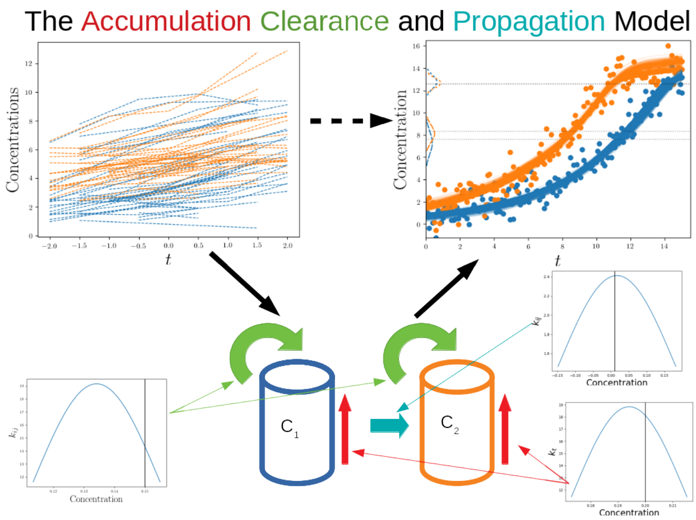

Figure 11. Schematic representation of our framework. Here we have two brain regions whose concentrations are collected for many subjects over a short term time span. The dynamics of such concentrations is described in terms of accumulation, clearance and propagation parameters. The proposed Bayesian framework estimates the distribution of such parameters and the long term trajectories with respect to the estimated disease time axis.

- Tested on multi-centric and multi-diagnosis databases (ADNI, PPMI and UK-Biobank) showed a clear differentiation between control and Alzheimer's subjects (Figure 12).
- Further developments of this study will extend the proposed analysis to large-scale imaging genetics data, such as in the context of the ENIGMA meta-study.

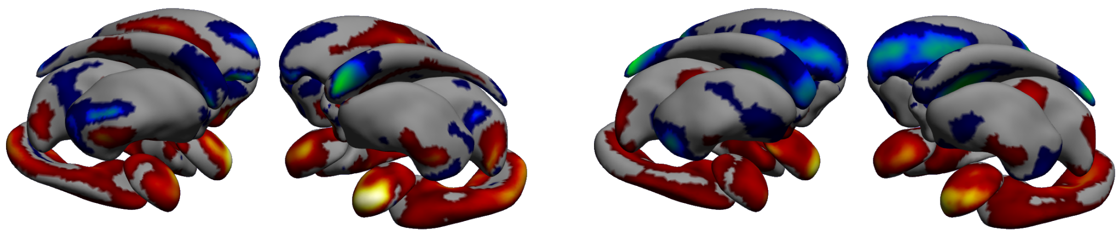

Figure 12. First principal component estimated with the proposed federated framework. The component maps prevalently hippocampi and amigdalae. ***Left:*** *Thickness.* ***Right:*** *Log-Jacobians.*

6.3. Computational Anatomy

6.3.1. 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 project is to develop a spatio-temporal model of Alzheimer's Disease (AD) progession [47]. 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 monotonic Gaussian processes (Figure 13, left-middle panel). We also compute an individual time-shift parameter to assess the disease stage of each subject (Figure 13, right panel).

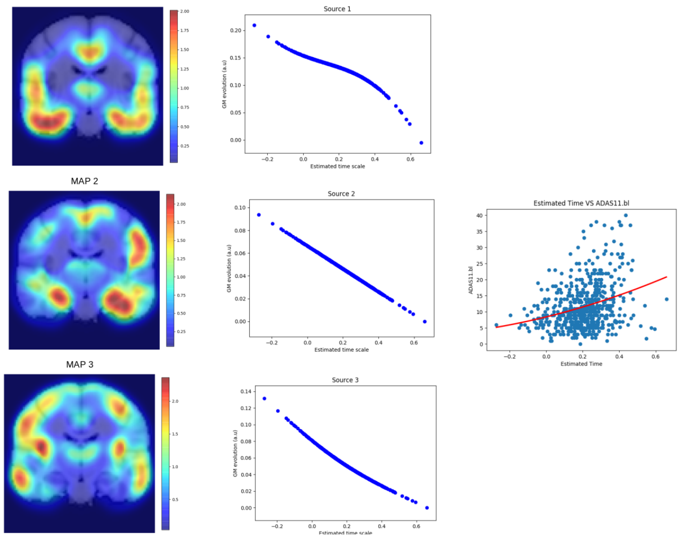

Figure 13. Left-Middle: Brain structures involved in AD along with their temporal evolution. Right: Correlation between ADAS11 cognitive score and the individual time-shift.

6.3.2. A model of brain morphological evolution

Participants: Raphaël Sivera [Correspondant], Hervé Delingette, Marco Lorenzi, Xavier Pennec, Nicholas Ayache.

Longitudinal modeling, Deformation framework, Brain morphology, Alzheimer's disease, Aging.

We proposed a deformation-based generative model of the brain morphological evolution that can jointly describes the effect of aging and Alzheimer's disease. It relies on longitudinal description of the aging and disease consequences and can be use to compute image-based cross-sectional progression markers. This approach is able to propose a description of the disease evolution, population and subject-wise(see Figure 14) and open the way to a better modeling of the disease progression.

6.3.3. Geometric statistics

Participant: Xavier Pennec [Correspondant].

This work is partially funded by the ERC-Adv G-Statistics.

Statistics on manifolds, Differential geometry,

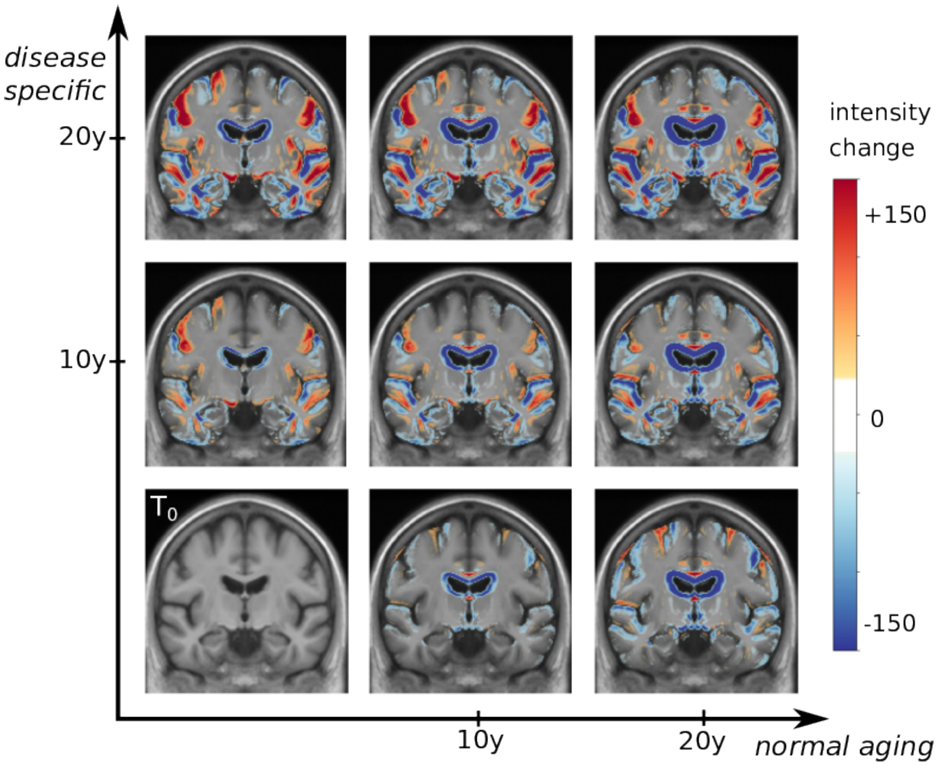

Figure 14. Representation of the 2D parametric template subspace generated by the model. In these images, the bottom row correspond to a healthy evolution, and the diagonal (from bottom left to top right) to a typical pathological evolution. The colors represent the voxel-wise intensity differences between the images and the reference T_0 to highlight the boundary shifts between tissues and CSF.

Beyond the mean value, Principal Component Analysis (PCA) is often used to describe the main modes of variability and to create low dimensional models of the data. Generalizing these tools to manifolds is a difficult problem. In order to define low dimensional parametric subspaces in manifolds, we proposed in [22] to use the locus of points that are weighted means of a number of reference points. These barycentric subspaces locally define submanifolds which can naturally be nested to provide a hierarchy of properly embedded subspaces of increasing dimension (a flag) approximating the data better and better. This defines a generalization of PCA to manifolds called Barycentric Subspace Analysis (BSA) which provides a new perspective for dimension reduction. It appears to be well suited for implicit manifolds such as the ones defined by multiple registrations in longitudinal or cross-section image analysis. An example of such an application was provided in [23] for 4D cardiac image sequences.

In classical estimation problems, the number of samples is always finite. The variability that this induces on the estimated empirical mean is a classical result of the law of large numbers in the asymptotic regime. In manifolds, it is not clear how the curvature influences the estimation of the empirical Fréchet mean with a finite number of samples. Preliminary results showed that there is an unexpected bias inversely proportional to the number of samples induced by the gradient of the curvature and a correction term of the same order on the covariance matrix slowering or accelerating the effective convergence rate towards the Fréchet mean of the underlying distribution. These preliminary results were derived using a new simple methodology that is also extending the validity from Riemannian manifolds to affine connection spaces [45].

6.3.4. Brain template as a Fréchet mean in quotient spaces

Participants: Nina Miolane [Correspondant], Xavier Pennec.

Computational anatomy, Morphological brain template, Hierarchical modeling.

Geometrically, the procedure used to construct the reference anatomy for normalizing the measurements of individual subject in neuroimaging studies can be summarized as the Fréchet mean of the images projected in a quotient space. We have previously shown that this procedure is asymptotically biased, therefore inconsistent. In [15], we presented a methodology that quantifies spatially the brain template's asymptotic bias. We identify the main variables controlling the inconsistency. This leads us to investigate the topology of the template's intensity levels sets, represented by its Morse-Smale complex. We have proposed a topologically constrained adaptation of the template computation that constructs a hierarchical template with bounded bias. We apply our method to the analysis of a brain template of 136 T1 weighted MR images from the Open Access Series of Imaging Studies (OASIS) database.

6.3.5. Cardiac Motion Evolution Modeling from Cross-Sectional Data using Tensor Decomposition

Participants: Kristin Mcleod [Simula Research Laboratory], Maxime Sermesant, Xavier Pennec.

Cardiac motion tracking, modeling cardiac motion evolution over time

Cardiac disease can reduce the ability of the ventricles to function well enough to sustain long-term pumping efficiency. We proposed in [14] a cardiac motion tracking method to study and model cohort effects related to age with respect to cardiac function. The proposed approach makes use of a Polyaffine model for describing cardiac motion of a given subject, which gives a compact parameterisation that reliably and accurately describes the cardiac motion across populations. Using this method, a data tensor of motion parameters is extracted for a given population. The partial least squares method for higher-order arrays is used to build a model to describe the motion parameters with respect to age, from which a model of motion given age is derived. Based on cross-sectional statistical analysis with the data tensor of each subject treated as an observation along time, the left ventricular motion over time of Tetralogy of Fallot patients is analysed to understand the temporal evolution of functional abnormalities in this population compared to healthy motion dynamics (see Figure 15).

6.3.6. Challenging cardiac shape and motion statistics

Participants: Marc-Michel Rohé [correspondant], Maxime Sermesant, Xavier Pennec.

Shape statistics, Non-rigid registration, Deep learning, Cardiac shape and motion

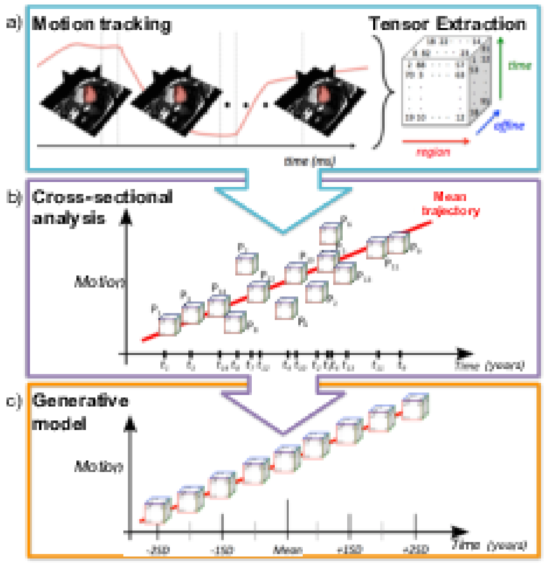

Figure 15. Building a generative model of the long-term motion changes in a population (c) by a) building a data tensor of polyaffine motion parameters that represent the motion over the cardiac cycle for each subject in the population using cross-sectional statistical analysis of polyaffine tensors and b) performing cross-sectional statistical analysis of the data tensors.

Two of the methods previously developed by Marc-Michel Rohé in his PhD were benchmarked against other state of the art methods in two successive MICCAI challenges. First, the SVF-net developed to perform a very-fast inter-subject heart registration based on convolutional neural networks was embedded into a multi-atlas segmentation pipeline and tested against other deep learning techniques for the automatic MRI cardiac multi-structures segmentation [2]. Second, a combination of polyaffine cardiac motion tracking and supervised learning was used to predict myocardial infarction [25]. Both challenges demonstrate the good performances of the tested methods.

6.4. Computational Physiology

6.4.1. CIMPLE : Cochlear Implantation Modeling, PLanning & Evaluation

Participants: Zihao Wang [Correspondant], Hervé Delingette, Thomas Demarcy [Oticon Medical], Clair Vandersteen [IUFC], Nicolas Guevara [IUFC], Charles Raffaelli [CHU], Dan Gnansia [Oticon Medical], Nicholas Ayache.

This work is funded by the Provence-Alpes-Côte-d'Azur region, the Université Côte d'Azur and Oticon Medical.

Statistic Learning, Image segmentation, Cochlea Implantation

The work aims to establish an effective, quantitative and rapid assessment method for human cochlear implantation planning and adjustment.

During last one year, our team explored a cost-effectively and practically algorithm to achieve the goal.

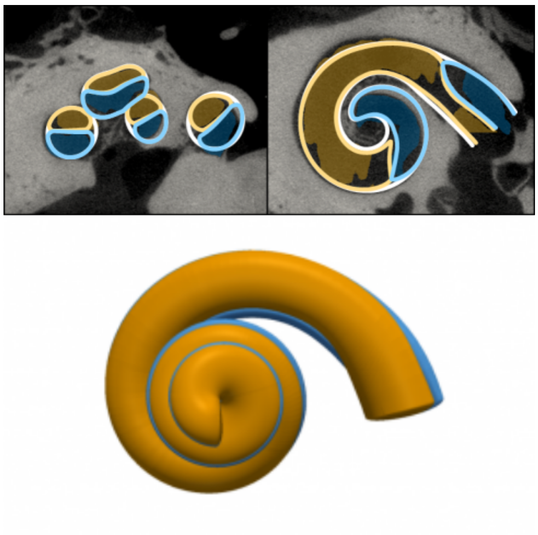

Figure 16. The figure shown a example segmentation on micro-CT image. Lower is the parametric model that quantitative mesure the cochea shape.

6.5. Computational Cardiology & Image-Based Cardiac Interventions

6.5.1. Population-based priors for group-wise Personalisation

Participants: Roch Molléro [Correspondant], Hervé Delingette, Xavier Pennec, Nicholas Ayache, Maxime Sermesant.

The authors acknowledge the partial funding by the MD-Paedigree EU Project.

Personalised cardiac model, Parameter observability, Statistical modeling, Dimensionality reduction, Heterogeneous clinical data, Imputation

Personalised cardiac models have a large number of parameters while the available data for a given patient is typically limited to a small set of measurements, thus the parameters cannot be estimated uniquely. This is a practical obstacle for clinical applications, where accurate parameter values can be important. Here we explore an original approach based on an algorithm called Iteratively Updated Priors (IUP), in which we perform successive personalisations of a full database through Maximum A Posteriori (MAP) estimation, where the prior probability at an iteration is set from the distribution of personalised parameters in the database at the previous iteration (Figure 17). At the convergence of the algorithm, estimated parameters of the population lie on a linear subspace of reduced (and possibly sufficient) dimension in which for each case of the database, there is a (possibly unique) parameter value for which the simulation fits the measurements. We first show how this property can help the modeler select a relevant parameter subspace for personalisation. In addition, since the resulting priors in this subspace represent the population statistics in this subspace, they can be used to perform consistent parameter estimation for cases where measurements are possibly different or missing in the database, which we illustrate with the personalisation of a heterogeneous database of 811 cases [18].

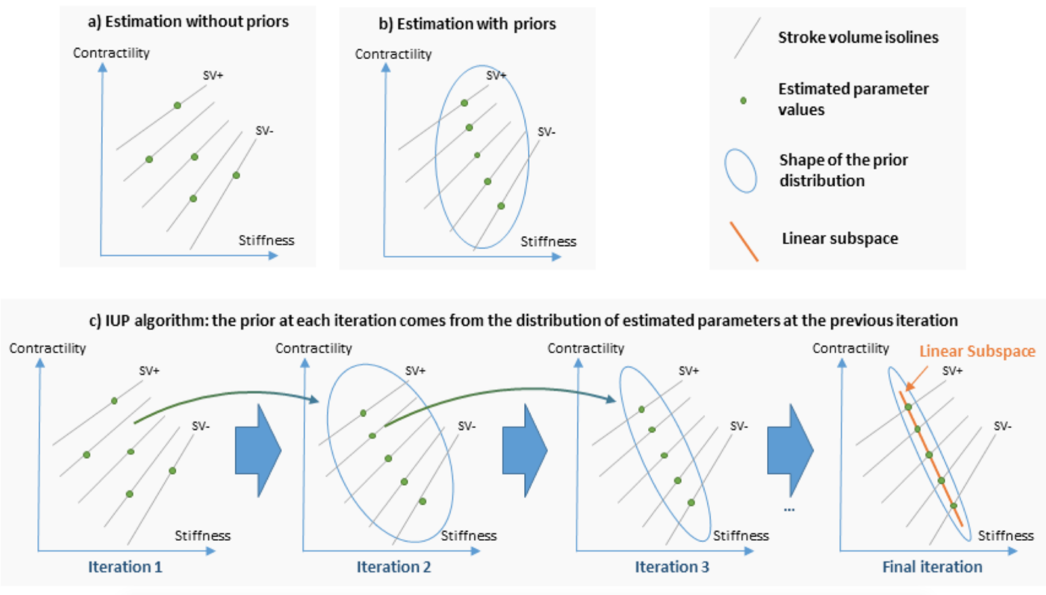

Figure 17. Schematic representation of parameter estimation problem: both contractility and stiffness are estimated from the stroke volume (SV). Both have an influence on the stroke volume (SV) so there are isolines of stroke volume (in grey) for varying parameters. (a) estimation without priors, the estimated values (green) for each case can be anywhere on an isoline (grey). (b) estimation performed with a prior (Gaussian covariance in blue), estimated values are grouped closer to prior mean. (c) Iteratively Updated Priors (IUP) algorithm performs successive estimations where the prior is set from the distribution of estimated parameters at the previous iteration. This leads the parameters to lie on a reduced linear subspace (orange).

6.5.2. Fast Personalized Computer Simulation of Electrical Activation from CT Imaging in Post-infarction Ventricular Tachycardia

Participants: Nicolas Cedilnik [Correspondant], Hubert Cochet [IHU Liryc, Bordeaux], Maxime Sermesant.

This work is funded by the IHU Liryc, in Bordeaux.

Cardiac modeling, Personalised simulation, ablation, intervention guidance.

In the vast majority of post-MI VT ablation procedures, VT is either non inducible or non mappable. We introduce a fast and robust model of cardiac electrophysiology that can be directly parameterized from CT images to predict activation maps (Figure 18). The model is based on the Eikonal equation for wave propagation, where local conduction velocities are estimated from CT. A fully automated method is used to segment the LV wall and assign local conduction velocity according to local LV thickness. Then, a "channelness" filter automatically detects potential VT isthmuses as channels of preserved thickness within severely thinned scar. The model can then be paced within each channel to produce simulated activation maps within seconds. A neural network for automated LV wall segmentation was trained on 450 CTs segmented by experts. Validation, performed on another 50 cases, showed excellent accuracy (Dice score vs. expert 0.95). In 11 patients undergoing post-MI VT ablation (age 58±13, 9 men), simulated activation maps were validated vs. 25 high density maps acquired in Rhythmia (16 paced, 9 VT). Quantitative differences between predicted and measured local activation times remained substantial, particularly in dense scar (> 50ms). Nonetheless, activation patterns were well predicted in most cases (22/25), the 3 poor correlations being observed in patients with fewer scar. Personalized simulation of activation maps from CT scan is feasible and reliably reproduces activation patterns in post-MI VT. The method is fast enough to be used clinically in an interactive fashion for procedural planning [4].

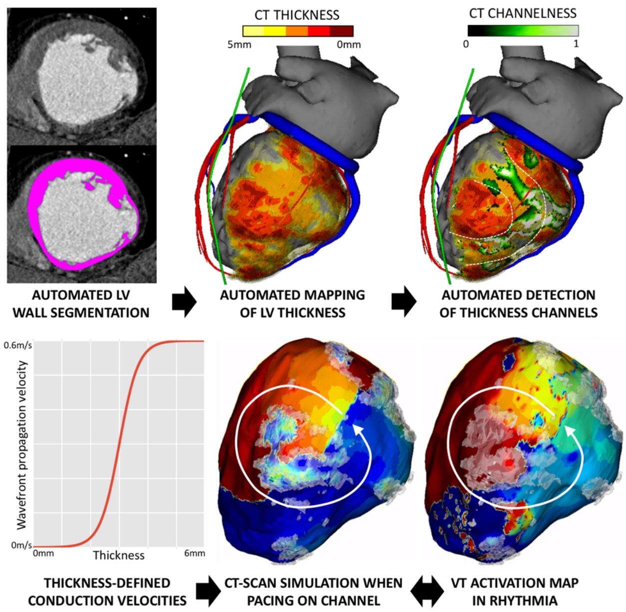

Figure 18. Our image-based model personalization pipeline

6.5.3. Cardiac Modeling, Medical Imaging and Machine Learning for Electrostructural Tomography

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.

Machine Learning, Cardiac modeling, Personalised simulation, Inverse problem of ECG, Electrical simulation.

Electrocardiographic imaging (ECGI) aims at reconstructing cardiac activity from torso measurements.To achieve this one has to solve the ill-posed inverse problem of the torso propagation. We propose a novel application for Deep Learning Networks to learn spatio-temporal correlations on ECGI (Figure 19). We developped a conditional variational auto-encoder (CVAE).The input are activation maps and the model takes two conditions: on one hand the cardiac shape(cardiac segmentation) and the other one the ECG signals.

The model currently involves simulated data: 120 activations maps were simulated from one cardiac geometry along with simulated body surface potential maps.80% of the data was used for training and the remaining 20% for testing. As a result we were able to observe a good prediction of the activation pattern.

Next, we will test the model with real data provided by the IHU Liryc.

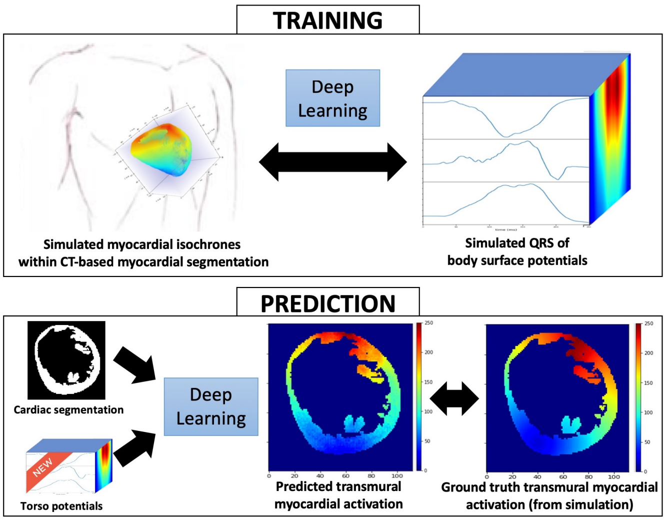

Figure 19. Setup of the conditional variational auto-encoder based on synthetic data

6.5.4. Discovering the link between cardiovascular pathologies and neurodegeneration through biophysical and statistical models of cardiac and brain images

Participants: Jaume Banus Cobo [Correspondant], Maxime Sermesant, Marco Lorenzi.

Université Côte d'Azur (UCA)

Lumped models - Biophysical simulation - Statistical learning

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 (Fig. 20). We are also testing data-driven statistical learning models for the discovery of associations between cardiac function and brain damage. For example, by applying CCA we identified a first component that shows a positive correlation between the volume of white matter hyper intensities (WMHs), the number of WMHs lesions, the brain ventricles volume and high blood pressure values. On the other side we observed a second component, inversely associated to the first one, in which we observe a strong correlation between ejection fraction (EF) and total brain volume (white matter plus grey matter).

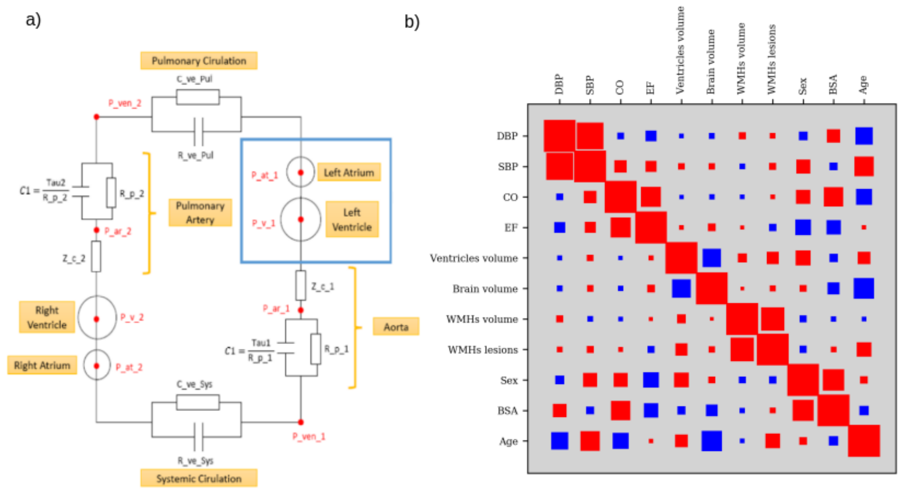

Figure 20. a) Schematic representation of the 0D model used to simulate the whole body circulation, its parameters are optimized to fit the available clinical measurements b) Partial correlations between cardiovascular, brain and demographic variables. Red represents positive correlation and blue negative correlation.

6.5.5. Automatic Image Segmentation of cardiac structures with Adapted U-Net

Participants: Shuman Jia [Correspondant], Antoine Despinasse, Zihao Wang, Hervé Delingette, Xavier Pennec, Hubert Cochet, Maxime Sermesant.

The authors acknowledge the partial funding by the Agence Nationale de la Recherche (ANR)/ERA CoSysMedSysAFib and ANR MIGAT projects.

We proposed automated, two-stage, three-dimensional U-Nets with a contour loss, to segment the left atrium, as explained in [28], which obtained state-of-the-art results in the STACOM international challenge (Figure 21). Using similar method, we participated in Data Challenge organised at Journées Francophones de Radiologie and obtained a second place for renal cortex segmentation.

6.5.6. Parallel Transport of Surface Deformation

Participants: Shuman Jia [Correspondant], Nicolas Duchateau, Pamela Moceri, Xavier Pennec, Maxime Sermesant.

The authors acknowledge the partial funding by the Agence Nationale de la Recherche (ANR)/ERA CoSysMedSysAFib and ANR MIGAT projects.

We looked into normalization of temporal deformation and proposed a more symmetric mapping scheme for pole ladder, which relies on geodesic symmetries around mid-points, as illustrated in [29] (Figure 22)). This modified parallel transport method method was shown to be of order 4 on general manifolds and exact in symmetric spaces [58].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

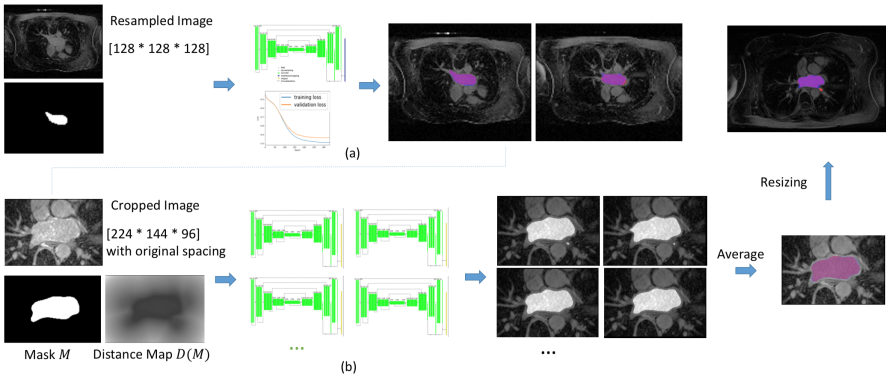

Figure 21. The framework of successive U-Nets training. (a) The fist U-Net - cropping; (b) the second U-Net - segmenting, with ensemble prediction models. We show here axial slices of MR images, overlapped with manual segmentation of the left atrium in blue, our segmentation in red, intersection of the two in purple.

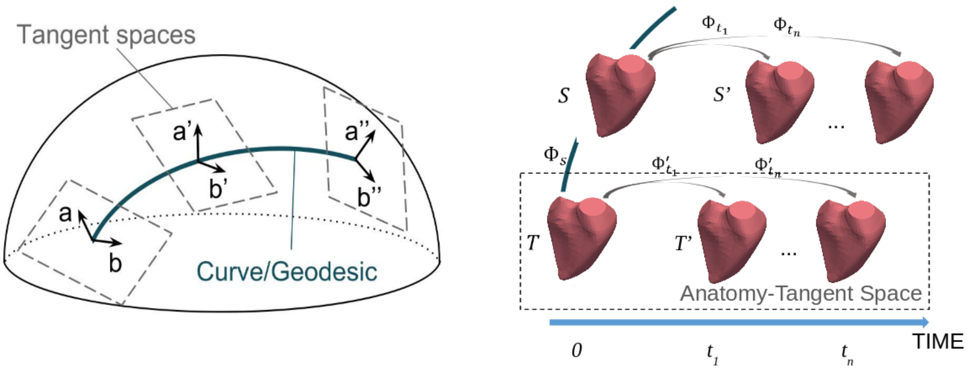

Figure 22. Illustration of parallel transport of vectors a and b along a curve (left) and its application to cardiac imaging (right) with a focus on surfaces.

7.1.1. Microsoft Research

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 Therapixel

Therapixel[0] is a spin-off of the Asclepios (Inria Sophia Antipolis) and Parietal (Inria Saclay) project teams founded in 2013. Therapixel makes surgical information systems. It relies on depth sensing, advanced software processing and innovative user interfaces to provide touchless control of the computer. This technology allows for a direct control of the computer, which sterility constraints made impractical in the past. In 2015, Therapixel obtained the CE marking of its product on touchless visualization of medical images.

7.1.3. Spin-off company inHEART

inHEART[0] is a spin-off of the Asclepios 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.

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. Median Technologies

Median technologies, Sophia Antipolis (FR) funded the 5 months gap year internship of Souhaiel Riahi and the 6 months Master 2 level internship of Nour Ediine al Orjany, co-advised by Xavier Pennec and Hervé Delingette on the characterization of hepatic lesions and fibrosis in CT image using machine learning methods

8. Partnerships and Cooperations

8.1. Regional Initiatives

- 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).
- 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.
- 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.

[0] http://www.msr-inria.fr/projects/4d-cardiac-mr-images
[0] http://www.msr-inria.fr/projects/medilearn
[0] http://www.therapixel.com/
[0] http://www.inheart.fr/

8.2. National Initiatives

8.2.1. Consulting for Industry

- Nicholas Ayache is a scientific consultant for the company Mauna Kea Technologies (Paris).
- Marco Lorenzi is a scientific consultant for the company MyDataModels (Sophia Antipolis).
- Xavier Pennec is a scientific consultant for the company Median Technologies (Sophia Antipolis)
- Maxime Sermesant is a scientific consultant for the company inHEART (Bordeaux)

8.2.2. 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
Inria contact: 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 led by X. Pennec 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. 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.

8.4.3.1.2. Massachusetts General Hospital, Boston

A collaboration with Dr Jan Unklebach, Assistant Professor of Radiation Oncology and Dr Jayashree Kalpathy-Cramer, radiology instructor was initiated in 2013 around the topics of tumor growth modeling, radiotherapy planning and edema characterization from MRI.

8.4.3.1.3. 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.

8.4.3.1.4. 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.

8.4.3.1.5. Other International Hospitals

Collaborations with several other European hospitals have been established through the European projects VP2HF, MD PAEDIGREE and SysAFib.

8.5. International Research Visitors

8.5.1. Visits of International Scientists

8.5.1.1. Internships

- Svenja Hüning, PhD student with Johannes Wallner at Graz University in Austria visited the Epione team in November 2018 to work with Xavier Pennec on subdivision schemes on manifolds.
- Santiago Smith Silva Rincon, Master student at the National University of Bogota (CO), visited the Epione team from May to October 2018 to work with Marco Lorenzi on distributed learning methods in imaging-genetics.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Member of the Organizing Committees

- M. Sermesant was a co-chair of the MICCAI 2018 Workshop Statistical Atlases and Computational Models of the Heart (STACOM 2018), which was held in Granada, September 16, 2018.
- H. Delingette was a member of the organizing committee of the scientific day at Inria Sophia Antipolis (September 10th) including two keynote speakers on "Digital privacy" and presenting the activities of the UCA academy on "Networks, Information and Digital Society".

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

- H. Delingette was Workshop and Tutorial co-chair for the international conference Medical Image Computing and Computer Aided Intervention (MICCAI 2018) held in Granada, Spain from Sept. 16-20.

9.1.2.2. Reviewer

- M. Lorenzi was a reviewer for the conferences Neural Information Processing Systems (NIPS 2018), International Conference on Machine Learning (ICML 2018), Medical Image Computing and Computer Aided Intervention (MICCAI 2018), International Conference on Learning Representations (ICLR 2019), IEEE International Symposium of Biomedical Imaging (ISBI 2017-19).
- X. Pennec was a reviewer for Medical Image Computing and Computer Aided Intervention (MICCAI 2018) and the MICCAI workshop on Shape in Medical Imaging (ShapeMI 2018).
- M. Sermesant was a reviewer for Medical Image Computing and Computer Aided Intervention (MICCAI 2018) and the MICCAI workshop STACOM.
- H. Delingette was a reviewer for the International Symposium on Biomedical Imaging (ISBI'18), the international conference on computer-aided interventions (IPCAI'18), the conference on Medical Image Computing and Computer Assisted Intervention (MICCAI 2018), the International Conference on Computer Vision and Pattern Recognition (CVPR 2018).

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- 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).
- H. Delingette is a member of the editorial board of the journal Medical Image Analysis (Elsevier).
- I. Strobant is editorial coordinator for Medical Image Analysis, Elsevier (since october 2001).
- X. Pennec is a member of the editorial board of the journal Medical Image Analysis (Elsevier), of the International Journal of Computer Vision (Springer), of the SIAM Journal on Imaging Sciences (SIIMS), and of the Journal of Mathematical Imaging and Vision (JMIV).
- 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).

9.1.3.2. 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.
- Xavier Pennec was a reviewer for IEEE Transactions on Information Theory, The Annals of Applied Statistics, Linear Algebra and its Applications.
- M. Sermesant was a reviewer for the following journals: Nature Cardiology Reviews, 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, IEEE Transactions in Biomedical Engineering.

9.1.4. Invited Talks

- **N. Ayache** gave the following plenary invited talks:
  - AI for Digital Patients, Int Conf on Image Comput. and Digital Medicine, Chengdu, China, 2018,
  - IA & Healthcare, IA Summit, Sophia Antipolis, 2018,
  - Patient numérique: images, apprentissage, intelligence artificielle, Collége de France 2018,
  - L'intelligence articifielle au coeur de la médecine de précision, Medicen, Paris, 2018.
- **M. Lorenzi** was a speaker for the panel IA & Santé of the SophIA Summit 2018, Sophia Antipolis, November 7th, 2018. He was also invited to give a lecture to the Armour College of Engineering of the Illinois Institute of Technology, Chicago, July 25th 2018, to the General Assembly of the European Clinical Project AMYPAD, Berlin, October 9th 2018, and to the Disease Progression Modeling Workshop of the European project EUROPOND, Geneva, February 19th, 2018.
- **X. Pennec** was invited speaker at the Mathematics and Image Analysis Conference (MIA 2018), 15-17 January 2018, Berlin (DE), at the MFO workshop on Nonlinear Data: Theory and Algorithms, Oberwolfach (DE), 22-28 April 2018, at the MFO workshop on Statistics for Data with Geometric Structure, Oberwolfach (DE), 21-27 January 2018.
- **M. Sermesant** was an invited speaker at the Fields Institute (Toronto) "Mathematics for Medicine" workshop, at the "Myocardial Function" workshop in Leuven, at the CardioFunxion Winter School in Lyon, at the "New Horizons in Heart Failure" conference in Paris, at the "Computing in Cardiology" conference in Maastricht, at the French Radiology Days meeting of Cardiac Imaging in Paris, at the PIC Marie Curie ITN meeting in Bordeaux.
- **H. Delingette** was a keynote speaker at the NAFEMS conference in Paris November 20th 2018, and an invited speaker at the SOFA workshop in Strasburg in November 2018, at the Data Science structuring program evaluation day in Sept. 2018.
- **N. Miolane** was invited speaker at the MFO workshop on Statistics for Data with Geometric Structure, Oberwolfach (DE), 21-27 January 2018, at the Workshop on Geometry in Machine Learning (GiMLi), July 15, 2018, Stockholm, Sweden and at the Seminar of John Hopkins University, Center of Imaging Science, May 19, 2018, Baltimore, USA.

9.1.5. Leadership within the Scientific Community

- **H. Delingette** is a member of the MICCAI Society Board of Directors.

9.1.6. Scientific Expertise

- **N. Ayache** is a member of the following scientific committes:
  - 2016 -: Scientific advisory committee for Région Ile de France (20 members),
  - 2015 -: 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.
- **M. Lorenzi** was reviewer of the funding agencies ANR (Agence Nationale de la Recherche, France) and an expert panel member for the evaluation of the projects submitted to the Flanders Research Foundation, Belgium. He is providing scientific consulting for the company MyDataModels through an Inria Tech research contract.
- **X. Pennec** was a member of the Junior researcher (CR) recruiting committee for Inria-Sophia Antipolis, for the Inria International Chairs Selection Committee, and an evaluator for the Netherlands Organisation for Scientific Research (NWO).
- **M. Sermesant** was an evaluator for the Wellcome Trust (UK) and the NSF (USA).
- **H. Delingette** was an evaluator for the Dutch research council NWO, and or the Research Council of KU Leuven.

9.1.7. Research Administration

- **Xavier Pennec** is co-director and at the board of the Ecole doctorale STIC of Université Côte d'Azur. He is a member of the Doctoral follow-up Committee (CSD) at Inria Sophia Antipolis, of the the "Comité de la Recherche Biomédicale en Santé Publique (CRBSP)" of the Nice hospitals and in charge of the relationships of Inria-Sophia with the Nice University Hospital (CHU). At University Côte d'Azur, 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.
- **Marco Lorenzi** is 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.
- **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 coordinator of the Academy of excellence on "Networks, Information and Digital Society" at the Université Côte d'Azur. He is member of the executive committee 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 Cachan, France.

Master: X. Pennec and H. Delingette, Advanced Medical Imaging, 21h course (28.5 ETD), Master 2 MVA and École Centrale de Paris, France.

9.2.2. Theses Defended

- Pamela Moceri, From normal right ventricle to pathology: shape and function analysis with different loading conditions using imaging and modelling. Started in 2015. Directed by M. Sermesant. Defended on January 25 2018.

9.2.3. PhD in progress

- 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.
- 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.
- Qiao Zheng, Deep learning for cardiac image analysis, Université Côte d'Azur. Started in January 2016. Co-directed by N. Ayache and H. Delingette.
- 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.
- 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.
- 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.

- 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.
- 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.
- 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.
- Nicolas Cedilnik, Personalised Modeling for Ventricular Tachycardia Ablation Planning, Université Côte d'Azur. Started in 2017. 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.
- 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.
- Zihao WANG, Cochlear Implantation Modeling, Planning & Evaluation. Started in 2018. Directed by H. Delingette.

9.2.4. Juries

- Marco Lorenzi was a jury member for the PhD probation exam of Kurt Kutajar and Remi Domingues (EURECOM), Isa Costantini (Athena, Inria), and Radia Zeghari (CoBTeK, Inria, CHU Nice).
- Xavier Pennec was co-supervisor of the PhD thesis of Pauline Bezivin Frere (U. Orsay) defended in July 2018, reviewer for the PhD of Maël Dugast, INSA Lyon, FR, Dec. 2018 and for the PhD of Baptiste Moreau, University of Montpellier II, FR, March 2018. He was the president of the jury of the HDR of Laurent Risser (HDR), U. Toulouse, FR, November 2018.
- Hervé Delingette was a reviewer in the PhD thesis committee of C. Jaquet (ESIEE- Univ. of Paris-Est).
- Maxime Sermesant was a reviewer and a member of the PhD jury of Josselin Duchateau, Bordeaux University (Dec 20), a reviewer for the PhD of Sergio Sanchez, UPF Barcelona (Sep 21) and a member of the PhD jury of Ketan Bacchuwar, ESIEE (Jun 5).

9.3. Popularization

9.3.1. Interventions

- Nicolas Cedilnik, Pierre Tramaloni, Thomas Demarcy, Hervé Delingette and Maxime Sermesant organised a cardiac intervention simulator demo and a cochlear implant demo for the Science Festival at Inria (Dec 7).
- On April the 10th, during the "mathematics week", 2 PhD students (Nicolas Cedilnik and Raphael Sivera) met young pupils (age 8-10) at the ESPE (école supérieure du professorat et de l'éducation) Nice. The pupils were introduced to mathematical concepts in a practical way through the use of toys.

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Team FACTAS

Functional Analysis for the ConcepTion and Assessment of Systems

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
Optimization and control of dynamic systems

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Team FACTAS

Creation of the Team: 2018 January 01

Keywords:

Computer Science and Digital Science:

A6.1.1. - Continuous Modeling (PDE, ODE)
A6.2.1. - Numerical analysis of PDE and ODE
A6.2.5. - Numerical Linear Algebra
A6.2.6. - Optimization
A6.3.1. - Inverse problems
A6.3.4. - Model reduction
A6.4.3. - Observability and Controlability
A6.4.4. - Stability and Stabilization
A6.4.5. - Control of distributed parameter systems
A6.5.4. - Waves
A8.2. - Optimization
A8.3. - Geometry, Topology
A8.4. - Computer Algebra

Other Research Topics and Application Domains:

B1.2.3. - Computational neurosciences
B2.6.1. - Brain imaging
B3.3. - Geosciences
B4.5. - Energy consumption
B6.2.2. - Radio technology
B6.2.3. - Satellite technology

1. Team, Visitors, External Collaborators

Research Scientists

Fabien Seyfert [Team leader, Inria, Researcher]
Laurent Baratchart [Inria, Senior Researcher, HDR]
Sylvain Chevillard [Inria, Researcher]
Juliette Leblond [Inria, Senior Researcher, HDR]
Martine Olivi [Inria, Researcher, HDR]

Faculty Member

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Adam Cooman [Ampleon, from Sep 2018]
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PhD Students

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Post-Doctoral Fellows

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Marie-Line Meirinho [Inria]

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 [67]. 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 [75] 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 [31].

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 [69], [54]. Apics contributed to this area 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 [59] 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] [29], [79]. 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 produce the same field outside this set; this phenomenon is called *balayage* [66]. 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 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], [39], [42]. 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 last year. The proposal for our new team Factas is since then being built and examined by the CEP (Comité des Équipes-Projets) of the Research Center, on its way to become a project-team.

3.2. Range of inverse problems

3.2.1. Elliptic partial differential equations (PDE)

Participants: Laurent Baratchart, Sylvain Chevillard, Juliette Leblond, 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 [52], [55].

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 [58]. 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 [5], [32]. The case of the critical exponent 2 is treated in [28], which apparently provides the first example of well-posedness for the 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 $r > 2$.

Generalized Hardy classes as above are used in [29] 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], [35], 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 [7], [36], [49]. Initial schemes to locate cracks or sources *via* rational approximation on planar domains were obtained this way [39], [42], [52]. 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 [8], [40]. 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 [11] 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 [24], [11].
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 [53], 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 3.4.1).

Let us mention that extensions of classical coupling matrix theory to frequency-dependent (reactive) couplings have been carried-out in recent years [1] for 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 [23] [10]. 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 [74], 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 [25]. Dwelling on this, Factas contributed differential parametrizations (atlases of charts) of lossless matrix functions [24], [68], [63] which are fundamental to our rational approximation software RARL2 (see Section 3.4.4). 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 and 8.2.2.

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 reactors, 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 generalization generates both doctoral and postdoctoral work by new students in the team.

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 [38], [41], [46], the solution to this convex infinite-dimensional optimization problem can be obtained when $p \ne 1$ 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 [61]:

> (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 $L^p(T)$.

The case $p = 1$ is more or less 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 [13]. In this form, the problem comes close to (but still is different from) H^∞ frequency optimization used in control [64], [73]. 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. Then, the Hardy spaces in Problem (P) are those of a so-called conjugate Beltrami equation: $\bar{\partial} f = \nu \overline{\partial f}$ [65], which are studied for $1 < p < \infty$ in [5], [28], [32] and [56]. 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 [58].

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 [77]. 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 [38] 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) [35].

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 [71].

Companion to problem (P_2) is problem (P_3) below.

(P_3) Let $1 \le p \le \infty$ 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 $1 \le p \le \infty$, $N \ge 0$ 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 [71].

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 former Miaou project (predecessor of Apics) designed a dedicated steepest-descent algorithm for the case $p = 2$ whose convergence to a *local minimum* is guaranteed; until 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 [30]. 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 3.4.4).

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 [43], [45]. 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) [47] and more generally Cauchy integrals over hyperbolic geodesic arcs [50]. 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 [26] in higher dimension is a worthy and timely endeavor today. Meanwhile, an analog to AAK theory was carried out for $2 \le p < \infty$ in [46]. Although not as effective computationally, it was recently used to derive lower bounds [4]. When $1 \le p < 2$, 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 [51], [48], 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 3.4.2 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 [57].

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 [62]. 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 [34], [37].

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 [30] and mentioned in Section 3.3.2.1 generalizes to the matrix-valued situation [60]. 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 ([24], [63], [68]). Some of these parametrizations are also interesting to compute realizations and achieve filter synthesis ([63], [68]). The rational approximation software "RARL2" developed by the team is described in Section 3.4.4.

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 [44]. Matrix-valued Markov functions are the only known example beyond this one [27].

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 [42]. 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 ([7], [42], [36]), 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 [39]. 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 3.4.2.

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. 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/

3.4.2. 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 [8].

The present version of FindSources3D (called FindSources3D-bolis) provides a modular, ergonomic, accessible and interactive platform, with a convenient graphical interface and a tool that can be distributed and used, 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).
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- URL: http://www-sop.inria.fr/apics/FindSources3D/en/index.html

3.4.3. 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/

3.4.4. 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

3.4.5. 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. A recent collaboration 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:

$$\int_{\Omega} \frac{\operatorname{div} m(x')\, dx'}{|x-x'|}\,, \tag{6}$$

outside the volume Ω of the object. The difference is that the distribution m is located in a volume in the case of EEG, and on a plane in the case of rock magnetization. This results in quite different identifiability properties, see [35] 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 (since September with the Geomathematics and Geoinformatics Group, Technische Universität Bergakademie Freiberg, Germany; until then, Univ. of Vienna, Austria), 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: Laurent Baratchart, Juliette Leblond, Jean-Paul Marmorat.

This work is conducted in collaboration with Maureen Clerc and Théo Papadopoulo from the team Athena (Inria Sophia).

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 [8]. 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 [7], [40]. 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 (see Sections 3.4.2 and 6.1), in collaboration with our partners at INS, hospital la Timone, Marseille.

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).

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.

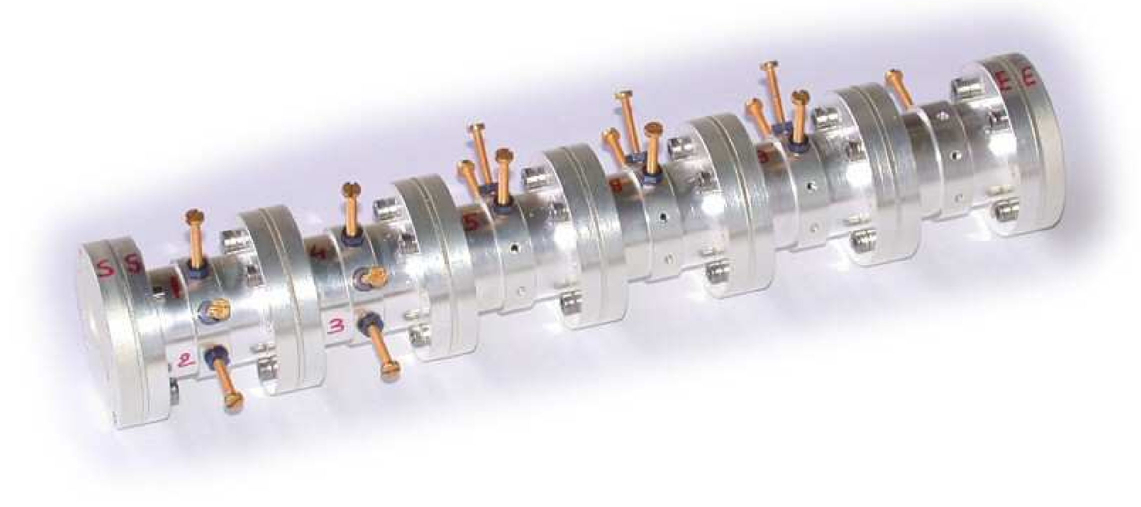

Figure 1. Picture of a 6-cavities dual mode filter. Each cavity (except the last one) has 3 screws to couple the modes within the cavity, so that 16 quantities must be optimized. Quantities such as the diameter and length of the cavities, or the width of the 11 slits are fixed during the design phase.

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).

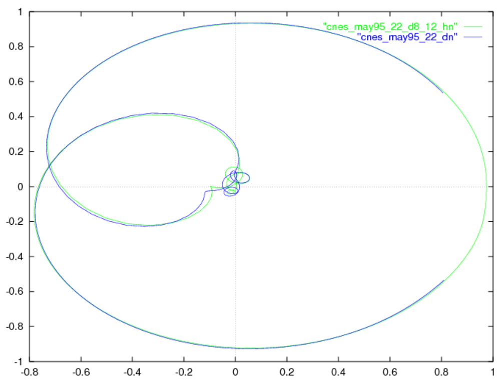

Figure 2. Nyquist Diagram. Rational approximation (degree 8) and data - S_{22}.

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). Non-physical couplings are less than 10^{-2}.

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 [10]. 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:

$$qq^* = p_1p_1^* + p_2p_2^*.$$

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 [78]. 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). Work by the team so far has 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 is now under investigation.

5. New Software and Platforms

5.1. 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

5.2. PUMA-HF

PUMA-HF: Passive Uniform Matching
KEYWORD: Transfer functions

FUNCTIONAL DESCRIPTION: PUMA computes a passive rational 2-port filtering function presenting a reference impedance (i.e. 50 Ohm) at the first port, and the conjugate of the given load impedance within a frequency band at the second port.

- Authors: David Martinez Martinez, Adam Cooman, Martine Olivi and Fabien Seyfert
- Partners: Xlim - DGA-MI - CNES
- Contact: Fabien Seyfert
- Publication: Synthesis Method for Matching Filters
- URL: https://project.inria.fr/puma/

6. New Results

6.1. Inverse problems for Poisson-Laplace equations

Participants: Laurent Baratchart, Sylvain Chevillard, Juliette Leblond, Jean-Paul Marmorat, Konstantinos Mavreas.

6.1.1. Inverse magnetization issues from planar data

This work has been carried out in the framework of the Inria Associate Team IMPINGE, comprising Cauê Borlina, Eduardo Andrade Lima and Benjamin Weiss from the Earth Sciences department at MIT (Boston, USA) and Douglas Hardin, Edward Saff and Cristobal Villalobos from the Mathematics department at Vanderbilt University (Nashville, USA).

The overall goal of IMPINGE was 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 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.

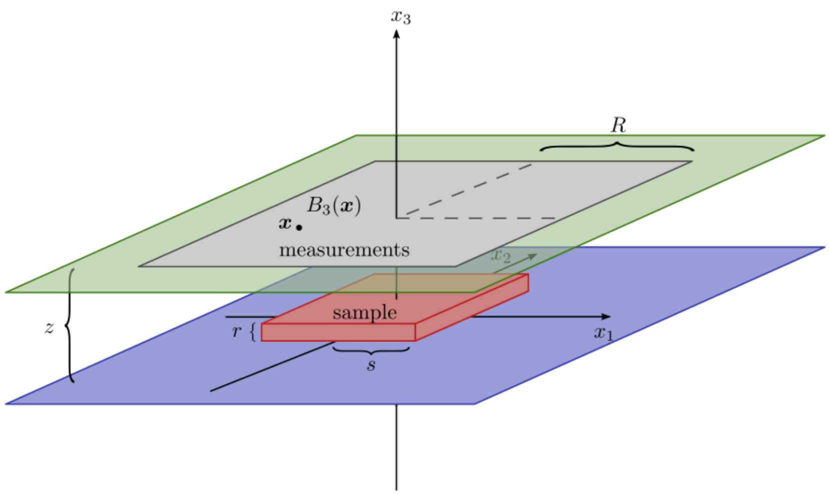

Figure 3. Schematic view of the experimental setup

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 research efforts towards designing algorithms for net moment recovery. The net moment is the integral of the magnetization over its support, and it is a valuable piece of information to physicists which has the advantage of being determined solely by the field: whereas two different magnetizations can generate the same field, the net moment depends only on the field and not on which magnetization produced it. Hence the goal may be described as to build a numerical magnetometer, capable of analyzing data close to the sample. This is in contrast to classical magnetometers which regard the latter as a single dipole, an approximation which is only valid away from the sample and is not suitable to handle weak fields which get quickly blurred by ambient magnetic sources if one measures the field at a distance from the sample.

The first approach consists in using the fact that the integral of B_3 against polynomials of order less or equal to 1 on some domains symmetric with respect to the origin provides an estimate of the net moment, asymptotically when R grows large [20], [72]. This year, on the one hand, we conducted with our colleagues at MIT a campaign of fairly systematic tests (with various sensitivity parameters for the sensor, step size between measurement points, overall size of the measurement rectangle, etc.) to observe how our method behaves on true data. The results are overall very good when the signal-to-noise ratio is not poor; however, this revealed a few situations where the observed asymptotics does not fit the theoretical one, and we have currently no clue of the reason of this phenomenon (is it a manipulation error on some of the samples of our campaign? a bug in our implementation? a noise on the data with a surprisingly large effect on the asymptotic? the fact that the asymptotic regime was not yet reached?) Understanding this phenomenon is still an on-going work. On the other hand, we spotted in the literature approaches that are somehow similar to ours: they compute the same integral, but on the whole plane, and try to account for the finiteness of the measurement rectangle by more or less heuristic methods. As the finiteness of the rectangle is built-in in our approach (we exploit the fact the nature of the asymptotic behavior with respect to R is analytically known), we have good hope that our method should compare favorably against its competitors, but we did not conduct systematic tests yet.

The second approach attempts to generalize the previous expansions in the case when R is moderately large (but only in the thin slab framework, modeling the sample as a rectangle). For this purpose, we setup a bounded extremal problem (BEP, see Section 3.3.1) and submitted an article last year on the subject. It has been accepted for publication this year, see [12].

A third approach developed during the previous years was to design an alternate procedure to compute a good linear estimator, dwelling on expansions on a family of piecewise affine functions, with a restricted number of pieces. A key point here is that it is possible to derive explicit formulas for the adjoint operator B_3^* (in appropriate L^2 spaces) to the operator B_3 mapping a magnetization to the vertical component of the field, when applied to polynomials. We derived this year explicit recurrence formulas that allow one to efficiently compute B_3^* of a polynomial of any degree in linear time with respect to the number of monomials. We currently only have draft notes of this research.

Concerning full inversion of thin samples, after preliminary experiments on regularization with L^1 constraints (a heavy trend in linear inverse problems today to favor sparse solutions), we started studying magnetizations modeled by signed measures. A loop decomposition of silent sources was obtained, which sharpens in 2-D setting the structure theorem of [76]. Moreover, a characterization of equivalent sources having minimal total variation has been obtained when the support of the magnetization is very scattered (namely: purely 1-unrectifiable, which holds in particular for dipolar models) and also for certain magnetizations of physical interest like unidirectional ones. Thus, it seems that constraining the total variation to regularize the recovery process is appropriate in some important cases. The theoretical analysis has shown that the optimum is then always sparse, in that it has Hausdorff dimension at most 1. This stems from the real analyticity of the operators relating the magnetization to the field, which prevents them from assuming constant level on large sets. Moreover, we proved 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 is currently being set up with promising results, discretization beforehand on a fixed grid. 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. [21].

Besides, 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, some best approximation issues related to inverse recovery and relevant BEP problems in Hardy classes of holomorphic functions (see Section 3.3.1). 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. This is the subject of ongoing work with E. Pozzi (Department of Mathematics and Statistics, St Louis Univ., St Louis, Missouri, USA).

For magnetizations supported in a volume Ω with boundary $\partial\Omega$, there is a greater variety of silent sources, since they have much more space to live in. Now, to each magnetization m supported in Ω there is a unique magnetization supported on $\partial\Omega$ (the balayage of m) and producing the same field outside Ω. Thus, describing silent sources supported on $\partial\Omega$ is a way to factor out some of the complexity of the situation. When m is located in the plane, the Hardy-Hodge decomposition introduced in [35] (see Section 3.3.1) was used there to characterize all silent magnetizations from above (resp. below) as being those having no harmonic gradient from below (resp. above) in their decomposition. When m is supported on a closed compact surface, a similar decomposition exists for $\mathbb{R}^3$-valued vector fields on $\partial\Omega$, (see Section 6.4), that allows us to characterize all magnetizations on $\partial\Omega$ which are silent from outside as being those whose harmonic components satisfy a certain spectral relation for the double layer potential on $\partial\Omega$. The significance and the algorithmic implications of that equation are under study.

Other types of inverse magnetization problems can be tackled using such techniques, in particular global Geomagnetic issues which arise in spherical geometry. In collaboration with C. Gerhards from the Technische Universität Bergakademie Freiberg (Germany), we developed a method to separate the crustal component of the Earth's magnetic field from its core component, if an estimate of the field is known on a subregion of the globe [33]. This assumption is not unrealistic: parts of Australia and of northern Europe are considered as fairly well understood from the magnetostatic view point. We are currently working to test the algorithm against real data, in collaboration with Geophysicists.

6.1.2. *Inverse magnetization issues from sparse cylindrical data*

The team Factas is a partner of the ANR project MagLune on Lunar magnetism, headed by the Geophysics and Planetology Department of Cerege, CNRS, Aix-en-Provence (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 is 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.

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 3.4.2 and 6.1.3), we try to recover the position and the moment of the dipole using the available measurements. This is still on-going work which constitutes the main topic of the PhD thesis of K. Mavreas.

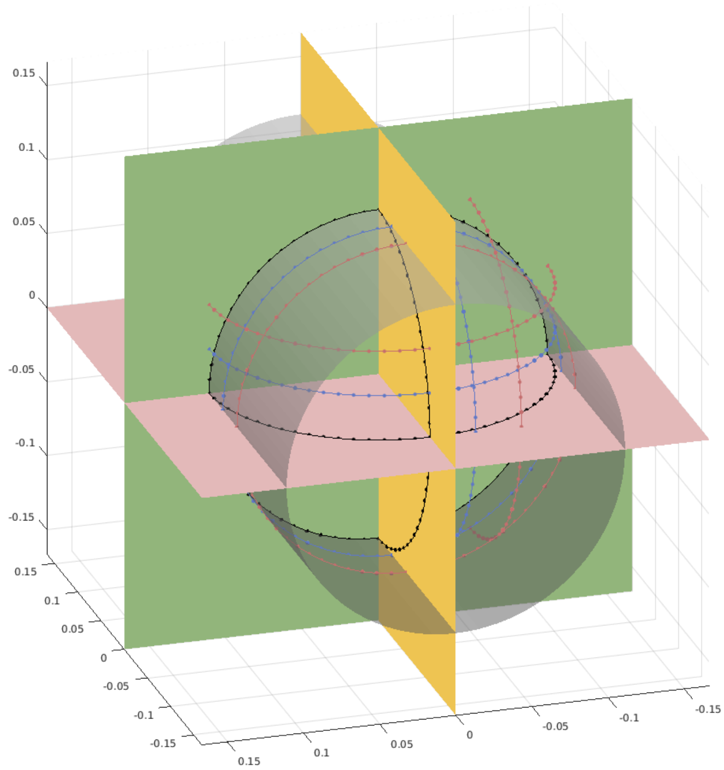

Figure 4. Typical measurements obtained with the instrument of Cerege. Measurements of the field are performed on nine circles, given as sections of three cylinders. On each circle, only one component of the field is measured: the component B_h along the axis of the corresponding cylinder (blue points), the component B_n radial with respect to the circle (black points), or the component B_τ tangential to the circle (red points).

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 a rational approximation technique which, for the circle of measurements at height h, gives us an estimate of the complex number $u_h = \frac{1+\rho^2+(h-z)^2}{\rho} e^{i\phi}$, from which ϕ is directly obtained. Besides, from the relation $\rho|u_h| = 1+\rho^2 + (h-z)^2$, we see that the point (ρ, z) lies on a circle C_h. Therefore, with measurements at three different heights h_i $(i = 1, 2, 3)$, we can in principle recover (ρ, z) as the intersection of the three circles C_{h_1}, C_{h_2} and C_{h_3}.

In practice, due to the many sources of imprecision (the first of all being that the field is not truly generated by a single dipole), the circles do not all truly intersect. This year, we studied three different strategies to estimate the pseudo-intersection point of the circles. In the plane, for a point P and a circle C of center O and radius R, we define $d(P, C) = |\|PO\| - R|$ where $\| \cdot \|$ denotes the Euclidean distance, and $h(P, C) = \|PO\|^2 - R^2$ and we formulate the problem of finding a pseudo-intersection point between C_{h_1}, C_{h_2} and C_{h_3} as either:

1. finding a point P that minimizes $d(P, C_{h_1}) + d(P, C_{h_2}) + d(P, C_{h_3})$;
2. finding a point P for which $h(P, C_{h_1}) = h(P, C_{h_2}) = h(P, C_{h_3})$;
3. finding a point P that minimizes $h(P, C_{h_1})^2 + h(P, C_{h_2})^2 + h(P, C_{h_3})^2$.

The first case turns out to actually be a generalization of two classical concepts: the Fermat point (or Torricelli point) of a triangle, and the Alhazen optical problem. The second case corresponds to a classical notion called the *radical center* of three circles (intersection of the three corresponding radical axes). Finally, the third case does not seem to have a documented solution. We solve it by writing the algebraic system of two equations corresponding to the critical points of the function, after an appropriate change of coordinates in order to reduce the degree. Finally, we get a superset of the solutions by estimating the roots of the resultant of both polynomials. First experiments showed that the third formulation led to the most satisfying estimate of the pseudo-intersection. We also implemented a heuristic numerical procedure (without theoretical formulas for its solution) to estimate the point P that minimizes $d(P, C_{h_1})^2 + d(P, C_{h_2})^2 + d(P, C_{h_3})^2$, and it also gives fairly acceptable estimates. This work has not yet been submitted for publication.

Another important part of our work this year has been to extensively test our implementation of the rational approximation procedure which is at the heart of our method (and which is also used for the problem described in Section 6.1.3). These tests allowed us to detect situations in which the algorithm was falling into an infinite loop or was converging towards a local minimum that was not really the best approximation. It also revealed that all initialization strategies for the iterative optimization algorithm were not equally sensitive to the noise. This led us to redesign our implementation.

Finally, the article that we submitted last year, with a rudimentary approach to recover ρ and z from the data obtained at several heights, has been accepted and will be published soon, see [14].

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 [7], [40] 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 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 3.4.2) is being developed, in collaboration with the Inria team Athena and the CMA - Mines ParisTech. In addition to the Matlab version of FS3D, a new (C++) version of the software that automatically performs the estimation of the quantity of sources is being built, specifically this year in the framework of the AMDT Bolis2 (“Action Mutualisée de Développement Technologique”, “Boîte à Outils Logiciels pour l’Identification de Sources”), together with engineers from the SED (Service d’Expérimentation et de Développement) of the Research Center. This new version, still under development, is modular, portable and possesses a nice GUI (using Qt5, dtk, vtk), while non regression (continuous integration) is ensured.

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 [8], there is no mathematical justification so far why multiple poles generate such strong accumulation of the poles of the approximants. 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). Last but not least, the version of the software currently under development takes as inputs actual EEG measurements, like time signals, and performs a suitable singular value decomposition in order to separate independent sources.

Magnetic data from MEG recently became available along with EEG data, by our medical partners at INS in Marseille; indeed, it is now possible to use simultaneously both 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 should enhance the accuracy of our source recovery algorithms. We will add the treatment of MEG data as another functionality of the software FS3D.

Concerning dipolar source estimation from EEG, joint work with Marion Darbas (Univ. Picardie Jules Verne, Laboratoire Amiénois de Mathématique Fondamentale et Appliquée, LAMFA) is in progress for neonates data and models. Their specificity is that the skull does not have a constant conductivity (at the fontanels location, the bone is spongy). We pursue together a study of the influence of the skull conductivity on the inverse EEG problem, using in particular FS3D, see also [70].

We also consider non quasi-static models in order to more precisely analyze the time influence on the behavior of the solutions to the inverse source problems in EEG and MEG. This is current work with Iannis Stratis and Atanasios Yannacopoulos (National and Kapodistrian University of Athens, Greece, Department of Mathematics).

6.2. Matching problems and their applications

Participants: Laurent Baratchart, Martine Olivi, Gibin Bose, David Martinez Martinez, Fabien Seyfert.

Filter synthesis is usually performed under the hypothesis that both ports of the filter are loaded on a constant resistive load (usually 50 Ohm). In complex systems, filters are however cascaded with other devices, and end up being loaded, at least at one port, on a non purely resistive frequency varying load. For example, in an emitter-receiver, the antenna is followed by a filter. Whereas the antenna can usually be regarded as a resistive load at some frequencies, this is far from being true on the whole pass-band. A mismatch between the antenna and the filter, however, causes irremediable power losses, both in emission and transmission. Antennas are not the only systems where matching is of importance: in multiplexer design, one of the most complicated problems among microwave device synthesis, each filter is plugged at one of its accesses on a load made of the common manifold and all other channel filters. This load is far from being matched, and leads to a complex simultaneous matching problem, of all filters connected via the common manifold junction. Our goal is therefore to develop a method for filter synthesis that allows us to match varying loads on specific frequency bands, while enforcing some rejection properties away from the pass-band.

Figure 5 shows a filter with scattering matrix S, plugged at its right port on a frequency varying load with reflection parameter $L_{1,1}$. If the filter is lossless, simple algebraic manipulations show that on the frequency axis the reflex-ion parameter satisfies:

$$|G_{1,1}| = \left| \frac{S_{2,2} - \overline{L_{1,1}}}{1 - S_{2,2} L_{1,1}} \right| = \delta(\overline{L_{1,1}}, S_{2,2}).$$

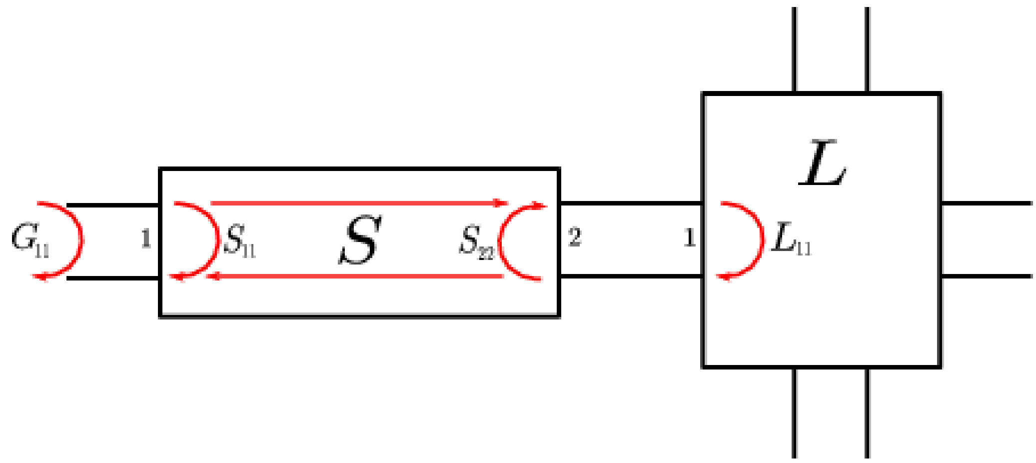

Figure 5. Filter plugged on a system with reflection coefficient L_{11}

The matching problem of minimizing $|G_{1,1}|$ amounts therefore to minimize the pseudo-hyperbolic distance δ between the filter's reflection parameter $S_{2,2}$ and the conjugate of the load's reflection $\overline{L_{1,1}}$, on a given frequency band. On the contrary enforcing a rejection level on a stop band, amounts to maintaining the value of $\delta(L_{1,1}, S_{2,2})$ above a certain threshold on this frequency band. For a broad class of filters, namely those that can be modeled by a circuit of n coupled resonators, the scattering matrix S is a rational function of McMillan degree n in the frequency variable. The matching problem thus appears to be a rational approximation problem in the hyperbolic metric.

6.2.1. Multiplexer synthesis via interpolation and common junction design

Based on our work linking Nevanlinna-Pick interpolation and point-wise matching techniques [6] we tackled the synthesis of a multiplexer on the basis of frequency specifications relative to a triplexer furnished by CNES and deemed to be problematic. Theoretical results guaranty the existence in this case, under a strict contractivity hypothesis on the common junction, of a simultaneous pointwise matching solution of all three channel filters. This result is however not constructive as it relies on Brouwer's fixed point theorem, a purely topological argument. In the context of the PhD of D. Martinez, we developed a continuation algorithm, starting from a completely decoupling junction and ending up with the manifold junction of interest. When the junction decouples all the channels, the overall matching problem results in 3 independent Nevanlinna-Pick interpolation problems as described in [6]: this yield the starting point of our continuation approach. The manifold peaks have also been identified as crucial here: these are resonances taking place in the common junction of the multiplexer, at which transmission of energy becomes impossible between a given channel and the common port. These peaks have been mathematically characterized, and a systematic combinatorial algorithm designed for the synthesis of a "peak free" manifold junction. In particular it was proven, that an extremely compact junction is needed to fit the specifications furnished by CNES: when dispersive effects increase (and they do with the size of the junction) the appearance of manifold peaks has been proven inevitable. Using a continuation approach to compute the channel filters responses and a combinatorial procedure to design a peak-free junction, a complete triplexer has been synthesized that fits the CNES specifications. The synthesis was first considered in terms of circuits and eventually transformed in a real hardware realized in waveguide technology (see Figure.6). The latter is currently being manufactured at XLIM laboratories, where our colleague S. Bila is co-advising D. Martinez' PhD.

6.2.2. Uniform matching and global optimality considerations

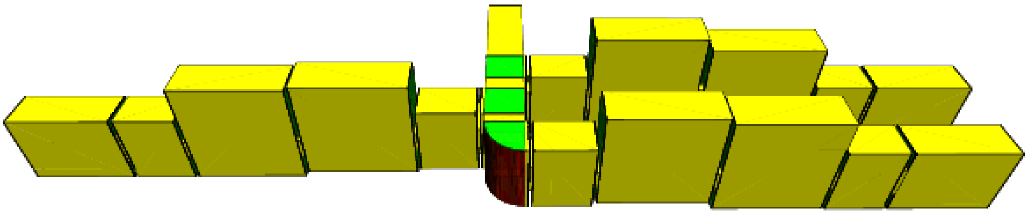

Figure 6. Full wave simulation of the realized triplexer, constituted of a very compact fishbone junction and three channel filters, each of order 6

The interpolation procedure of [6] provides us with matching/rejecting filtering characteristics at a discrete set of frequencies. It can serve as a starting point for heavier optimization procedures, where the matching and rejection specifications are expressed uniformly over the bandwidth. Although the practical results thus obtained are quite convincing, we have no proof of their global optimality. This has led us to seek alternative approaches allowing us to assess, at least in simple cases, global optimality of the obtained response. By optimality of a response we mean, as in classical filtering, a best match of the response in the uniform norm on a given pass-band, while meeting given rejection constraints on a stop-band, and this for a given maximal degree n_c of the matching network. Following the approach of Fano and Youla, we considered the problem of designing a 2×2 loss-less frequency response, under the condition that a specified load can be "unchained" from one of its port. This classically amounts to set interpolation conditions on the response at the transmission zeros of the Darlington extension of the load. When the load admits a rational representation of degree $n_a = 1$, and if the transmission zeros of the overall system are fixed, we were able to show that the uniform matching problem over an interval, together with rejection constraints at other frequency locations, reduces to a convex minimization problem with convex constraints over the set of non-negative polynomials of given degree. When the load is of degree greater than 1, our approach is a convex relaxation of the original problem as the computed matching circuit has in general degree $n_c + n_a - 1$. This delivers lower bounds for the original matching problem, the first that are known of this problem under degree constraint.

The internal representation of our problem, relies on the use of a Pick matrix $\mathcal{P}$ depending on a positive polynomial p, that needs to be positive in terms of matrices, that is $\mathcal{P}(p) \succeq 0$. Although we know for the convexity of our global formulation [17], the concavity of the matrix valued map $\mathcal{P}$ is not evident at all. Using arguments of matrix valued Nevanlinna-Pick interpolation we were able to establish it this years, that is: for all pair of positive polynomials (p_1, p_2) the following holds,

$$\mathcal{P}(\alpha p_1 + (1-\alpha)p_2) \succeq \alpha\mathcal{P}(p_1) + (1-\alpha)\mathcal{P}(p_2).$$

This is an important result, as it justifies the use of Lagrangian relaxation for our problem that appears to be a non-linear, convex, semi-definite optimization program (NLSDP), the hardest class among current convex optimization. We plan to build on this result, in order to obtain a critical point equation to our problem, in terms of extremal points of the involved polynomials.

The software implementation developed within the PhD of D. Martinez, combining logarithmic barrier functions and Lagrangian relaxation techniques has been made available for practitioners as Matlab library called Puma 5.2. Results obtained thank to this tool, have been presented in [15], [18] and on a dedicated workshop at the conference IMS2018. Design of use cases, for antenna matching problems relevant in 5G and IOT applications are currently being analyzed with LEAT, within the context of G. Bose's PhD.

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, in particular to detect instability at an early stage of the design. This activity has gained momentum with the doctoral work of (S. Fueyo), co-advised with J.-B. Pomet (from the McTao Inria project-team) and the postdoctoral stay of (A. Cooman) that eventually resulted in substantial software developments. Application of our work to oscillator design methodologies started recently 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. As regards devices devised to operate at relative low frequencies, time domain simulations, based on the integration of the underlying non-linear dynamical system, answers these questions satisfactorily. 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 simple electrical wire at low frequency) becomes so small that simulations are intractable in reasonable time. In addition to this problem, most linear components of these circuits are known through their frequency response, and require therefore a preliminary, numerically unstable step to obtain their impulse response, prior to any time domain simulation.

For all these reasons it is widely preferred to perform the analysis of such systems 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 dynamic is considered. This is done by means of the analysis of transfer impedance functions computed at some ports of the circuit. We have shown, that under some realistic hypothesis on the building blocks of the circuit, these transfer functions are meromorphic functions of the frequency variable s, with at most a finite number of unstable poles in the right half-plane [19].

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 [9], that we further improved in [16] to address the design of oscillators, in collaboration with Smain Amari. The evaluation of the admittance function of interest is furnished, on a finite frequency band, by a circuit simulator. Progress were made on the interpolation procedure and the determination of a filtering function that are used to obtain a functional representation of high order of the unstable part of the admittance function to be analyzed. The latter was tested on a time-delayed Chua oscillator circuit: the analytical model of this circuit is known in closed form, and using continuation techniques on the involved delay components it is possible to compute the exact unstable poles of this circuit: two being exactly at the oscillators frequency, while two others spurious poles at DC frequency are present and are usually hard to detect with classical methods. Our approximation based procedure, which was fed with incomplete frequency data estimation of the admittance, was able to recover all poles within a relative error of less than 0.01%. A real world example of an MMIC oscillator was also analyzed and confirmed the procedure's effectiveness. A complete software library called pisa (see Section 5.1) have been developed to render these techniques accessible for practitioners. Although these results are very satisfying in practice, we are aiming for a result that would link together, the width of the measurement band, the density of the measurement points with the precision with which a pole, located within a certain depth into the complex plan can be identified. Extensions of our procedure to the strong signal case, where linearization is considered around a periodic trajectory, yielding harmonic transfer functions is also being worked on.

When stability is studied around a periodic trajectory, which is 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 infinite dimensional setting when delays are considered. Dwelling on the theory of retarded systems, S. Fueyo's PhD work showed in previous years that, for certain simple circuits with properly positioned resistors, the monodromy operator is a compact perturbation of a stable operator, and that only finitely many unstable point of its spectrum can occur. This year, we proved a similar result for general circuits, provided that they are passive at very high frequency. For this, we use Lyapunov functions for the transmission lines to establish exponential L^2-stability, and then rely on counting techniques and impulse response estimates to obtain L^∞ stability from the exponential L^2-stability. We are currently developing the link between the monodromy operators of a general circuit and the so-called Harmonic Transfer Function of the circuit. A practical application of this result will be to generalize the previously described techniques of stability assessment around a functioning point into a stability assessment technique around periodic trajectories. This can be recast in terms of the finiteness of the number of abscissas of unstable poles of the Harmonic Transfer functions of the circuit. It will be of great importance to generalize such considerations to more complex circuits, whose structure is less well understood at present.

6.4. The Hardy-Hodge decomposition

Participant: Laurent Baratchart.

(This is joint work with T. Qian and P. Dang from the university of Macao.) It was proven in previous year that on a smooth 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. This year we extended this result to Lipschitz surfaces for $2-\varepsilon<p<2+\varepsilon'$, 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 is valid on surfaces (not just hypersurfaces), and an article is currently being written on this topic. The Hardy-Hodge decomposition generalizes the classical Plemelj formulas from complex analysis.

6.5. Imaging and modeling ancient materials

Participants: Vanna Lisa Coli, Juliette Leblond.

This is a very recent activity of the team, linked to images classification in archaeology in the framework of the project ToMaT, "Multiscale Tomography: imaging and modeling ancient materials, technical traditions and transfers" (see Section 8.1), 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 data 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; we are currently focusing our investigation on 2-D slices displaying pores locations and we considering several data processing treatments, such as multiresolution processing and Hough transform (derived from Radon transform), in order to evaluate their outcome when applied to these very particular images. Different possibilities of investigation will be analyzed as well, such as "a contrario" analysis and deep learning techniques.

6.6. Behavior of poles in meromorphic approximation

Participant: Laurent Baratchart.

We proved this year that if a function is holomorphic outside a disk of radius $r < 1$ in the complex plane, then its best approximant on the unit circle, in the uniform norm, by a meromorphic function having at most n poles in the unit disk has at most m poles of modulus greater than r, where m is independent of n. This is the first result on the behavior of singularities in meromorphic approximation to a function with 2-D singular set. We are currently working on analogs in a non-circular geometry and in rational rather than meromorphic approximation.

6.7. Tools for numerically guaranteed computations

Participant: Sylvain Chevillard.

The overall and long-term goal is to enhance the quality of numerical computations. The software tool Sollya (see Section 3.4.5), developed together with C. Lauter (Université Pierre et Marie Curie) intends to provide an interactive environment for performing numerically rigorous computations. It comes as a standalone tool and also as a C library that allows one to benefit from all the features of the tool in C programs.

In September 2018, we released version 7.0. Among other things, this release fixes some bugs and improves the way base functions are internally handled. Another important novelty of 2018 is that Sollya now comes with the companion `pythonsollya`[0] proposed by third-party developers to provide all the features of Sollya within Python. Some of the novelties in the API of the library version of Sollya 7.0, were made to ease the development of `pythonsollya`.

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) accompanies the PhD of David Martinez and focuses 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 will be considered.

[0] https://gitlab.com/metalibm-dev/pythonsollya/

7.1.2. Contract Inria-SKAVENJI

This is a scientific consulting activity for the start-up company SKAVENJI. The latter develops an innovative and communicative device to facilitate the production and home consumption of small amounts of energy, produced by one or more local sources of renewable energy. Our contribution consisted in designing a simple controller improving the energy efficiency of the energy production while minimizing the number of charge and discharge cycles of the associated battery. The retained control strategy was based on consumption and production profiles.

8. Partnerships and Cooperations

8.1. Regional Initiatives

- The team participates in the project WIMAG (Wave IMAGing) funded by the Idex UCA$^{\text{Jedi}}$. It aims at identifying and gathering the research and development by partners of UCA involved in wave imaging systems. Other partners are UNS and CNRS (GéoAzur, I3S, LEAT, LJAD), together with Orange Labs.
- 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 transverse action C4PO funded by the Idex UCA$^{\text{Jedi}}$. This "Center for Planetary Origin" brings together scientists from various fields to advance and organize Planetary Science at the the University of Nice, and supports research and teaching initiatives within its framework, among which the workshop "Inverse problems and approximation techniques in planetary sciences" organized by members of Factas in May, about inverse problems in harmonic electromagnetism and approximation, with applications mainly dedicated to geomagnetism and paleomagnetism, see Section 9.1.1.
- The team also 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 6.5.

8.2. National Initiatives

8.2.1. ANR MagLune

The ANR project MagLune (Magnétisme de la Lune) has been approved July 2014. It involves 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 are 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) is 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 participates 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 are instrumental for this purpose.

8.2.2. ANR Cocoram

The ANR (Astrid) project Cocoram (Co-design et co-intégration de réseaux d'antennes actives multi-bandes pour systèmes de radionavigation par satellite) started January 2014 and ended October 2018. We were associated with three other teams from XLIM (Limoges University), geared respectively towards filters, antennas and amplifiers design. The core idea of the project was to realize dual band reception an emission chains by co-conceiving the antenna, the filters, and the amplifier. A complete chain has been synthesized using matching filters placed after each of the accesses of a network of 4 bi-polarized antennas, resulting in a substantial gain in energy effectiveness of 30%. This communication chain has been manufactured by our partner XLIM, and presented to the final meeting of the ANR in October.

8.3. European Initiatives

8.3.1. Collaborations with Major European Organizations

Apics 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 Associate Teams Not Involved in an Inria International Labs

8.4.1.1. IMPINGE

Title: Inverse Magnetization Problems IN GEosciences.

International Partner (Institution - Laboratory - Researcher):

Massachusetts Institute of Technology (United States) - Department of Earth, Atmospheric and Planetary Sciences - Benjamin P. Weiss

Start year: 2016

See also: http://www-sop.inria.fr/apics/IMPINGE/

This proposal is concerned with the inverse problem of recovering a magnetization distribution from measurements of the magnetic field in a portion of space nearby. The application domain is to Earth and planetary sciences. Indeed, the remanent magnetization of rocks provides valuable information on their history. The proposal aims at renewing the existing "Équipe Associée" Impinge ending 2015, between Apics (now Factas) team at Inria and the Department of Earth, Atmospheric and Planetary Sciences at MIT (Cambridge, MA, USA), with the Department of Mathematics at Vanderbilt University (Nashville, TN, USA) as a secondary partner. Several research paths were broken towards magnetization recovery and promising numerical experiments have been conducted. This initial effort must be continued to achieve a reasonably complete methodology for reconstructing magnetizations and checking for hypotheses by geophysicists (e.g., unidirectionality of magnetization distributions).

8.4.2. Inria International Partners

8.4.2.1. Informal International Partners

MIT-France seed funding is a competitive collaborative research program ran by the Massachusetts Institute of Technology (Cambridge, Ma, USA). Together with E. Lima and B. Weiss from the Earth and Planetary Sciences dept. at MIT, Apics obtained two-years support from the above-mentioned program to run a project entitled: "Development of Ultra-high Sensitivity Magnetometry for Analyzing Ancient Rock Magnetism"

NSF Grant L. Baratchart, S. Chevillard and J. Leblond are external investigators in the NSF Grant 2015-2018, "Collaborative Research: Computational methods for ultra-high sensitivity magnetometry of geological samples" led by E. B. Saff (Vanderbilt Univ.) and B. Weiss (MIT).

8.5. International Research Visitors

8.5.1. Visits of International Scientists

- Axel Ringh (KTH Royal Institute of Technology, Stockholm, Sweden), June 11 -July 10.
- Elodie Pozzi (St Louis Univ., St. Louis, Missouri, USA), Brett Wick (Washington University, St. Louis, Missouri, USA), July 25.
- Cristobal Villalobos, Douglas Hardin, Edward Saff (Vanderbilt University, Nashville, Tennessee, USA), December, 6-19, 13-19, and 13-20 respectively.
- M. Olivi proposed with B. Hanzon and R. Peeters a Research in Pair event at CIRM « A state-space approach to parametrization of lossless and stable systems ». which was accepted and took place on August 27-31 https://conferences.cirm-math.fr/2126.html

8.6. List of international and industrial partners

- Collaboration under contract with Thales Alenia Space (Toulouse, Cannes, and Paris), CNES (Toulouse), XLIM (Limoges), LEAT (Sophia Antipolis), University of Bilbao (Universidad del País Vasco / Euskal Herriko Unibertsitatea, Spain), Flextronics.
- Regular contacts with research groups at UST (Villeneuve d'Asq), Universities of Bordeaux-I (Talence), Orléans (MAPMO), Aix-Marseille (CMI-LATP), Nice Sophia Antipolis (Lab. JAD), Grenoble (IJF and LJK), Paris 6 (P. et M. Curie, Lab. JLL), Inria Saclay (Lab. Poems, ENSTA), IMT Atlantique (Institut Mines-Télécom., Brest), Cerege-CNRS (Aix-en-Provence), CWI (the Netherlands), MIT (Boston, USA), Vanderbilt University (Nashville USA), Steklov Institute (Moscow), Michigan State University (East-Lansing, USA), Texas A&M University (College Station USA), Indiana University-Purdue University at Indianapolis, St Louis University and Washington University (St Louis, Missouri, USA), Cinvestav (Queretaro, Mexico), Politecnico di Milano (Milan, Italy), University of Trieste (Italy), RMC (Kingston, Canada), University of Leeds (UK), of Maastricht (the Netherlands), of Cork (Ireland), Vrije Universiteit Brussel (Belgium), TU-Wien and Universität Wien (Austria), TFH-Berlin and Technische Universität Bergakademie Freiberg (Germany), ENIT (Tunis), KTH (Stockholm), University of Cyprus (Nicosia, Cyprus), University of Macau (Macau, China), SIAE Microelettronica (Milano), Université Picardie Jules Verne (France), National and Kapodistrian University of Athens (Greece).
- The project is involved in the GDR-project AFHP (CNRS), in the ANR (Astrid program) project Cocoram (with XLIM, Limoges, and DGA), in the ANR (Défis de tous les savoirs program) project MagLune (with Cerege, IPGP, ISTerre, Irphe), in a MIT-France collaborative seed funding, in the Associate Inria Team IMPINGE (with MIT, Boston), and in a NSF grant (with Vanderbilt University and MIT).

9. Dissemination

9.1. Promoting Scientific Activities

- V. L. Coli presented oral communications at the "Journées Idex UCA$^{\text{JEDI}}$ Matière, Lumière, Interactions", October 4-5, Fréjus, France, http://univ-cotedazur.fr/events/MLI/fr, and at the Journée d'échanges "Applications de la tomographie par rayons X", November 23, Paris, France, https://jea-tomo3d-2018.sciencesconf.org/.
- J. Leblond and K. Mavreas presented oral communications at the 5th International Conference "Modern Mathematical Methods in Science and Technology 2018 (M3ST '18)", September 2-4, Kalamata, Greece.
- K. Mavreas gave a talk at the PhD Seminar at Inria Sophia, France, November 13, https://phd-seminars-sam.inria.fr.

- G. Bose, S. Fueyo and D. Martinez Martinez presented posters at the Workshop ERNSI 2018, http://mlg.eng.cam.ac.uk/ernsi2018/.
- G. Bose gave a talk at the 23rd International Symposium on Mathematical Theory of Networks and Systems http://mtns2018.ust.hk/, July 16-20 2018, Hong-Kong.
- D. Martinez Martinez gave a talk at the 7th International Workshop on Microwave Filters https://artes.esa.int/news/7th-international-workshop-microwave-filters, 17-19 Apr 2018, Noordwijk, Netherlands, and a talk at the 2nd URSI AT-RASC (Atlantic Radio Science) http://www.ursi.org/events.php?atrasc=on, May 28 - June 1, 2018, Gran Canaria, Spain, and a talk at IMS 2018 https://ims2018.org/, June 10-15 2018., Philadelphia, USA
- A. Cooman gave a talk at IMS 2018 https://ims2018.org/, June 10-15, 2018, Philadelphia, USA.
- F. Seyfert gave a talk at IMS 2018 https://ims2018.org/, June 10-15 2018, Philadelphia, USA and at the KTH's seminar May 15, Stockholm, Sweden and at XLIM seminar, October 3, Limoges, France

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

- L. Baratchart, S. Chevillard, and J. Leblond organized (scientifically and practically) the Spring School/Workshop "Inverse problems and approximation techniques in planetary sciences" [0], at Inria Sophia Antipolis, May 16-18. It was financially supported by UCA[Jedi] and gathered around 20 participants.

9.1.1.2. Member of the Organizing Committees

- L. Baratchart and J. Leblond organized a mini-symposium [0] on "Inverse source problems with applications to planetary sciences and medical imaging" at the 9th international conference "Inverse problems: modeling and simulation (IPMS 2018)", Malta, May 21-25.
- Fabien Seyfert organized a workshop at IMS 2018, on "Advanced Synthesis Techniques for reduced size filtering techniques", https://ims2018.org/technical-program/workshops-and-short-courses#2018-06-15, Philadelphia, USA.

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

L. Baratchart sits on the Program Committee of *Applied Inverse Problems 2019*, to be held in Grenoble, France.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

L. Baratchart sits on the editorial boards of "Constructive Methods in Function Theory" and "Complex Analysis and Operator Theory".

9.1.3.2. Reviewer - Reviewing Activities

S. Chevillard was a reviewer for the journal *Transactions on Mathematical Software*.

J. Leblond was a reviewer for the journals *Numerical Algorithms, DMV Jahresberichte*.

M. Olivi was a reviewer for the journal *Automatica* and for the *18th IFAC Symposium on System Identification* (SYSID 2018).

F. Seyfert is a reviewer of *IEEE Transactions on Microwave Theory and Techniques*.

L. Baratchart was a reviewer for the seed fund program at MIT.

9.1.4. Invited Talks

[0] http://www-sop.inria.fr/apics/IPAPS18/
[0] http://www.ipms-conference.org/ipms2018/index.php/m20

- L. Baratchart was an invited speaker at the SIGMA day organized by SMAI at Université Pierre et Marie Curie, November 30.
- L. Baratchart and J. Leblond were invited to give talks at the IPMS 2018 conference, Malta, May (see Section 9.1.1). They were invited speakers at the Conference "Advances in Operator Theory with Applications to Mathematical Physics", http://www1.chapman.edu/~alpay/conf2018/conf2018.html, Chapman University, Orange, CA, USA, November.
- L. Baratchart and K. Mavreas gave talks at the workshop "Inverse problems and approximation techniques in planetary sciences", Sophia Antipolis, France, May.

9.1.5. Scientific Expertise

L. Baratchart is sitting on committee 40 of the ANR.

J. Leblond was a reviewer for the Strategic Research Programmes of the Research Council of the Vrije Universiteit Brussel (VUB, Brussel, Belgium).

F. Seyfert is a member of the IEEE MTT-8 committee for filters and passive components.

9.1.6. Research Administration

L. Baratchart sits on the committee "Mathématiques et Informatique" of the French Agency for research (ANR).

J. Leblond is an elected member of the "Conseil Scientifique" and of the "Commission Administrative Paritaire" of Inria.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Colles: S. Chevillard is giving "Colles" at Centre International de Valbonne (CIV) (2 hours per week).

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.

PhD in progress: D. Martinez Martinez, *Méthodologie et Outils de Synthèse pour des Fonctions de Filtrage Chargées par des Impédances complexes*, since October 2015, advisors: L. Baratchart, F. Seyfert, M. Olivi.

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).

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).

Post-doc.: A. Cooman, from January 2017 until June 2018, advisors: F. Seyfert and M. Olivi.

9.2.3. Juries

J. Leblond was a member of the "Comités de Suivi Doctoraux" (preliminary evaluation committees, after one year of PhD) for the ongoing PhDs of Kostiantyn Maksymenko (project-team Athena, doctoral school STIC, UCA), and for Arne Bechensteen (project-team Morpheme, I3S-CNRS), May. She was a member of a "Comité de Sélection" for professors at the University Paris Descartes (MAP5).

M. Olivi was a member of the "jury d'admission du concours CR" of the Inria Research Center.

9.3. Popularization

9.3.1. Internal or external Inria responsibilities

M. Olivi is responsible for Scientific Mediation and president of the Committee MASTIC (Commission d'Animation et de Médiation Scientifique) https://project.inria.fr/mastic/. Her main contributions related with this mission were:

- submit applications to get founding for 2019: "cordées de la réussite" (accepted) et "APOCS région".
- co-organize 10 robotic sessions for 2 classes of middle school students (device "MEDITES" http://meditès.fr, founded by ANRU, the "Agence Nationale de Rénovation Urbaine"),
- co-organize the "stage MathC2+" https://project.inria.fr/mastic/mediation/stage-mathc2/, a four-day internship for 50 high school students ("secondes", about 16 years old) organized by the Committee MASTIC and its partners (June 19-22),
- co-organize Inria participation to the event "Le Village des Sciences et de l'Innovation" in Antibes (October 20-21, 10000 people), and the event "Mouans-Sartoux fête les sciences du quotidien" http://univ-cotedazur.fr/events/fetedelascience.
- co-organize about 10 "cafés scientifiques" (c@fé-in's and cafés Techno, 30 to 80 participants each) https://project.inria.fr/mastic/category/cafein/.

9.3.2. Education

- M. Olivi animated a half-day workshop session "activités débranchées" at "l'ESPE de Nice" for primary school students (April 10).

9.3.3. Interventions

- National events: M. Olivi participated to the event "Le Village des Sciences et de l'Innovation" in Antibes (October 20-21, 8000 people) and to the event "Mouans-Sartoux fête les sciences du quotidien" (October 13, 1000 people).
- In educational institutions: M. Olivi participated to the event "bilan Medium's" at the "collège Émile Roux, Le Cannet".
- Welcoming of schoolchildren or the general public in an Inria center: M. Olivi animated a workshop session during the "stage MathC2+", a four-day internship for high-school students organized by the Committee MASTIC and its partners (June 19-22).

9.3.4. Internal action

- M. Olivi presented the scientific objects produced during the year at the CaféIn of the Research Center, https://project.inria.fr/mastic/cafe-in-12-fevrier-manipulons-et-echangeons/, February.
- J. Leblond together with members of the SED gave a communication at the CaféIn of the Research Center, http://project.inria.fr/mastic/category/cafein/, October.

9.3.5. Creation of media or tools for science outreach

M. Olivi participated in the creation of the web pages https://pixees.fr/jouons-avec-des-experiences-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

Keywords:

Computer Science and Digital Science:

A1. - Architectures, systems and networks
A1.3. - Distributed Systems
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 [42], [41], [43], 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. New Software and Platforms

5.1. 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/

5.2. 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 2018 Jolie was complemented by the creation of the JIoT project, aimed at integrating IoT-related technologies into the Jolie language. The final goal is to provide easy-to-use and flexible communication abstractions to interconnect and make interact disparate IoT islands. Jolie currently supports some of the main technologies used in SOAs (e.g., HTTP). However, only a limited amount of IoT devices uses the media and protocols already supported by Jolie. Indeed, protocols such as CoAP and MQTT, which are widely used in IoT scenarios, are not implemented in Jolie. Integrating these protocols, as we have done, is essential in order to allow Jolie programs to directly interact with the majority of IoT devices. We note that emerging frameworks for interoperability, such as the Web of Things, rely on the same protocols we mentioned for IoT, thus JIoT is also compliant with them. Concretely, work in 2018 comprised the inclusion of the CoAP/UDP and MQTT/TCP protocols among the communication technologies supported by the language. The Jolie implementation of MQTT and CoAP, as well as the UDP transport protocol used by CoAP, are based on the JAVA framework Netty.

- Participants: Claudio Guidi, Fabrizio Montesi, Maurizio Gabbrielli, Saverio Giallorenzo and Ivan Lanese
- Contact: Fabrizio Montesi
- URL: http://www.jolie-lang.org/

5.3. 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/

5.4. 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 distributed system as an AIOC, 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 2018 we did minor changes to AIOCJ, including the possibility of generating code only for a few roles, thus avoiding the need for deployment information for other roles.

- 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

5.5. CauDEr

Causal-consistent Debugger for Erlang
KEYWORDS: Debug - Reversible computing
SCIENTIFIC DESCRIPTION: The 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 and undo consequences of a given action. 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.

- Partner: Universitat Politècnica de València
- Contact: Ivan Lanese
- URL: https://github.com/mistupv/cauder

5.6. 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. New Results

6.1. Service-Oriented Computing

Participants: Mario Bravetti, Maurizio Gabbrielli, Saverio Giallorenzo, Claudio Guidi, Ivan Lanese, Cosimo Laneve, Fabrizio Montesi, Davide Sangiorgi, Gianluigi Zavattaro, Stefano Pio Zingaro.

6.1.1. Orchestrations and choreographies

The practice of programming distributed systems is extremely error-prone, due to the complexity in correctly implementing separate components that, put together, enact an agreed protocol. Usage of contracts and session types in orchestration languages guarantees correct communication [22]. Asynchronous subtyping for binary session types has been thought to be decidable for 8 years, before we proved in previous work it to be undecidable. We have now highlighted some practically-relevant fragments of session types where asynchronous subtyping is indeed decidable [14].

We also studied practical aspects of choreographies, that is multiparty contracts. On the one hand we extended the classical proof of correctness of the projection of a choreography on one participant, which is the cornerstone of the theory of choreographies. Indeed, the classical proof considers projection to a model based on channels in the CCS style, while practice mainly relies on correlation sets. We bridged this gap by giving a correctness proof towards a real-world execution model based on correlation sets [31].

We then studied how to apply choreographies for cross-organizational system integration. More precisely, we proposed a software development process to build integrations composed by distributed, independent connectors whose global behaviour is correct by construction [30]. Choreographies and choreography projection are at the heart of the proposed development process.

6.1.2. Microservices

We continued the study of microservice-oriented computing started in past years, in particular by using our microservice-oriented language Jolie. We focused, in particular, on the use of Jolie in an Internet of Things (IoT) setting [28]. Technically, a key feature of Jolie is that it supports in a uniform way multiple service-oriented communication protocols such as HTTP and SOAP. We extended Jolie in order to support, uniformly as well, also lightweight protocols such as MQTT and CoAP, which are largely used in IoT. These are very different from service-oriented protocols which are point-to-point and based on TCP since MQTT is publish-subscribe while CoAP is based on UDP.

6.2. Models for Reliability

Participant: Ivan Lanese.

6.2.1. Reversibility

We have continued the study of reversibility started in the past years, concentrating on contracts and debugging, and applying the results related to debugging to the Erlang programming language. Concerning contracts, in [12] we further studied the retractable contracts that we defined in previous work. The main novelty consists in showing how retractable contracts can be obtained by taking standard contracts, making them reversible using the general approach presented by Phillips and Ulidowski [44], and then applying suitable control policies.

Concerning debugging, we highlighted in [18] the general approach that can be used to build a causal-consistent reversible debugger for a given language. We then instantiated this general approach to a relevant subset of the language Erlang, first defining uncontrolled and controlled reversible semantics for it [16], and then building an actual causal-consistent reversible debugger called CauDEr [32].

6.3. Probabilistic Systems and Resource Control

Participants: Martin Avanzini, Mario Bravetti, Raphaelle Crubillé, Ugo Dal Lago, Francesco Gavazzo, Davide Sangiorgi, Gabriele Vanoni, Akira Yoshimizu.

6.3.1. Probabilistic Rewriting and Computation

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 sized-type system. In 2018, Focus has produced another work along these lines, based on intersection types [23]. In the usual, pure, lambda-calculus, various notions of terminating terms can be characterised by way of intersection types, in such a way that the class of terminating terms *coincides* with the one of typable terms. The presence of probabilistic choices together with the aforementioned recursion theoretical limitations prevents the same scenario to happen in probabilistic lambda-calculi, i.e., lambda-calculi endowed with some form of probabilistic choice. Nevertheless, Breuvart and Dal Lago proved that capturing the probability of termination in an approximate way by means of intersection types is indeed possible [23].

In 2018, we have also been active in laying out a novel foundation for *probabilistic abstract reduction systems* (*probabilistic ARSs*). ARSs constitute a general framework to study fundamental properties of computations, such as termination or confluence. These properties are intricately related to the well-definedness of functions, and consequently, play key roles in the formal study of programming languages. Specifically, in collaboration with Yamada, Avanzini and Dal Lago [20] introduced a new notion of probabilistic computation by means of a reduction relation over multidistributions. This relation enables the seamless combination of non-deterministic and probabilistic choice, thereby, considerably simplifying earlier notions of reduction semantics by means of schedulers and Markov chains. On top of this, a partially flawed characterisation of positive almost sure termination by means of Lyapunov ranking functions, initially due to Bournez and Garnier, could be clarified. Moreover, the *interpretation method*, which is maybe the most fundamental technique to investigate termination and runtime complexity of term rewrite systems, could be lifted to probabilistic systems.

Finally, we have been able to propose a novel and natural way of giving the reduction semantics for Markovian process algebras [13], a model of concurrent interaction which is particularly appropriate to the performance analysis of concurrent systems.

6.3.2. Complexity Analysis of Functional Programs

A research topic which lies at the core of Focus since its inception is the complexity analysis of functional programs, through tools like implicit complexity and linear logic. During 2018, we have published an extended version of a paper in which we proved that the most general form of ramified recursion, a key tool in term rewriting, remains sound for polynomial time computation, although requiring some nontrivial machinery based on sharing and memoisation [11]. We have also started to investigate along a new and promising research direction concerning the efficient implementation of functional programming languages through randomised strategies. We have shown that even the simplest strategy is nontrivial for the pure, untyped lambda-calculus [25], being in certain cases more efficient than both innermost and outermost strategies.

6.3.3. Reasoning About Effectful and Concurrent Programs

Pure functional programs are relatively easy to reason about due to referential transparency, a property inherent to functional programs that renders their semantics close to the one of mathematical expressions.

Quite recently, functional programming has found its way into main stream programming languages. Thus functional programming is *combined* with various forms of computational effects, such as exceptions, state, or even nondeterministic choice. Since a couple of years, we are interested in studying the impact of effects on the metatheory of functional programming languages, with an eye to coinductive methodologies akin to those employed in concurrency, coinduction *in primis*. In 2018, Francesco Gavazzo has extended some of our previous work about a generic approach to behavioural equivalences for higher-order effectual languages to *metrics*, themselves a much more natural way to compare programs in many cases (e.g., in the presence of probabilistic choice). His contribution has been published in the top conference in logic in computer science in 2018 [29].

6.4. Verification Techniques

Participants: Mario Bravetti, Adrien Durier, Daniel Hirschkoff, Ivan Lanese, Cosimo Laneve, Davide Sangiorgi.

We analyze sensible properties of concurrent systems such as deadlock freedom, and proof techniques for deriving behavioural equalities and preorders on processes.

6.4.1. Deadlock detection

We have continued the work on deadlock detection of previous years, on languages of concurrent objects. Thus in [33] we have applied and refined previous techniques so to handle multi-threaded programs with reentrant locks. For this we have defined a simple calculus featuring recursion, threads and synchronizations that guarantee exclusive access to objects. We detect deadlocks by associating an abstract model to programs and we define an algorithm for verifying that a problematic object dependency (e.g. a circularity) between threads will not be manifested.

In [15] we give two different notions of deadlock for systems based on active objects and futures. One is based on blocked objects and conforms with the classical definition of deadlock. The other one is an extended notion of deadlock based on blocked processes which is more general than the classical one. We introduce a technique to prove deadlock freedom in which an abstract version of the program is translated into Petri nets. Extended deadlocks, and then also classical deadlock, can be detected via checking reachability of a certain forms of marking.

6.4.2. Proof techniques based on unique solutions

We study bisimilarity, a behavioural equivalence whose success is much due to the associated bisimulation proof method. In particular, we discuss different proof methods, based on unique solution of equations or of special forms of inequations called contractions, and inspired by Milner's theorem on unique solution of equations. The techniques are at least as powerful as the bisimulation proof method and its up-to context enhancements. The techniques can be transferred onto other behavioural equivalences, possibly contextual and non-coinductive. This enables a coinductive reasoning style on such equivalences. An overview paper on these techniques is [19].

The paper [36] discusses a rather comprehensive formalisation of the core of the theory of CCS in the HOL theorem prover (HOL4), with a focus towards the theory of unique solutions of contractions. (The formalisation consists of about 20,000 lines of proof scripts in Standard ML.) Some refinements of the theory itself are obtained. In particular we remove the constraints on summation, which must be weakly-guarded, by moving to rooted contraction, that is, the coarsest precongruence contained in the contraction preorder.

In [26] we apply the above techniques to study Milner's encoding of the call-by-value λ-calculus into the π-calculus. We show that, by tuning the encoding to two subcalculi of the π-calculus (Internal π and Asynchronous Local π), the equivalence on λ-terms induced by the encoding coincides with Lassen's eager normal-form bisimilarity, extended to handle η-equality. As behavioural equivalence in the π-calculus we consider contextual equivalence and barbed congruence. We also extend the results to preorders.

On a different, but related, strand of work [17], we study the tree structures that result when writing call-by-name functions as processes, and give general conditions under which this representation produces Lévy-Longo Trees and Böhm Trees, the best known tree structures on the lambda-calculus.

6.5. 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 particular in the context of K-12 education (students aged approximately from 5 to 18). We study philosophical, sociological and historical motivations to teach computer science at all school levels. Furthermore, we study what concepts and skills related to computer science are not barely 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 (particularly gender-related issues); teacher training (particularly non-specialist teachers).

6.5.1. Computational thinking and constructionism

In the last ten years, the expression “computational thinking” has been used to talk about the introduction of CS in K-12 education. The expression was originally used in the 1980s by Seymour Papert, a pioneer in Math education using programming (he is the principal inventor of the LOGO programming language). We analysed [37] the original context in which the expression originated: the constructionist learning theory, that promotes an active way of learning by constructing meaningful computational artifacts. Papert aimed to teach Math and Physics, but we think CS too is a breeding ground for applying constructionist practices like creative learning, iterative and incremental development, learning by doing, learning by trial and error, project-based learning [35].

6.5.2. CS in the school curriculum

As there is no established practice in teaching CS, academics should facilitate the introduction of CS principles in the school curriculum, to avoid misconceptions and to focus mainly on scientific principles, rather than on technical aspects. Within a CINI (Italian National Interuniversity Consortium for Informatics) group, we designed a proposal [27] for CS teaching in Italian K-10 schools, that focuses on CS principles, and gives space to the use of digital technologies only as tools for self-expression through computation. When introducing a new discipline, often misconceptions arise. In a large sample of primary teachers, we investigate [38], [24] the ideas about the “buzzword” *coding*, that is more and more used to talk about CS at school. Only 60% of teachers correctly linked “coding” to “programming” (some of them implicitly), and many misconceptions (e.g. “coding is only for children”, or “coding is the transversal use of computational thinking at school”, “programming is only for professionals”) were found. After defining a curriculum, one should also provide some materials to concretely teach the discipline and ensure learning objectives will be achieved. We presented [21] the structure of a nationwide initiative by the Italian Ministry of Education: Problem Solving Olympics (OPS). Preliminary analysis of students’ results in the last five editions suggests the competition fosters learning of computational thinking knowledge and skills.

6.5.3. Growth mindset and teacher training

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. Teachers’ mindset directly affects students’ one. By contrast, applying constructionists approaches seems to foster a growth mindset. In facts, we found a statistically significative, albeit little, increase of pre-service primary teacher’s growth mindset after a “creative computing and computational thinking” course [34].

6.6. 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 this area a *portfolio solver* combines a variety of different constraint solvers for solving a given problem. This fairly recent approach enables to significantly boost the performance of single solvers, especially when multicore architectures are exploited. In [10] we give a brief overview of the portfolio solver sunny-cp, and we discuss its performance in the MiniZinc Challenge —the annual international competition for CP solvers —where it won two gold medals in 2015 and 2016.

7. Partnerships and Cooperations

7.1. National Initiatives

- ELICA (Expanding Logical Ideas for Complexity Analysis) is an ANR project that started on October 2014 and that finished on September 2018. ELICA focused on methodologies for the static analysis of programs and their resource consumption. The project's aim was to further improve on logical methodologies for complexity analysis (type systems, rewriting, etc.). More specifically, one would like to have more powerful techniques with less false negatives, being able at the same time to deal with nonstandard programming paradigms (concurrent, probabilistic, etc.). Main persons involved: Avanzini, Dal Lago, Martini.
- 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 will finish 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.

7.2. European Initiatives

7.2.1. 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 proposed project aims to bring the existing prototype tools based on these technologies to mainstream programming languages and development frameworks used in industry.

7.2.2. Collaborations in European Programs, Except FP7 & H2020

- 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).
- ICT COST Action IC1402 ARVI (Runtime Verification beyond Monitoring). Initiated in December 2014 and with a 4-year duration, this COST Action studies runtime verification, a computing analysis paradigm based on observing a system at runtime to check its expected behaviour.

  Main persons involved: Bravetti, Lanese.

7.2.3. 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.
- Facultad de Informatica, Universidad Complutense de Madrid (on web services). Contact person(s) in Focus: Bravetti. Bravetti is an external collaborator in the project “Desarrollo y Análisis formal de sistemas complejos en contextos DistribuidOS: fundamentos, herramientas y aplicaciones (DArDOS)” (Development and formal analysis of complex systems in distributed contexts: foundations, tools and applications) January 2016 - December 2018, funded by the Spanish Ministerio de Economia y Competitividad.

7.3. International Initiatives

7.3.1. Inria Associate Teams Not Involved in an Inria International Labs

7.3.1.1. 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.

7.3.2. 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.

7.3.2.1. AYAME

CRECOGI

Title: Concurrent, Resourceful and Effectful Computation by Geometry of Interaction

International Partner (Institution - Laboratory - Researcher):

JSPS (Japan) - Kyoto University /Research Institute for Mathematical Sciences - Naohiko Hoshino

Duration: 2015 - 2020 The description of the project can be found in Section 7.3.1.1.

7.4. International Research Visitors

7.4.1. 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.

- Filippo Bonchi (ENS Lyon and University of Pisa) “Sound up-to techniques and complete abstract domain”.

- Luis Fernando Llana Díaz (Universidad Complutense de Madrid) “Probabilistic software product lines”.
- Claudia Faggian (Université Paris-Diderot – Paris 7) : “Probabilistic Lambda Calculus – beyond deterministic evaluation”
- Nao Hirokawa (Japan Advanced Institute of Science and Technology): “Transformations for Lazy Evaluation and Theorem Proving”.
- Guilhem Jaber (University of Nantes): “Game semantics for higher-order functions with state”.
- Thomas Leventis (Institut de Mathematiques de Marseille): “Taylor Expansion of lambda terms and differential linear logic.”
- Gabriel Scherer (Inria Parsifal). “Keep (re)playing until your get all the successes”.
- Emilio Tuosto (University of Leicester): “On pomsets as models of asynchronous message-passing languages”.
- Akihisa Yamada (NII Tokyo): “Mathematics for Complexity in Isabelle/HOL”.

7.4.2. Visits to International Teams

- Francesco Gavazzo visited the Faculty of Mathematics and Physics (University of Ljubljana) hosted by Alex Simpson, from 02/10/2017 to 31/01/2018.
- U. Dal Lago has spent overall a few weeks in Japan (University of Kyoto and University of Tokyo), collaborations with Naohiko Hoshino and Naoki Kobayashi.

7.4.2.1. Sabbatical programme

Simone Martini is Fellow at the Collegium - Lyon Institute for Advanced Studies, since September 2018 and until June 2019 https://collegium.universite-lyon.fr.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. General Chair, Scientific Chair

S. Martini: Workshop “Formalisms at the interface with machines, languages and systems”, Bertinoro October 16-17 2018. https://programme.hypotheses.org/autumn-workshop-formalisms-at-the-interface-with-machines-languages-and-systems

U. Dal Lago: First Workshop on Probabilistic Interactive and Higher-Order Computation, http://pihoc2018.cs.unibo.it/

8.1.1.2. Member of the Organizing Committees

Steering Committee membersip:

I. Lanese: Conference on Reversible Computation (RC); Microservices, DevOps, and Service-Oriented Architecture (MiDOS) track of the Annual ACM Symposium on Applied Computing (SAC); IFIP Int. Conference on Formal Techniques for Distributed Objects, Components and Systems (FORTE)

8.1.2. Scientific Events Selection

8.1.2.1. Chair of Conference Program Committees

U. Dal Lago: 21st Int. Conference on Foundations of Software Science and Computation Structures (FoSSaCS)

8.1.2.2. Member of the Conference Program Committees

M. Bravetti: IEEE Int. Conference on Big Data (BigData 2018); 12th IEEE Int. Conference On Big Data Science and Engineering (BigDataSE 2018); 18th IEEE Int. Conference on Software Quality, Reliability, and Security (QRS 2018); 30th IFIP Int. Conference on Testing Software and Systems (ICTSS 2018); 16th Int. Conference on Software Engineering and Formal Methods (SEFM 2018); 15th Int. Conference on Applied Computing (AC 2018)

U. Dal Lago: Thirty-Third Annual ACM/IEEE Symposium on Logic in Computer Science (LICS); Third Int. Conference on Formal Structures for Computation and Deduction (FSCD); 13th Workshop on Logical and Semantic Frameworks with Applications (LSFA);

I. Lanese: 11th IEEE Int. Conference on Service-Oriented Computing and Applications (SOCA 2018); 11th Interaction and Concurrency Experience (ICE 2018); 10th Conference on Reversible Computation (RC 2018); 15th Int. Conference on Formal Aspects of Component Software (FACS 2018); Second Int. Workshop on Microservices: Agile and DevOps Experience (MADE18)

D. Sangiorgi: 27th European Symposium on Programming (ESOP); 13th int. conf. on Software Technologies (ICSOFT'18); Symposium on Dependable Software Engineering (SETTA'18); IFIP Int. Conference on Formal Techniques for Distributed Objects, Components and Systems (FORTE); int. conf. on Logic for Programming, Artificial Intelligence and Reasoning (LPAR-22).

A. Yoshimizu: Games for Logic and Programming Languages XIII (GaLoP 2018).

8.1.3. Journal

8.1.3.1. 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.

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.

8.1.4. Invited Talks

I. Lanese: 10th Conference on Reversible Computation (RC 2018)

D. Sangiorgi: 19th Italian Conference on Theoretical Computer Science (ICTCS'18)

Schools:

U. Dal Lago: "Lambda Calcolo e Teoria dei Tipi", Scuola AILA, Gargnano 2018

8.1.5. 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 the vice-presiden of EQANIE (European Quality Assurance Network for Informatics Education), since 1 January 2018.

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.

S. Martini is a member of the Board of CINI (Italian National Interuniversity Consortium for Informatics), designated by the Ministry for Semplificazione e Pubblica Amministrazione, from 2015.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

- Mario Bravetti

  Master: “Linguaggi, Compilatori e Modelli Computazionali”, 120 hours, 1st year, University of Bologna, Italy.
- Ugo Dal Lago

  Undergraduate: “Introduction to Programming in Python”, 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”, 36 Hours, 2nd 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”, 56 hours, 1st year, University of Bologna, Italy.

  Master: “Ingegneria del Software Orientata ai Servizi”, 22 hours, 2nd 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

  Undergraduate: “Programming in Python”, 72 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

  Undergraduate: “Computer Architectures”, 60 hours, 1st year, University of Bologna, Italy

  Undergraduate: “Algoritmi e strutture dati”, 60 hours, 2nd year, University of Bologna, Italy

8.2.2. Supervision

Below are the details on the PhD students in Focus: starting date, topic or provisional title of the thesis, supervisor(s). These are all PhDs in progress.

- Raphaelle Crubillé, October 2015, “Bisimulation Metrics and Probabilistic Lambda Calculi”, Université Denis Diderot and University of Bologna. Supervisors Thomas Ehrhard and 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.
- Francesco Gavazzo, October 2015, “Coinductive Techniques for Effectful Lambda Calculi”. Supervisor U. Dal Lago.
- Michael Lodi, January 2017, “Growth Mindset and Computational Thinking”. Supervisor: S. Martini.
- Tong Liu, November 2015, “Constraint based languages for Software Defined Networks”. Supervisor: Maurizio Gabbrielli.
- Stefano Pio Zingaro, November 2016, “High level languages for Internet of Things applications”. Supervisor: Maurizio Gabbrielli.
- Gabriele Vanoni, November 2018. “Optimal Reduction, Geometry of Interaction, and the Space-Time Tradeoff”. Supervisor Ugo Dal Lago.

8.2.3. Juries

Daniel Hirschkoff was reviewer (rapporteur) for the PhD thesis Guvan Cabon, in december 2018 (Univ. Rennes).

Simone Martini has been member of the PhD jury of Francesco di Giacomo, Università Ca’ Foscari Venezia (June 2018) and Tilburg University (November 2018)

8.3. Popularization

8.3.1. Education

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.
- S. Martini has given various talks at institutes and workshops on the teaching methods for Computer Science, including a talk on ”Abbiamo davvero bisogno del pensiero computazionale?”, at the conference ”I bit rotolano dovunque”, Università di Roma Tor Vergata, May 2018.

8.3.2. Interventions

Daniel Hirschkoff was part of the organising committee for the "École Jeunes Chercheurs en Programmation", 25-29 june 2018, in Lyon.

8.3.3. Other duties

S. Martini has been Head of the Department of Computer Science and Engineering, University of Bologna, until May 2018.

M. Gabbrielli is Deputy Head of the Department of Computer Science and Engineering, University of Bologna, since May 2018.

G. Zavattaro is coordinator of undergraduate studies at the Department of Computer Science and Engineering, University of Bologna (Informatica per il Management).

9. Bibliography

Major publications by the team in recent years

[1] M. BRAVETTI, G. ZAVATTARO.*A Foundational Theory of Contracts for Multi-party Service Composition*, in "Fundam. Inform.", 2008, vol. 89, n^{o} 4, p. 451-478

[2] N. BUSI, M. GABBRIELLI, G. ZAVATTARO.*On the expressive power of recursion, replication and iteration in process calculi*, in "Mathematical Structures in Computer Science", 2009, vol. 19, n^{o} 6, p. 1191-1222

[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

[8] F. MONTESI, C. GUIDI, G. ZAVATTARO.*Composing Services with JOLIE*, in "Fifth IEEE European Conference on Web Services (ECOWS 2007)", 2007, p. 13-22

[9] D. SANGIORGI.*An introduction to Bisimulation and Coinduction*, Cambridge University Press, 2012

Publications of the year

Articles in International Peer-Reviewed Journal

[10] R. AMADINI, M. GABBRIELLI, J. MAURO.*SUNNY-CP and the MiniZinc challenge*, in "Theory and Practice of Logic Programming", January 2018, vol. 18, n^{o} 01, p. 81 - 96 [*DOI :* 10.1017/S1471068417000205], https://hal.inria.fr/hal-01931324

[11] M. AVANZINI, U. DAL LAGO.*On sharing, memoization, and polynomial time*, in "Information and Computation", August 2018, vol. 261, p. 3 - 22 [*DOI :* 10.1016/J.IC.2018.05.003], https://hal.archives-ouvertes.fr/hal-01926431

[12] F. BARBANERA, I. LANESE, U. DE'LIGUORO.*A theory of retractable and speculative contracts*, in "Science of Computer Programming", December 2018, vol. 167, p. 25 - 50 [*DOI :* 10.1016/J.SCICO.2018.06.005], https://hal.inria.fr/hal-01912858

[13] M. BRAVETTI.*Reduction Semantics in Markovian Process Algebra*, in "Journal of Logical and Algebraic Methods in Programming", 2018, vol. 96, p. 41-64 [*DOI :* 10.1016/J.JLAMP.2018.01.002], https://hal.inria.fr/hal-01921194

[14] M. BRAVETTI, M. CARBONE, G. ZAVATTARO.*On the Boundary between Decidability and Undecidability of Asynchronous Session Subtyping*, in "Theoretical Computer Science", 2018, vol. 722, p. 19-51 [*DOI :* 10.1016/J.TCS.2018.02.010], https://hal.inria.fr/hal-01921168

[15] F. S. DE BOER, M. BRAVETTI, M. D. LEE, G. ZAVATTARO.*A Petri Net Based Modeling of Active Objects and Futures*, in "Fundamenta Informaticae", 2018, vol. 159, n^o 3, p. 197-256 [*DOI :* 10.3233/FI-2018-1663], https://hal.inria.fr/hal-01919136

[16] I. LANESE, N. NISHIDA, A. PALACIOS, G. VIDAL.*A theory of reversibility for Erlang*, in "Journal of Logical and Algebraic Methods in Programming", November 2018, vol. 100, p. 71 - 97 [*DOI :* 10.1016/J.JLAMP.2018.06.004], https://hal.inria.fr/hal-01912856

[17] D. SANGIORGI, X. XU.*Trees from functions as processes*, in "Logical Methods in Computer Science", August 2018, https://arxiv.org/abs/1804.05797 [*DOI :* 10.2168/LMCS-14(3:11)2018], https://hal.inria.fr/hal-01931186

Invited Conferences

[18] I. LANESE.*From Reversible Semantics to Reversible Debugging*, in "Reversible Computation", Leicester, United Kingdom, Lecture Notes in Computer Science, September 2018, vol. 11106, https://hal.inria.fr/hal-01912920

[19] D. SANGIORGI.*Bisimilarity via unique-solution techniques*, in "19th Italian Conference on Theoretical Computer Science", Urbino, Italy, September 2018, https://hal.inria.fr/hal-01931203

International Conferences with Proceedings

[20] M. AVANZINI, U. DAL LAGO, A. YAMADA.*On Probabilistic Term Rewriting*, in "Functional and Logic Programming - 14th International Symposium, Proceedings", Nagoya, Japan, May 2018, https://hal.archives-ouvertes.fr/hal-01926502

[21] R. BORCHIA, A. CARBONARO, G. CASADEI, L. FORLIZZI, M. LODI, S. MARTINI.*Problem Solving Olympics: an inclusive education model for learning Informatics*, in "Informatics in Schools. Fundamentals of Computer Science and Software Engineering - 11th International Conference on Informatics in Schools: Situation, Evolution, and Perspectives, ISSEP 2018", St. Petersburg, Russia, Lecture Notes in Computer Science, October 2018, vol. 11169, p. 319–335 [*DOI :* 10.1007/978-3-030-02750-6_25], https://hal.inria.fr/hal-01913064

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[23] F. BREUVART, U. DAL LAGO.*On Intersection Types and Probabilistic Lambda Calculi*, in "20th International Symposium on Principles and Practice of Declarative Programming", Frankfurt am Main, Germany, ACM Press, September 2018 [*DOI :* 10.1145/3236950.3236968], https://hal.archives-ouvertes.fr/hal-01926420

[24] I. CORRADINI, M. LODI, E. NARDELLI.*An Investigation of Italian Primary School Teachers' View on Coding and Programming*, in "Informatics in Schools. Fundamentals of Computer Science and Software Engineering - 11th International Conference on Informatics in Schools: Situation, Evolution, and Perspectives, ISSEP 2018", St. Petersburg, Russia, Lecture Notes in Computer Science, October 2018, vol. 11169, p. 228–243 [*DOI :* 10.1007/978-3-030-02750-6_18], https://hal.inria.fr/hal-01913059

[25] U. DAL LAGO, G. VANONI.*On Randomised Strategies in the λ-Calculus*, in "19th Italian Conference on Theoretical Computer Science", Urbino, Italy, September 2018, https://hal.archives-ouvertes.fr/hal-01926512

[26] A. DURIER, D. HIRSCHKOFF, D. SANGIORGI.*Eager Functions as Processes*, in "the 33rd Annual ACM/IEEE Symposium", Oxford, United Kingdom, Proceedings of the 33rd Annual ACM/IEEE Symposium on Logic in Computer Science, LICS 2018, ACM Press, July 2018 [*DOI :* 10.1145/3209108.3209152], https://hal.archives-ouvertes.fr/hal-01917255

[27] L. FORLIZZI, M. LODI, V. LONATI, C. MIROLO, M. MONGA, A. MONTRESOR, A. MORPURGO, E. NARDELLI.*A Core Informatics Curriculum for Italian Compulsory Education*, in "Informatics in Schools. Fundamentals of Computer Science and Software Engineering - 11th International Conference on Informatics in Schools: Situation, Evolution, and Perspectives, ISSEP 2018", St. Petersburg, Russia, Lecture Notes in Computer Science, October 2018, vol. 11169, p. 141–153 [*DOI :* 10.1007/978-3-030-02750-6_11], https://hal.inria.fr/hal-01913057

[28] M. GABBRIELLI, S. GIALLORENZO, I. LANESE, S. P. ZINGARO.*A Language-based Approach for Interoperability of IoT Platforms*, in "Hawaii International Conference on System Science", Waikoloa Village, United States, November 2018, https://hal.inria.fr/hal-01912958

[29] F. GAVAZZO.*Quantitative Behavioural Reasoning for Higher-order Effectful Programs: Applicative Distances*, in "LICS '18- Proceedings of the 33rd Annual ACM/IEEE Symposium on Logic in Computer Science", Oxford, United Kingdom, July 2018 [*DOI :* 10.1145/3209108.3209149], https://hal.inria.fr/hal-01926069

[30] S. GIALLORENZO, I. LANESE, D. RUSSO.*ChIP: a Choreographic Integration Process*, in "On the Move to Meaningful Internet Systems", La Valletta, Malta, October 2018, https://hal.inria.fr/hal-01912917

[31] S. GIALLORENZO, F. MONTESI, M. GABBRIELLI.*Applied Choreographies*, in "38th International Conference on Formal Techniques for Distributed Objects, Components, and Systems (FORTE)", Madrid, Spain, C. BAIER, L. CAIRES (editors), Formal Techniques for Distributed Objects, Components, and Systems, Springer International Publishing, June 2018, vol. LNCS-10854, p. 21-40 [*DOI :* 10.1007/978-3-319-92612-4_2], https://hal.inria.fr/hal-01824812

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[34] M. LODI.*Can Creative Computing foster Growth Mindset?*, in "Joint Proceedings of the 1st Co-Creation in the Design, Development and Implementation of Technology-Enhanced Learning workshop (CC-TEL 2018) and Systems of Assessments for Computational Thinking Learning workshop (TACKLE 2018) co-located with 13th European Conference on Technology Enhanced Learning (ECTEL 2018)", Leeds, United Kingdom, CEUR Workshop Proceedings, September 2018, vol. 2190, https://hal.inria.fr/hal-01913053

[35] M. MONGA, M. LODI, D. MALCHIODI, A. MORPURGO, B. SPIELER.*Learning to program in a constructionist way*, in "Proceedings of Constructionism 2018", Vilnius, Lithuania, August 2018, https://hal.inria.fr/hal-01913065

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National Conferences with Proceeding

[37] M. LODI.*Computational Thinking: from "samba schools of computation" to CoderDojos*, in "Atti del convegno DIDAMATICA 2018", Cesena, Italy, April 2018, https://hal.inria.fr/hal-01913063

Other Publications

[38] I. CORRADINI, M. LODI, E. NARDELLI.*Coding and Programming: What Do Italian Primary School Teachers Think? (Abstract Only)*, ACM Press, February 2018, SIGCSE '18 - Proceedings of the 49th ACM Technical Symposium on Computer Science Education, Poster [*DOI :* 10.1145/3159450.3162268], https://hal.inria.fr/hal-01913062

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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

Keywords:

Computer Science and Digital Science:

A3.1.4. - Uncertain data
A3.1.10. - Heterogeneous data
A3.4.1. - Supervised learning
A3.4.6. - Neural networks
A3.4.8. - Deep learning
A5.1. - Human-Computer Interaction
A5.1.1. - Engineering of interactive systems
A5.1.2. - Evaluation of interactive systems
A5.1.8. - 3D User Interfaces
A5.1.9. - User and perceptual studies
A5.3.5. - Computational photography
A5.4.4. - 3D and spatio-temporal reconstruction
A5.4.5. - Object tracking and motion analysis
A5.5. - Computer graphics
A5.5.1. - Geometrical modeling
A5.5.2. - Rendering
A5.5.3. - Computational photography
A5.6. - Virtual reality, augmented reality
A5.9.1. - Sampling, acquisition
A5.9.3. - Reconstruction, enhancement
A6.3.5. - Uncertainty Quantification
A8.3. - Geometry, Topology
A9.2. - Machine learning
A9.3. - Signal analysis

Other Research Topics and Application Domains:

B5. - Industry of the future
B5.2. - Design and manufacturing
B5.7. - 3D printing
B8. - Smart Cities and Territories
B8.3. - Urbanism and urban planning
B9. - Society and Knowledge
B9.1.2. - Serious games
B9.2. - Art
B9.2.2. - Cinema, Television
B9.2.3. - Video games
B9.6. - Humanities
B9.6.6. - Archeology, History

1. Team, Visitors, External Collaborators

Research Scientists
George Drettakis [Team leader, Inria, Senior Researcher, HDR]
Adrien Bousseau [Inria, Researcher, HDR]

External Collaborator
Frédéric Durand [MIT]

Technical Staff
Yulia Gryaditskaya [Inria]
Sebastian Vizcay [Inria]
Bastien Wailly [Inria]
Georgios Kopanas [Inria, Research Engineer, until Feb 2018]
Sebastien Morgenthaler [Inria, from Oct 2018]

PhD Students
Johanna Delanoy [Inria]
Valentin Deschaintre [Optis]
Jean-Dominique Favreau [Inria, until Mar 2018]
David Jourdan [Inria, from Oct 2018]
Julien Philip [Inria]
Simon Rodriguez [Ministère de l'Enseignement Supérieur et de la Recherche]
Theo Thonat [Inria]

Post-Doctoral Fellows
Gabriel Cirio [Inria, until Feb 2018]
Rada Deeb [Inria, from Dec 2018]
Tibor Stanko [Inria, from Feb 2018]
Abdelaziz Djelouah [Disney Research, until Jan 2018]
Georgios Koulieris [Durham University, until Feb 2018]

Visiting Scientists
Miika Aittala [MIT, from Jun 2018 until Jul 2018]
Yotam Gingold [George Mason University, from Jun 2018 until Jul 2018]

Administrative Assistant
Sophie Honnorat [Inria]

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.

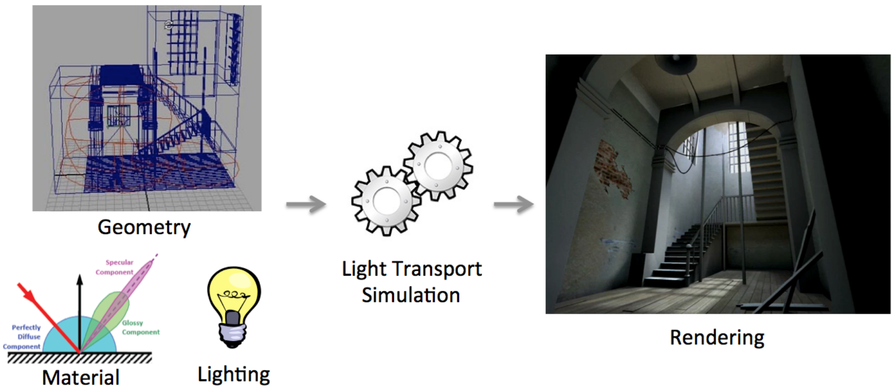


Figure 1. Traditional computer graphics pipeline. Rendering from www.thegnomonworkshop.com

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

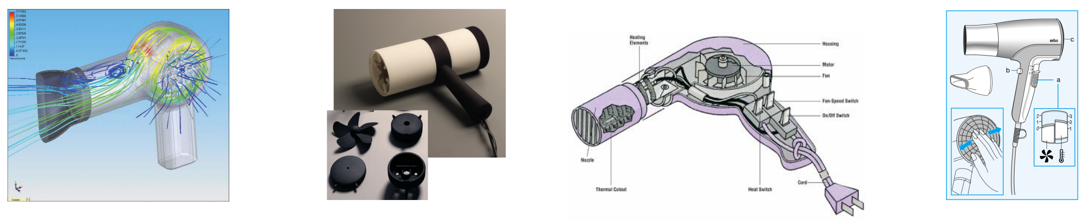
3.1. Introduction

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. Figure 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.

Figure 3. Image-Based Rendering (IBR) techniques use input photographs and approximate 3D to produce new synthetic views.

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.

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

This year marked the start of the ERC Starting grant FunGraph coordinated by George Drettakis, on managing uncertainty in rendering of captured content. This activity already includes the principal investigator, one engineer (S. Morgenthaler), one postdoc (R. Deeb), and an intern (S. Diolatzis). The scientific production this year included three papers in ACM Transactions on Graphics (two at SIGGRAPH and one at SIGGRAPH Asia), three papers in Computer Graphics Forum (two at EGSR and one at Eurographics), and two papers at the ACM Symposium on Interactive 3D Graphics and Games.

4.1.1. Awards

George Drettakis received a medal from University Côte d'Azur for his ERC grant.

5. New Software and Platforms

5.1. 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 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, e.g., compute shadow maps of both exact and reconstructed representations etc.

- Contact: George Drettakis

5.2. 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.

- Contact: George Drettakis

5.3. SIBR

Simple Image-Based Rendering
KEYWORD: Graphics
FUNCTIONAL DESCRIPTION: This 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.

It includes basic support for a large set of computer graphics and computer vision functionalities and includes implementations of several image-based rendering algorithms. The code base has become quite mature and is in the process of being used for tech transfer.

- Contact: George Drettakis

5.4. SynthDraw

KEYWORDS: Non-photorealistic rendering - Vector-based drawing
FUNCTIONAL DESCRIPTION: The SynthDraw library extracts occluding contours and sharp features over a 3D shape, computes all their intersections using a binary space partitionning algorithm, and finally makes 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. SynthDraw is based on the geometry processing library libIGL.

RELEASE FUNCTIONAL DESCRIPTION: This first version extracts occluding contours and creases, and computes their visibility with brute-force ray casting.

- Contact: Bastien Wailly

5.5. 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.

- Contact: Adrien Bousseau

6. New Results

6.1. Computer-Assisted Design with Heterogeneous Representations

6.1.1. 3D Sketching using Multi-View Deep Volumetric Prediction

Participants: Johanna Delanoy, Adrien Bousseau.

Drawing is the most direct way for people to express their visual thoughts. However, while humans are extremely good are perceiving 3D objects from line drawings, this task remains very challenging for computers as many 3D shapes can yield the same drawing. Existing sketch-based 3D modeling systems rely on heuristics to reconstruct simple shapes, require extensive user interaction, or exploit specific drawing techniques and shape priors. Our goal is to lift these restrictions and offer a minimal interface to quickly model general 3D shapes with contour drawings . While our approach can produce approximate 3D shapes from a single drawing, it achieves its full potential once integrated into an interactive modeling system, which allows users to visualize the shape and refine it by drawing from several viewpoints (Figure 4). At the core of our approach is a deep convolutional neural network (CNN) that processes a line drawing to predict occupancy in a voxel grid. The use of deep learning results in a flexible and robust 3D reconstruction engine that allows us to treat sketchy bitmap drawings without requiring complex, hand-crafted optimizations. While similar architectures have been proposed in the computer vision community, our originality is to extend this architecture to a multiview context by training an updater network that iteratively refines the prediction as novel drawings are provided.

This work is a collaboration with Mathieu Aubry from Ecole des Ponts ParisTech and Alexei Efros and Philip Isola from UC Berkeley. The work was published in Proceedings of the ACM on Computer Graphics and Interactive Techniques and presented at the ACM SIGGRAPH I3D Symposium on Interactive Computer Graphics and Games [12].

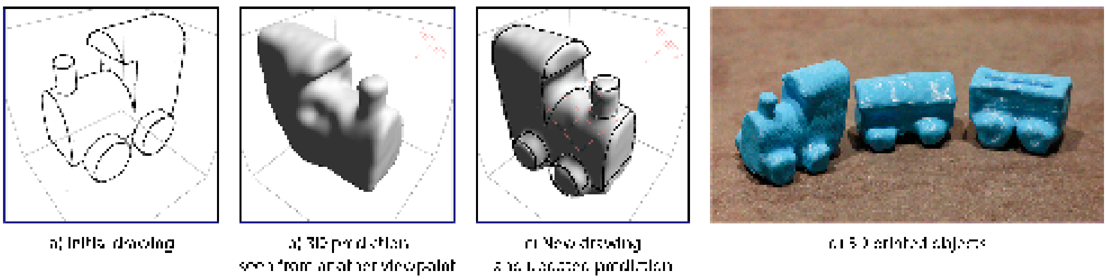


Figure 4. Our sketch-based modeling system can process as little as a single perspective drawing (a) to predict a volumetric object (b). Users can refine this prediction and complete it with novel parts by providing additional drawings from other viewpoints (c). This iterative sketching workflow allows quick 3D concept exploration and rapid prototyping (d).

6.1.2. Procedural Modeling of a Building from a Single Image

Participant: Adrien Bousseau.

Creating a virtual city is demanded for computer games, movies, and urban planning, but it takes a lot of time to create numerous 3D building models. Procedural modeling has become popular in recent years to overcome this issue, but creating a grammar to get a desired output is difficult and time consuming even for expert users. In this paper, we present an interactive tool that allows users to automatically generate such a grammar from a single image of a building. The user selects a photograph and highlights the silhouette of the target building as input to our method. Our pipeline automatically generates the building components, from large-scale building mass to fine-scale windows and doors geometry. Each stage of our pipeline combines convolutional neural networks (CNNs) and optimization to select and parameterize procedural grammars that reproduce the building elements of the picture. In the first stage, our method jointly estimates camera parameters and building mass shape. Once known, the building mass enables the rectification of the facades, which are given as input to the second stage that recovers the facade layout. This layout allows us to extract individual windows and doors that are subsequently fed to the last stage of the pipeline that selects procedural grammars for windows and doors. Finally, the grammars are combined to generate a complete procedural building as output. We devise a common methodology to make each stage of this pipeline tractable. This methodology consists in simplifying the input image to match the visual appearance of synthetic training data, and in using optimization to refine the parameters estimated by CNNs. We used our method to generate a variety of procedural models of buildings from existing photographs.

The work was published in Computer Graphics Forum, presented at Eurographics 2018 [15].

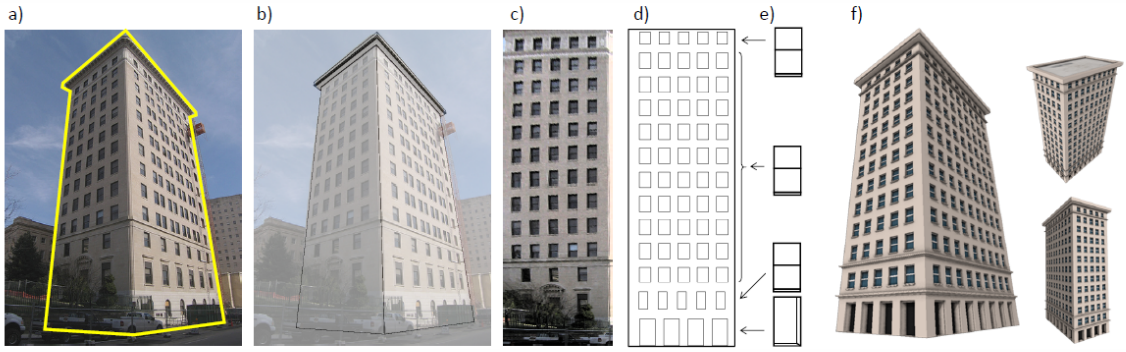


Figure 5. (a) Given an image and a silhouette of a building, (b) our approach automatically estimates the camera parameters and generates a building mass grammar as a first step. Then, (c) the facade image is rectified, and (d) the facade grammar is generated. (e) For each window non-terminal, the best window grammar is selected by maximum vote. (f) Finally the output grammar is constructed and a corresponding 3D geometry is generated.

6.1.3. OpenSketch: A Richly-Annotated Dataset of Product Design Sketches

Participants: Yulia Gryaditskaya, Frédéric Durand, Adrien Bousseau.

We collected a dataset of more than 400 product design sketches, representing 12 man-made objects drawn from two different view points by 7 to 15 product designers of varying expertise. Together with industrial design teachers, we distilled a taxonomy of the methods designers use to accurately sketch in perspective and used it to label each stroke of the 214 sketches drawn from one of the two viewpoints. We registered each sketch to its reference 3D model by annotating sparse correspondences. We made an analysis of our annotated sketches, which reveals systematic drawing strategies over time and shapes. We also developed several applications of our dataset for sketch-based modeling and sketch filtering. We will distribute our dataset under the Creative Commons CC0 license to foster research in digital sketching.

This work is a collaboration with Mark Sypesteyn, Jan Willem Hoftijzer and Sylvia Pont from TU Delft, Netherlands. It is currently under review.

6.1.4. Line Drawing Vectorization using a Global Parameterization

Participants: Tibor Stanko, Adrien Bousseau.

Despite the progress made in recent years, automatic vectorization of line drawings remains a difficult task. For drawings containing noise, holes and oversketched strokes, the main challenges are the correct classification of curve junctions, filling the missing information, and clustering multiple strokes corresponding to a single curve. We propose a new line drawing vectorization method, which addresses the above challenges in a global manner. Inspired by the quad meshing literature, we compute a global parametrization of the input drawing, such that nearby strokes are mapped to a single straight line in the parametric domain, while junctions are mapped to straight line intersections. The vectorization is obtained by following the straight lines in the parametric domain, and mapping them back to the original space. This allows us to process both clean and sketchy drawings.

This work is an ongoing collaboration with David Bommes from University of Bern, Mikhail Bessmeltsev from University of Montreal, and Justin Solomon from MIT.

6.1.5. Image-Space Motion Rigidification for Video Stylization

Participants: Johanna Delanoy, Adrien Bousseau.

Existing video stylization methods often retain the 3D motion of the original video, making the result look like a 3D scene covered in paint rather than the 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. 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 is currently under review.

6.1.6. Computational Design of Tensile Structures

Participants: David Jourdan, Adrien Bousseau.

Tensile structures are architectural shapes made of stretched elastic material that can be used to create large-span roofs. Their elastic properties make it quite challenging to obtain a specific shape, and the final shape of a tensile structure is usually found rather than imposed. We created a design tool for tensile structures that, unlike existing software, lets the user specify the shape they want and finds the closest fit.

This work is an ongoing collaboration with Melina Skouras from IMAGINE (Inria Rhone Alpes). A preliminary version was presented at JFIG (Journées Françaises d'Informatique Graphique) 2018.

6.2. Graphics with Uncertainty and Heterogeneous Content

6.2.1. Single-Image SVBRDF Capture with a Rendering-Aware Deep Network

Participants: Valentin Deschaintre, Aittala Miika, Frédéric Durand, George Drettakis, Adrien Bousseau.

Texture, highlights, and shading are some of many visual cues that allow humans to perceive material appearance in single pictures. Yet, recovering spatially-varying bi-directional reflectance distribution functions (SVBRDFs) from a single image based on such cues has challenged researchers in computer graphics for decades. We tackle lightweight appearance capture by training a deep neural network to automatically extract and make sense of these visual cues. Once trained, our network is capable of recovering per-pixel normal, diffuse albedo, specular albedo and specular roughness from a single picture of a flat surface lit by a hand-held flash. We achieve this goal by introducing several innovations on training data acquisition and network design. For training, we leverage a large dataset of artist-created, procedural SVBRDFs which we sample and render under multiple lighting directions. We further amplify the data by material mixing to cover a wide diversity of shading effects, which allows our network to work across many material classes. Motivated by the observation that distant regions of a material sample often offer complementary visual cues, we design a network that combines an encoder-decoder convolutional track for local feature extraction with a fully-connected track for *global feature* extraction and propagation. Many important material effects are view-dependent, and as such ambiguous when observed in a single image. We tackle this challenge by defining the loss as a differentiable SVBRDF similarity metric that compares the *renderings* of the predicted maps against renderings of the ground truth from several lighting and viewing directions. Combined together, these novel ingredients bring clear improvement over state of the art methods for single-shot capture of spatially varying BRDFs.

The work was published in ACM Transactions on Graphics and presented at SIGGRAPH 2018 [13], and was cited by several popular online ressources (https://venturebeat.com/2018/08/15/researchers-develop-ai-that-can-re-create-real-world-lighting-and-reflections/, https://www.youtube.com/watch?v=UkWnExEFADI).

Figure 6. From a single flash photograph of a material sample (insets), our deep learning approach predicts a spatially-varying BRDF. See supplemental materials for animations with a moving light.

6.2.2. Material Acquisition using an Arbitrary Number of Inputs

Participants: Valentin Deschaintre, Aittala Miika, Frédéric Durand, George Drettakis, Adrien Bousseau.

Single-image material acquisition methods try to solve the very ill-posed problem of appearance to parametric BRDF. We explore different acquisition configurations to solve the most important ambiguities while still focusing on convenience of acquisition. Our main exploration directions are multiple lights and view angles over multiple pictures. This is possible thanks to the use of deep learning and in-line input data rendering, allowing us to easily explore a wide variety of configurations simultaneously. We also specialize our network architecture to make the most of an arbitrary number of input, provided in any order.

6.2.3. Exploiting Repetitions for Image-Based Rendering of Facades

Participants: Simon Rodriguez, Adrien Bousseau, Frédéric Durand, George Drettakis.

Street-level imagery is now abundant but does not have sufficient capture density to be usable for Image-Based Rendering (IBR) of facades. We presented a method that exploits repetitive elements in facades – such as windows – to perform data augmentation, in turn improving camera calibration, reconstructed geometry and overall rendering quality for IBR. The main intuition behind our approach is that a few views of several instances of an element provide similar information to many views of a single instance of that element. We first select similar instances of an element from 3-4 views of a facade and transform them into a common coordinate system (Fig. 7 (a)), creating a “platonic” element. We use this common space to refine the camera calibration of each view of each instance (Fig. 7 (b)) and to reconstruct a 3D mesh of the element with multi-view stereo, that we regularize to obtain a piecewise-planar mesh aligned with dominant image contours (Fig. 7 (c)). Observing the same element under multiple views also allows us to identify reflective areas – such as glass panels – (Fig. 7 (d)) which we use at rendering time to generate plausible reflections using an environment map. We also combine information from multiple viewpoints to augment our initial set of views of the elements (Fig. 7 (e)). Our detailed 3D mesh, augmented set of views, and reflection mask enable image-based rendering of much higher quality than results obtained using the input images directly(Fig. 7 (f)).

The work was published in Computer Graphics Forum, presented at the Eurographics Symposium on Rendering 2018 [16].

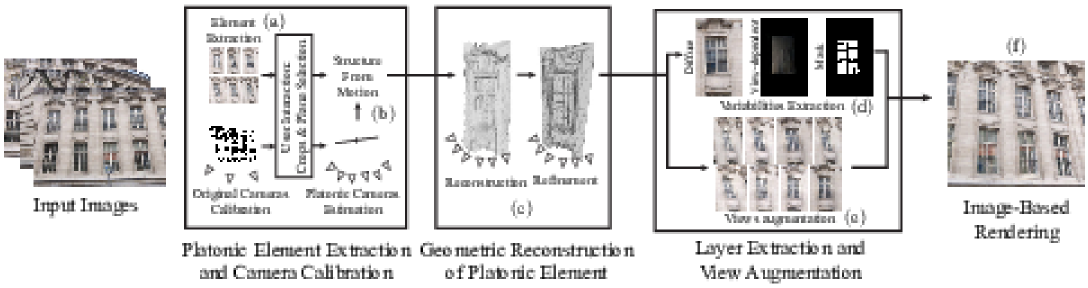


Figure 7. Overview of our technique for Image-Based Rendering of facades.

6.2.4. Plane-Based Multi-View Inpainting for Image-Based Rendering in Large Scenes

Participants: Julien Philip, George Drettakis.

Image-Based Rendering (IBR) allows high-fidelity free-viewpoint navigation using only a set of photographs and 3D reconstruction as input. It is often necessary or convenient to remove objects from the captured scenes, allowing a form of scene editing for IBR. This requires multi-view inpainting of the input images. Previous methods suffer from several major limitations: they lack true multi-view coherence, resulting in artifacts such as blur, they do not preserve perspective during inpainting, provide inaccurate depth completion and can only handle scenes with a few tens of images. Our approach addresses these limitations by introducing a new multi-view method that performs inpainting in intermediate, locally common planes. Use of these planes results in correct perspective and multi-view coherence of inpainting results. For efficient treatment of large scenes, we present a fast planar region extraction method operating on small image clusters. We adapt the resolution of inpainting to that required in each input image of the multi-view dataset, and carefully handle image resampling between the input images and rectified planes. We show results on large indoors and outdoors environments.

The work was presented at the ACM SIGGRAPH I3D Symposium on Interactive Computer Graphics and Games [19].

6.2.5. Deep Blending for Free-Viewpoint Image-Based Rendering

Participants: Julien Philip, George Drettakis.

Free-viewpoint image-based rendering (IBR) is a standing challenge. IBR methods combine warped versions of input photos to synthesize a novel view. The image quality of this combination is directly affected by geometric inaccuracies of multi-view stereo (MVS) reconstruction and by view- and image-dependent effects that produce artifacts when contributions from different input views are blended. We present a new deep learning approach to blending for IBR, in which we use held-out real image data to learn blending weights to combine input photo contributions. Our Deep Blending method requires us to address several challenges to achieve our goal of interactive free-viewpoint IBR navigation. We first need to provide sufficiently accurate geometry so the Convolutional Neural Network (CNN) can succeed in finding correct blending weights. We do this by combining two different MVS reconstructions with complementary accuracy vs. completeness tradeoffs. To tightly integrate learning in an interactive IBR system, we need to adapt our rendering algorithm to produce a fixed number of input layers that can then be blended by the CNN. We generate training data with a variety of captured scenes, using each input photo as ground truth in a held-out approach. We also design the network architecture and the training loss to provide high quality novel view synthesis, while reducing temporal flickering artifacts. Our results demonstrate free-viewpoint IBR in a wide variety of scenes, clearly surpassing previous methods in visual quality, especially when moving far from the input cameras.

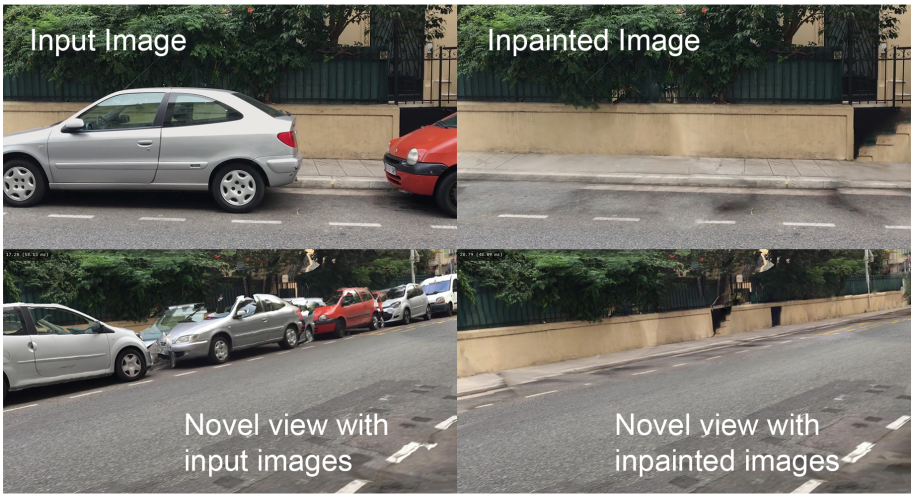


Figure 8. Our plane-based multi-view inpainting method allows us to remove cars in this large urban scene.

This work is a collaboration with Peter Hedman and Gabriel Brostow from University College London and True Price and Jan-Michael Frahm from University of North Carolina at Chapel Hill. It was published in ACM Transactions on Graphics and presented at SIGGRAPH Asia 2018 [14].

Figure 9. Deep Blending for Free-Viewpoint Image-Based Rendering

6.2.6. Thin Structures in Image Based Rendering

Participants: Theo Thonat, Abdelaziz Djelouah, Frédéric Durand, George Drettakis.

This work proposes a novel method to handle thin structures in Image-Based Rendering (IBR), and specifically structures supported by simple geometric shapes such as planes, cylinders, etc. These structures, e.g. railings, fences, oven grills etc, are present in many man-made environments and are extremely challenging for multi-view 3D reconstruction, representing a major limitation of existing IBR methods. Our key insight is to exploit multi-view information to compute multi-layer alpha mattes to extract the thin structures. We use two multi-view terms in a graph-cut segmentation, the first based on multi-view foreground color prediction and the second ensuring multi-view consistency of labels. Occlusion of the background can challenge reprojection error calculation and we use multi-view median images and variance, with multiple layers of thin structures. Our end-to-end solution uses the multi-layer segmentation to create per-view mattes and the median colors and variance to extract a clean background. We introduce a new multi-pass IBR algorithm based on depth-peeling to allow free-viewpoint navigation of multi-layer semi-transparent thin structures. Our results show significant improvement in rendering quality for thin structures compared to previous image-based rendering solutions.

The work was published in the journal Computer Graphics Forum, and was presented at the Eurographics Symposium on Rendering (EGSR) 2018 [17].

Figure 10. Thin structures are present in many environments, both indoors and outdoors (far left). Our solution extracts multi-view mattes together with clean background images and geometry (center). These elements are used by our multi-layer rendering algorithm that allows free-viewpoint navigation, with significantly improved quality compared to previous solutions (right).

6.2.7. Multi-Scale Simulation of Nonlinear Thin-Shell Sound with Wave Turbulence

Participants: Gabriel Cirio, George Drettakis.

Thin shells – solids that are thin in one dimension compared to the other two – often emit rich nonlinear sounds when struck. Strong excitations can even cause chaotic thin-shell vibrations, producing sounds whose energy spectrum diffuses from low to high frequencies over time – a phenomenon known as wave turbulence. It is all these nonlinearities that grant shells such as cymbals and gongs their characteristic “glinting” sound. Yet, simulation models that efficiently capture these sound effects remain elusive. In this project, we proposed a physically based, multi-scale reduced simulation method to synthesize nonlinear thin-shell sounds. We first split nonlinear vibrations into two scales, with a small low-frequency part simulated in a fully nonlinear way, and a high-frequency part containing many more modes approximated through time-varying linearization. This allows us to capture interesting nonlinearities in the shells’ deformation, tens of times faster than previous approaches. Furthermore, we propose a method that enriches simulated sounds with wave turbulent sound details through a phenomenological diffusion model in the frequency domain, and thereby sidestep the expensive simulation of chaotic high-frequency dynamics. We show several examples of our simulations, illustrating the efficiency and realism of our model, see Fig. 11.

This work is a collaboration with Ante Qu from Stanford, Eitan Grinspun and Changzi Zheng from Columbia. This work was published at ACM Transactions on Graphics, and presented at SIGGRAPH 2018 [11].

6.2.8. Learning to Relight Multi-View Photographs from Synthetic Data

Participants: Julien Philip, George Drettakis.

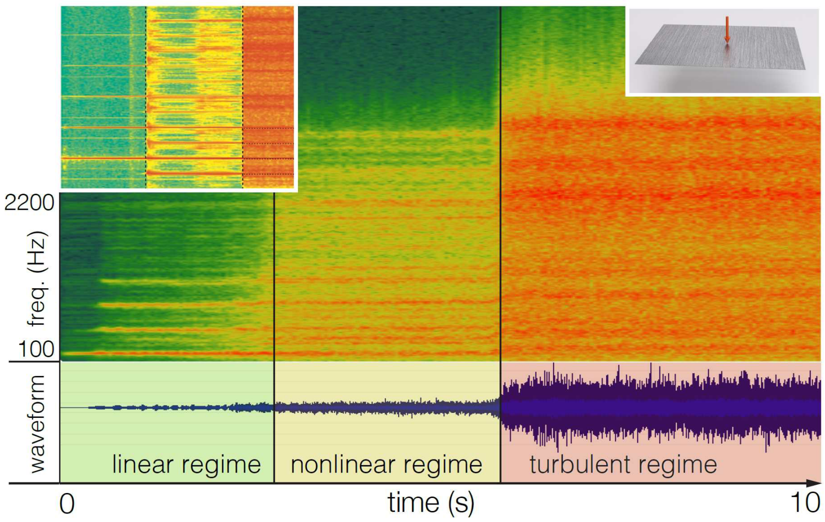


Figure 11. Thin-shell bifurcation. We excite a thin plate with increasing forces (the red arrow in the top-right inset) and simulate its dynamical responses). As the force increases, its vibration bifurcates, changing from linear vibration (left) to nonlinear (middle), and finally moving into a turbulent regime (right). This spectrogram is generated without any wave turbulence enrichment, indicating that model is able to capture chaos, albeit in low frequencies. We note that this spectrogram is qualitatively close to spectrograms from physical experiments, shown in the top-left inset (Image courtesy of Cyril Touzé).

We introduce an image relighting method that allows users to alter the lighting in their photos given multiple views of the same scene. Our method uses a deep convolutional network trained on synthetic photorealistic images. The use of a 3D reconstruction of the surroundings allows to guide the relighting process.

This ongoing project is a collaboration with Tinghui Zhou and Alexei A. Efros from UC Berkeley, and Michael Gharbi from Adobe research.

6.2.9. Exploiting Semantic Information for Street-level Image-Based Rendering

Participants: Simon Rodriguez, George Drettakis.

Following our work on facade rendering (Sec. 6.2.3), this ongoing project explores the use of semantic segmentation to inform Image-Based Rendering algorithms. In particular, we plan to devise algorithms that adapt to different types of objects in the scene (cars, buildings, trees).

6.2.10. Casual Video Based Rendering of Stochastic Phenomena

Participants: Theo Thonat, Miika Aittala, Frédéric Durand, 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 or DSLR camera, and a tripod. We focus on stochastic time-dependent textures such as leaves in the wind, water or fire, to cope with the challenge of using unsynchronized videos.

This ongoing work is a collaboration with Sylvain Paris from Adobe Research.

6.2.11. Cutting-Edge VR/AR Display Technologies

Participant: Koulieris Georgios.

Near-eye (VR/AR) displays suffer from technical, interaction as well as visual quality issues which hinder their commercial potential. We presented a tutorial that delivered an overview of cutting-edge VR/AR display technologies, focusing on technical, interaction and perceptual issues which, if solved, will drive the next generation of display technologies. The most recent advancements in near-eye displays were presented providing (i) correct accommodation cues, (ii) near-eye varifocal AR, (iii) high dynamic range rendition, (iv) gaze-aware capabilities, either predictive or based on eye-tracking as well as (v) motion-awareness (Fig. 12). Future avenues for academic and industrial research related to the next generation of AR/VR display technologies were analyzed.

This work is a collaboration with Kaan Akşit (NVIDIA), Christian Richardt (University of Bath), Rafal Mantiuk (University of Cambridge) and Katerina Mania (Technical University of Crete). The work was presented at IEEE VR 2018, 18-22 March, Reutlingen, Germany [18].

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.
- As part of a long standing collaboration with Adobe, Theo Thonnat interned with Sylvain Paris (Boston), Julien Philip works with Michael Gharbi (San Francisco) and J. Delanoy with Aaron Hertzmann (San Francisco).
- 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.

Figure 12. We presented novel display technologies, including but not limited to (left-to-right) varifocal augmented reality displays, body-tracking displays and focus-tunable displays.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ADT PicPlay

Participants: Sebastien Bonopera, George Drettakis.

The Technology Development Action (ADT) PicPlay a technology tranfer pre-maturation project, supported by Inria and by UCA Jedi. The objective is to create a startup company based on image based rendering technologies, taking benefit from the team's research and experience over the last 8 years. At this early stage, we evaluated the market and produced several Proof-of-Concept demonstrations for potential clients. One of the demonstrations is our new asset streaming capability that allows the use for huge datasets. We also developed a new solution to improve rendering quality. This solution uses a 3D mesh for each view and refines it according to this view only, before blending each view. PicPlay involved the development of several tools for converting and processing datasets. During this year we established contacts with industrial partners in the automobile industry and in the construction/public works industry who expressed interest in using the technology in their projects for visualization and navigation of captured environments.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. ERC D3

Participants: Yulia Gryaditskaya, Tibor Stanko, Bastien Wailly, David Jourdan, Adrien Bousseau.

Designers draw extensively to externalize their ideas and communicate with others. However, drawings are currently not directly interpretable by computers. To test their ideas against physical reality, designers have to create 3D models suitable for simulation and 3D printing. However, the visceral and approximate nature of drawing clashes with the tediousness and rigidity of 3D modeling. As a result, designers only model finalized concepts, and have no feedback on feasibility during creative exploration. Our ambition is to bring the power of 3D engineering tools to the creative phase of design by automatically estimating 3D models from drawings. However, this problem is ill-posed: a point in the drawing can lie anywhere in depth. Existing solutions are limited to simple shapes, or require user input to ”explain” to the computer how to interpret the drawing. Our originality is to exploit professional drawing techniques that designers developed to communicate shape most efficiently. Each technique provides geometric constraints that help viewers understand drawings, and that we shall leverage for 3D reconstruction.

Our first challenge is to formalize common drawing techniques and derive how they constrain 3D shape. Our second challenge is to identify which techniques are used in a drawing. We cast this problem as the joint optimization of discrete variables indicating which constraints apply, and continuous variables representing the 3D model that best satisfies these constraints. But evaluating all constraint configurations is impractical. To solve this inverse problem, we will first develop forward algorithms that synthesize drawings from 3D models. Our idea is to use this synthetic data to train machine learning algorithms that predict the likelihood that constraints apply in a given drawing. In addition to tackling the long-standing problem of single-image 3D reconstruction, our research will significantly tighten design and engineering for rapid prototyping.

8.2.1.2. ERC FunGraph

Participants: Sébastien Morgenthaler, George Drettakis, Rada Deeb, Diolatzis Stavros.

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 will do this by providing the means to authors of cultural products to create high-quality, interactive, personalized digital stories.

GRAPHDECO contributes by developing novel image-based rendering techniques to help museum curators and archeologists provide more engaging experiences. In 2018, we developed a mixed reality plugin for Unity that allows the use of IBR in a VR experience used in one of the EMOTIVE user experiences using a VIVE HMD.

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

- University College London (G. Brostow, P. Hedman)
- UC Berkeley (A. Efros)
- Purdue University (D. Aliaga)
- George Mason University (Y. Gingold)
- Tu Delft (M. Sypesteyn, J. W. Hoftijzer and S. Pont)

8.4. International Research Visitors

8.4.1. Visits of International Scientists

- Carol O'Sullivan, Trinity College Dublin, visited the group for one week in August.
- Peter Hedman, University College London, visited us for a few days in July.
- Miika Aittala, MIT, visited the group for one month in July.
- Yotam Gingold, George Mason University, visited the group for one month in June.

8.4.2. Visits to International Teams

8.4.2.1. Research Stays Abroad

Several students and postdocs visited our international collaborators:

- Yulia Gryaditskaya and Valentin Deschaintre visited the research group of Fredo Durand at MIT for two weeks. They presented their work to several groups (HCI, geometry, computer graphics).
- Tibor Stanko spent two weeks at RWTH Aachen University, Germany, to collaborate with David Bommes.
- Johanna Delanoy did a 3-months internship at Adobe Research (San Francisco) to collaborate with Aaron Hertzmann.
- Julien Philip spent a week at University College London to visit Gabriel Brostow and five weeks at University of California, Berkeley, to visit Alexei A. Efros. During this visit, he presented his work to the computer graphics groups of Stanford and UC Berkeley.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

G. Drettakis chairs the Eurographics (EG) working group on Rendering, and the steering committee of EG Symposium on Rendering.

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

- George Drettakis participated in the program committee of Eurographics Symposium on Rendering (EGSR) 2018 and Eurographics 2018 STAR.
- Adrien Bousseau participated in the program committee of Eurographics 2018 and SIGGRAPH 2018.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- George Drettakis was an Associate Editor of ACM Transactions on Graphics until May 2018, and of Computational Visual Media (CVM). He also chaired the ACM TOG Editor-in-Chief (EiC) search committee, which appointed Marc Alexa as ACM TOG EiC.
- Adrien Bousseau is an Associate Editor of The Visual Computer Journal.

9.1.3.2. Reviewer - Reviewing Activities

- Yulia Gryaditskaya has been a reviewer for Eurographics.
- Tibor Stanko has been a reviewer for DGCI 2019 – International Conference on Discrete Geometry for Computer Imagery, and the Computers and Graphics journal.
- Adrien Bousseau was reviewer for SIGGRAPH Asia 2018, ACM Transactions on Graphics, ACM CHI.
- George Drettakis was reviewer for SIGGRAPH.

9.1.4. Invited Talks

- George Drettakis gave a keynote talk at Driving Simulation Conference (DSC '18) (http://dsc2018.org/)
- Adrien Bousseau gave an invited talk at the SophIA summit event on artificial intelligence (http://sophia-summit.fr/) and a keynote talk at the Skin of Things workshop on material perception and depiction (https://theskinofthings.github.io/).
- Tibor Stanko was invited to present his PhD work at Journées Informatique et Géométrie (JIG) 2018 in Lyon.

9.1.5. Scientific Expertise

Adrien Bousseau reviewed a grant proposal for the ANR.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence : Simon Rodriguez, theoretical computer science (L1) and software engineering (L3), 40h eq. TD, Polytech Nice-Sophia - Université Côte d'Azur (France)

Licence : Julien Philip, Introduction au Web et Application du Web, L2, 64h, Polytech Nice-Sophia - Université Côte d'Azur (France)

Master: George Drettakis and Adrien Bousseau, Introduction to Computer Graphics, M1, 20h eq. TD, Université Côte d'Azur (France)

9.2.2. Supervision

PhD : Jean-Dominique Favreau, Compact image vectorization by stochastic approaches, Université Côte d'Azur, March 15th 2018, Florent Lafarge (Titane) and Adrien Bousseau

PhD in progress : Johanna Delanoy, Data-driven sketch-based modeling, since October 2015, Adrien Bousseau

PhD in progress : Valentin Deschaintre, Data-driven material capture, since November 2016, Adrien Bousseau and George Drettakis

PhD in progress : David Jourdan, Interactive architectural design, since October 2018, Adrien Bousseau and Melina Skouras (Imagine)

PhD in progress : Julien Philip, Data-driven image-based rendering and relighting, since November 2016, George Drettakis

PhD in progress : Simon Rodriguez, Leveraging semantic information in image-based rendering, since November 2016, George Drettakis

PhD in progress : Théo Thonat, Image-based rendering of thin and stochastic structures, since November 2015, George Drettakis

9.2.3. Juries

- George Drettakis was a Ph.D. Reviewer for Fabian Langguth (TU Darmstadt), and member “commité suivi de thèse” of J-P. Bauchet.
- Adrien Bousseau was a Ph.D. Reviewer for James Hennessey (University College London) and Dorian Nogeng (Ecole Polytechnique).

9.3. Popularization

9.3.1. Internal or external Inria responsibilities

- George Drettakis chairs the local “Jacques Morgenstern” Colloquium organizing committee.
- Adrien Bousseau is a member of “commité du centre” and “commité du suivi doctoral”.

9.3.2. Articles and contents

- Nice Matin published an article about the ERC project of George Drettakis.

9.3.3. Interventions

- Bastien Wailly gave a demo of our sketch-based modeling tool during *Fete de la Science*.
- Valentin Deschaintre presented his work to high school student and advised them on a small scientific project for *Math C2+*.

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Articles in International Peer-Reviewed Journal

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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

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]
Rallou Thomopoulos [INRA, Researcher, HDR]

Faculty Members

Michel Chein [Univ de Montpellier, Emeritus, HDR]
Madalina Croitoru [Univ de Montpellier, Associate Professor, HDR]
Jérôme Fortin [Univ de Montpellier, Associate Professor]
Michel Leclère [Univ de Montpellier, Associate Professor]
Marie-Laure Mugnier [Team leader, Univ de Montpellier, Professor, HDR]
Federico Ulliana [Univ de Montpellier, Associate Professor]

External Collaborators

Meghyn Bienvenu [CNRS, team member until Sept 2018]
Patrice Buche [INRA]
Alain Gutierrez [CNRS]

Technical Staff

Abdelraouf Hecham [Univ de Montpellier, PhD until Aug 2018, postdoc from Sep 2018]
Martin Jedwabny [INRA, from Sep 2018]
Olivier Rodriguez [Institut polytechnique de Grenoble, from Sep 2018]
Clément Sipieter [INRA]

PhD Students

Efstathios Delivorias [Univ de Montpellier]
Bruno Yun [Univ de Montpellier]

Administrative Assistant

Annie Aliaga [Inria]

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. We follow a logic-oriented approach: the different kinds of knowledge have a logical semantics and reasoning mechanisms correspond to inferences in this 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 (which also feed back into theoretical work).

2.3. Main Challenges

GraphIK focuses on some of the main challenges in KR:

- ontological query answering, *i.e.*, query answering taking an ontology into account, and able to process large datasets;
- reasoning with rule-based languages;
- reasoning in presence of inconsistency and
- decision making.

2.4. Scientific Directions

GraphIK has three main scientific directions:

1. **decidability, complexity and algorithms** for problems in languages corresponding to first-order logic fragments;
2. the addition of expressive and **non-classical features** (to the first-order logic languages studied in the first direction) with a good expressivity/efficiency trade-off;
3. the integration of theoretical tools to **real knowledge-based systems**.

From an applicative viewpoint, two themes are currently privileged:

- knowledge representation and reasoning for agronomy, oriented towards knowledge-based systems to aid decision-making for the quality control in food processing.
- knowledge representation and reasoning for data journalism, oriented towards efficient ontology-mediated query answering of heterogeneous information sources.

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.

A problem generalizing the above described problems, and particularly relevant in the context of multiple data/metadata sources, is *querying hybrid knowledge bases*. In a hybrid knowledge base, each component may have its own formalism and its own reasoning mechanisms. There may be a common ontology shared by all components, or each component may have its own ontology, with mappings being defined among the ontologies. The question is what kind of interactions between these components and/or what limitations on the languages preserve the decidability of basic problems and if so, a “reasonable” complexity. Note that there are strong connections with the issue of data integration in databases.

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 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 that typically expresses domain knowledge, heterogeneous data sources, and mappings that relate these data sources expressed with their own vocabulary and querying capabilities, to a (possibly virtual) factbase expressed using the ontological vocabulary. Ontologies play a central role as they act both as a mediation layer that glue together pieces of knowledge extracted from heterogeneous data sources, and as an inference layer that allow to draw new knowledge. In the context of data journalism, those ontologies require challenging features that we need to take into account:

- the wide range of topics addressed in journalism requires a rich top-level ontology, though very specific ontologies might be required to handle specific knowledge (e.g. detailed knowledge on finance to handle the panama papers).
- in data journalism, each piece of knowledge requires different timestamps (temporal information represented within the data, for instance when an event effectively takes place, and temporal information about the data itself, for instance when this event is recorded / validated in the system). Temporal relations (such as Allen’s) can be used to express constraints between timestamps and ensure the consistency of the (virtual) knowledge base.
- in data journalism, each piece of knowledge has an identified source. The analysis of conflicting knowledge in the (virtual) knowledge base has to take the source fiability into account.

Besides pure knowledge representation and reasoning issues, querying such systems raise issues at the crossroad of data and knowledge management. In particular, the notion of mappings has 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

5.1.1. Highlights

- A new ANR project led by GraphIK on *Complex ontological Queries over Federated and heterogeneous Data (CQFD)* has been accepted. This project, starting in January 2019, is on a core issue for GraphIK and gathers main national teams on this subject. The consortium has a long standing history of research collaboration and the current project will build upon these results.

5.1.2. Awards

The work of two PhD students of our group was recognized by international event awards:

- Stathis Delivorias and co-authors were awarded the best paper award at the International Joint Conference on Rules and Reasoning (RuleML+RR 2018) for the paper entitled "On the k-Boundedness for Existential Rules"
- Bruno Yun participated to the 3rd Summer School on Argumentation (SSA 2018): Computational and Linguistic Perspectives, and got the best student paper prize for his presentation entitled "How can you Mend a Broken Inconsistent KB in Existential Rules Using Argumentation?" (no formal proceedings available).

BEST PAPERS AWARDS :

[23]

S. DELIVORIAS, M. LECLÈRE, M.-L. MUGNIER, F. ULLIANA.*On the k-Boundedness for Existential Rules*, in "RuleML+RR: Rules and Reasoning", Luxembourg, Luxembourg, September 2018, vol. LNCS, n^{o} 11092, p. 48-64, https://arxiv.org/abs/1810.09304 [*DOI :* 10.1007/978-3-319-99906-7_4], https://hal-lirmm.ccsd.cnrs.fr/lirmm-01921140

6. New Software and Platforms

6.1. 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: Release of a new version (V3) resulting from heavy refactoring to benefit from NetBeans plugin-extensible platform architecture and graphical libraries (total replacement of the graphical editors).

This new version requires to completely revise the user documentation, which is in progress.

- Participants: Alain Gutierrez, Michel Chein, Marie-Laure Mugnier, Michel Leclère and Madalina Croitoru
- Partner: LIRMM
- Contact: Michel Chein
- URL: http://www.lirmm.fr/cogui/

6.2. DAGGER

KEYWORDS: Graph algorithmics - Logic programming

FUNCTIONAL DESCRIPTION: We introduce DAGGER: a generator for logic based argumentation frameworks instantiated from inconsistent knowledge bases expressed using Datalog. The tool allows to import a knowledge base in DLGP format and the generation and visualisation of the corresponding argumentation graph. Furthermore, the argumentation framework can also be exported in the Aspartix format.

- Contact: Madalina Croitoru
- URL: http://www.lirmm.fr/~yun/tools.html

6.3. Eldr

Existential Logic for Defeasible Reasoning
KEYWORDS: Knowledge representation - Logic programming
FUNCTIONAL DESCRIPTION: Eldr 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.

- Contact: Madalina Croitoru
- URL: https://github.com/hamhec/graal-elder

6.4. GRAAL

KEYWORDS: Knowledge database - Ontologies - Querying - Data management
SCIENTIFIC DESCRIPTION: Graal is a Java toolkit dedicated to querying knowledge bases within the framework of existential rules, aka Datalog+/-.
FUNCTIONAL DESCRIPTION: Graal has been designed in a modular way, in order to facilitate software reuse and extension. It should make it easy to test new scenarios and techniques, in particular by combining algorithms. The main features of Graal are currently the following: (1) a data layer that provides generic interfaces to store various kinds of data and query them with (union of) conjunctive queries, currently: MySQL, PostgreSQL, Sqlite, in memory graph and linked list structures, (2) an ontological layer, where an ontology is a set of existential rules, (3) a knowledge base layer, where a knowledge base is composed of a fact base (abstraction of the data via generic interfaces) and an ontology, (4) algorithms to process ontology-mediated queries, based on query rewriting and/or forward chaining (or chase), (5) a rule analyzer, which performs a syntactic and structural analysis of an existential rule set, (6) several IO formats, including imports from OWL 2.

RELEASE FUNCTIONAL DESCRIPTION: Version 1.3.0 (2017) fixes some bugs, makes the dlgp parser more flexible (dlgp being our serialization format for existential rules) and improves the efficiency of the forward chaining (chase) algorithms.

Version 1.3.1 (2018) provides minor optimizations and small bug fixes.
NEWS OF THE YEAR: 2018: Version 1.3.1, with small bug fixes and minor improvements. Several new functionalities were developed by internships in 2018 but the code is not integrated to Graal yet. 2017: New stable version (1.3.0) realised. Moreover, Graal website has been deeply restructured and enriched with new tools, available online or for download, and documentation including tutorials, examples of use, and technical documentation about all Graal modules.

- Participants: Marie-Laure Mugnier, Clément Sipieter, Jean-François Baget, Mélanie König, Michel Leclère and Swan Rocher
- Contact: Marie-Laure Mugnier
- Publications: Graal: A Toolkit for Query Answering with Existential Rules - Datalog+, RuleML and OWL 2: Formats and Translations for Existential Rules
- URL: https://github.com/graphik-team

7. New Results

7.1. Ontology Mediated Query Answering

Participants: Jean-François Baget, Meghyn Bienvenu, Efstathios Delivorias, Michel Leclère, Marie-Laure Mugnier, Federico Ulliana.

Ontolology-mediated query answering (OMQA) is the issue of querying data while taking into account inferences enabled by ontological knowledge. This gives rise to *knowledge bases*, composed of a factbase (in database terms: an instance that contains incomplete data) and an ontology. Answers to queries are logically entailed from the knowledge base. Two families of formalisms for representing and reasoning with the ontological component have been considered in this context: *description logics* (DLs) and *existential rules* (aka Datalog+, or tuple-generating dependencies in database theory). Both frameworks correspond to fragments of first-order logic, which are incomparable in general but closely related in the context of OMQA: indeed, most DLs considered for OMQA, known as lighthweight DLs, are naturally translated into specific classes of existential rules. Importantly, the foundational work carried by the knowledge representation community led to the definition of several W3C standards for Semantic Web languages, namely the family of OWL 2 ontology languages, which can be used in combination with the RDF(S) Semantic Web language. This paradigm is also supported by commercial systems, such as Oracle.

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 (also known as the *chase* in databases), 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 can be divided into two steps: first, the query is *rewritten* using the rules into a first-order query (typically a union of conjunctive queries, but possibly a more compact form); then the rewritten query is evaluated against the factbase (again, as in a classical database system). Some classes of existential rules and lightweight description logics ensure the termination of the chase and/or query rewriting, but not all.

7.1.1. Revisiting the Chase

The interest for existential rules in the OMQA context brought again to light a fundamental tool in database theory, namely the chase. Several chase variants are known: they all yield logically equivalent results, but differ on how they handle redundancies possibly caused by the introduction of unknown individuals (often called nulls). Briefly, detecting redundancies leads to smaller saturated factbases, and prevents some infinite chase sequences, but it is costly. Given a chase variant, the (all-instances) 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 inclusion dependencies. We showed the decidability of the (all-instances) chase termination problem on linear rules for three main chase variants, namely *semi-oblivious*, *restricted* and *core* chase. The restricted chase is the most used variant of the chase, however it is notoriously tricky to study 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 these results, we introduced a novel approach based on so-called derivation trees and a single notion of forbidden pattern. Besides the theoretical interest of an unified approach and new proofs, we provided the first positive decidability results 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? [37] [27] (also to appear at ICDT 2019).

As part of Stathis Delivorias' PhD thesis, we considered the related problem of *boundedness*, which asks if a given set of existential rules is bounded, i.e., whether there is a predefined upper bound on the depth of the chase, independently from any factbase. This problem is already undecidable in the specific case of datalog rules (whose head has no existential variables). However, knowing that a set of rules is bounded for some chase variant does not help much in practice if the bound is unknown. Hence, we investigated the decidability of the k-boundedness problem, which asks whether a given set of rules is bounded by an integer k. We proved that k-boundedness is decidable for three main chase variants, namely the oblivious, semi-oblivious and restricted chase [23].

We investigated the combination of existential rules and answer set programming. The combination of the two formalisms requires to extend existential rules with nonmonotonic negation and to extend ASP with existential variables. To this aim, we introduced the syntax and semantics of existential non-monotonic rules using skolemization which join together the two frameworks. Building on our previous work published at ECAI and NMR, we presented syntactic conditions that ensure the termination of the chase for existential rules and discussed extension of these results in the nonmonotonic case [13].

7.1.2. Complexity of Ontology-Mediated Query Rewriting

Extending our previous work published at LICS, we carried out a systematic study on two fundamental problems in ontology-mediated query answering, in the context of the description logic OWL 2 QL. This dialect of the W3C standard ontology language OWL 2 is aimed towards efficient query answering on large data and ensures that every conjunctive ontology-mediated-query (OMQ) is rewritable into a first-order query. The first problem is the *succintness* of first-order rewritings of OMQs, which consists in understanding how difficult it is to built rewritings for queries in some OMQ class, and in particular to determine whether OMQs in the class have polynomial-size rewritings. The second problem is the *complexity* of OMQ answering. We classified OMQs according to the shape of their conjunctive queries (treewidth, the number of leaves) and the existential depth of their ontologies. For each of these classes, we determined the combined complexity of OMQ answering, and whether all OMQs in the class have polynomial-size first-order, positive existential and nonrecursive datalog rewritings. We obtained the succinctness results using hypergraph programs, a new computational model for Boolean functions, which makes it possible to connect the size of OMQ rewritings and circuit complexity [14].

7.1.3. Ontology-Based Data Access

In the above settings, data is supposed to be stored in a factbase built on the same vocabulary as the ontology. We now consider a more general setting, often called *Ontology-Based Data Access (OBDA)*, in which data is stored in one or several databases, which were generally built independently from the ontology. Hence, the ontological level acts as a mediating level, and a new component, namely *mappings*, allows to transfer the answers to queries over the data into facts expressed in the ontology vocabulary. Mappings may be triggered to actually materialize the factbase, but such materialization may be not possible nor desirable, in which case the factbase remains virtual.

OBDA is the core setting we consider in the Inria Project Lab iCODA on data journalism (https://project.inria.fr/icoda/). As part of Maxime Buron's PhD thesis (co-supervision shared between CEDAR and GraphIK teams), we investigate several frameworks and query answering techniques in the OBDA setting. We consider the Semantic Web language RDFS to express the (possibly virtual) factbase and the core ontology, RDF rules that include classical RDF entailment rules but possibly richer ontological knowledge, expressive mappings (namely global-local-as-view mappings, whereas most existing work in the area is restricted to global-as-view mappings), and queries which, in the spirit of RDF, can interrogate both the ontology and the data at the same time. In particular, we proposed a new way of answering queries by a reduction to database query rewriting with views [21]. Software development and experiments are under progress.

We also pursued our work on inconsistency-tolerant query answering, revisiting existing complexity results obtained for OMQA in the wider context of OBDA, i.e., considering mappings. We formalized the problem and performed a detailed analysis of the data complexity of inconsistency-tolerant OBDA for ontologies formulated in data-tractable description logics, considering different semantics, notions of repairs and classes of GAV mappings. Our results imply that adding plain GAV mappings to the OMQA framework does not affect data complexity of inconsistency-tolerant query answering, but considering mappings with negated atoms leads to higher complexity [20].

Note that the latter work can also be seen as a contribution to maxi-consistent reasoning (see Section 7.2.2).

7.2. Reasoning with Inconsistency

Participants: Meghyn Bienvenu, Pierre Bisquert, Patrice Buche, Abdelraouf Hecham, Madalina Croitoru, Jérôme Fortin, Rallou Thomopoulos, Bruno Yun.

When reasoning about inconsistent logical KBs, one has to deploy reasoning mechanisms that do not follow the classical logical inference. This is due to the fact that, in classical logic, falsum implies everything. Alternative reasoning techniques are therefore needed in order to make sense of such KBs. In this section we present our results using two main classes of such techniques: defeasible reasoning and maxi-consistent reasoning.

7.2.1. Defeasible Reasoning

Defeasible reasoning is used to evaluate claims or statements in an inconsistent setting where the rules encoding the ontological knowledge may contradict each other. Unfortunately, there is no universally valid way to reason defeasibly. An inherent characteristic of defeasible reasoning is its systematic reliance on a set of intuitions and rules of thumb, which have been long debated between logicians. For example, could an information derived from a contested claim be used to contest another claim (i.e., ambiguity handling)? Could “chains” of reasoning for the same claim be combined to defend against challenging statements (i.e., team defeat)? Is circular reasoning allowed? Etc. We got interested in the task of a data engineer looking to select what existing tool to use to perform defeasible reasoning. To this end we proposed the first benchmark in the literature for first-order logic defeasible reasoning tools profiling and showed how to use the proposed benchmark in order to categorize existing tools based on their semantics (e.g. ambiguity handling), logical language (e.g. existential rules) and expressiveness (e.g. priorities) [25]. Furthermore, we proposed a new logical formalism called Statement Graphs (SGs) that captures the state-of-the-art defeasible reasoning features via a flexible labelling function [24].

7.2.2. Maxi-Consistent Reasoning

We now consider reasoning with inconsistent knowledge bases, when making the assumption that the ontological knowledge (here expressed by rules) is reliable, hence inconsistencies come from the data (or factbase), which may contradict ontological knowledge. We consider maximally consistent subsets of the factbase as the basis for inference (in short, “maxi-consistent” reasoning).

Repair semantics. One of the main challenges of reasoning with inconsistency is handling the inherent inconsistency that might occur amongst independently built data sources partially describing the same knowledge of interest. Inconsistency-tolerant semantics consider all maximally consistent subsets of a factbase, called repairs, that they manipulate using a modifier of these repairs (e.g. saturating them by the rules) and an inference strategy (e.g. answers have to be found in all repairs). However, using all repairs might be inappropriate for certain applications that would rather focus on particular data sources. For instance, when considering more reliable sources (i.e., sensor information, provenance data etc.) one could focus on repairs using mostly facts from such sources. When there is no given preference order on sources, we propose to use an intrinsic preference on facts based on their participation in inconsistencies, which generates a preference of repairs (i.e., those that contain less controversial facts are preferred). This led us to define a novel framework that takes into consideration the inconsistency on the facts and restricts the set of repairs to the “best” with respect to inconsistency values. We showed the significance and the practical interest of our approach using the real data collected in the framework of the Pack4Fresh project for reducing food wastes. During this project, we collected data using an online poll from a set of professionals of the food industry, including wholesalers, quality managers, floorwalkers and warehouse managers, about food packagings and their characteristics. The framework was able to rank the repairs efficiently and the results were then analysed and evaluated by experts from the packaging industry [35].

Argumentation. Argumentation is a reasoning under inconsistency technique, that allows to build arguments and attacks over an inconsistent data. The arguments represent the various inferences one can make. The attacks capture the inconsistency between the different pieces of knowledge. The set of arguments and the corresponding set of attacks is referred to as an argumentation framework (AF). AFs are visually represented using a directed graph where the nodes represent the arguments and the directed edges the attacks between the arguments. Classically, reasoning with argumentation systems consists of finding the maximal sets of arguments that (1) are not attacking each other and (2) defend themselves (as a group) from all incoming attacks. Such sets are called extensions.

Argumentation as a reasoning method over logic knowledge bases has the added value of providing better explanations to users than classical methods. However, one drawback of logic based argumentation frameworks is the large number of arguments generated. We provided a methodology for filtering semantically redundant arguments adapted for knowledge bases without rules or knowledge bases with rules. In the first case of knowledge bases without rules, we use the observation that free facts (i.e., facts that are not touched by any negative constraints) induce an exponential growth on the argumentation graph without any impact on its underlying structure. Therefore, we first generate the argumentation graph corresponding to the knowledge base without the free facts and then redo the whole graph including the arguments of the free facts in an efficient manner. In the second case, of the knowledge bases with rules, we introduce a new structure for the arguments and the attacks. In this new structure, we have significantly less arguments [28] (extended in [31]).

Furthermore, we provided a tool called Dagger that allows a knowledge engineer to (1) input a KB in a commonly used format and then (2) generate, (3) visualise or (4) export the argumentation graph [30]. Using the tool we were able to provide the first benchmark of logic based argumentation graphs in the litterature [32].

An alternative to the extension based semantics explained above are the ranking based semantics used mainly in the case where arguments are seen as abstract entities (and not necessarily logic derivation). There is a difference in the output format between these two approaches: when using a ranking based semantics, the output is a ranking on the arguments; in the case of extension based semantics, the output is a set of extensions. While the ranking and the scores (which are present in many ranking based semantics) allow to better assess the acceptability degree of each individual argument, the question "what are the different points of view of the argumentation framework?" stays unanswered when using a ranking based semantics. We have proposed a modular framework that is generic enough to be able to accommodate various application scenarios. In this case, one important property of the framework lies in its versatility and its capacity to yield different results according to various instantiations [33].

7.3. Decision Support Systems Applied to Agronomy

Participants: Pierre Bisquert, Patrice Buche, Abdelraouf Hecham, Madalina Croitoru, Jérôme Fortin, Rallou Thomopoulos, Bruno Yun.

High-level decision-making needs to take into account the often-conflicting interests of different stakeholders with the goal of finding solutions to provide trade-offs and build consensus towards the adoption of so-called win-win solutions. In order to enrich the deliberation process we have proposed several complementary approaches that combine various methods for an unified approach towards decision making. This has been applied in practical domains as explained below.

First, in [17] we presented a systematic method to assess possible options, based on the complementarity of argumentation modeling and system dynamics (SD) simulation, in conjunction with field experimentation. Taking advantage of the argument analysis, SD simulations are used to: 1) compare different cultural strategies available to farmers in current operating, market and regulatory conditions; 2) propose plausible what-if scenarios anticipating technological progress, and exploring the impact of adopting potential incentives and dissuasive regulatory measures.

Second, voting theory has been applied at the service of decision making. We employed Computational Social Choice (CSC) and Argumentation Framework (AF) as a combination to propose socially fair decisions which take into account both (1) the involved agents' preferences and (2) the justifications behind these preferences. Furthermore we implemented a software tool for decision-making which is composed of two main systems, i.e., the social choice system and the deliberation system [16]. This work was evaluated in practice [18]. Note that the use of argumentation in practice, when not considering fully formalised domains is very challenging. This specifically concerns decision support systems as shown in [34] where we focused on the following research question: "How to define an attack relation for argumentative decision making in socio-economic systems?" To address this question we proposed three kinds of attacks that could be defined in the context of a specific application (packaging selection) and studied how the non-computer-science experts evaluated, against a given set of decision tasks, each of these attacks.

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 is usually acquired over a long time. This knowledge is today mainly transmitted by apprenticeship and a concrete risk of knowledge forgetting is raised by the evolution of practices in the sector. Using new methods for expert knowledge capitalization the main goal of the project is to develop a new approach for expert knowledge elicitation and a dedicated software for decision making. The novel part of the decision making tool will consist 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 collaboration is starting with the research laboratory UMR SYSTEM (Tropical and mediterranean cropping system functioning and management) on knowledge representation and reasoning for agro-ecological systems.
https://www.hdigitag.fr/en/

8.1.5. Informal National Partners

We continue to work informally with the following partners:

- Michael Thomazo (VALDA Inria team) on Ontology-Mediated Query Answering [37], [27].
- Jérôme Bonnet and Sarah Gouiziou, from the Center for Structural Biochemistry of Montpellier (CBS), on the encoding of Boolean functions in biological systems [15].
- Jean-Claude Léon (IMAGINE Inria team) on the developement of an ontology-mediated query answering system applied to the field of CAD (Computer Aided Design).
- Srdjan Vesic (CRIL) on logical argumentation systems [35], [28], [30], [31], [32] . In particular, Srdjan Vesic is a co-supervisor of Bruno Yun PhD thesis, started in Sept 2016.

8.2. European Initiatives

8.2.1. NoAW (H2020, Oct. 2016-Sept. 2020)

Participants: Patrice Buche, Pierre Bisquert, Madalina Croitoru, Nikolaos Karanikolas, 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

8.2.2. 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/.

8.2.3. 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

8.2.4. Informal International Partners

- University of Toronto (Canada): collaboration with Sheila McIlraith and her research group on temporal logics [22].
- Birkbeck College, University of London (UK): collaboration with Michael Zacharyaschev, Roman Kontchakov, and Stanislav Kikot on the complexity of ontology-mediated query answering [14].
- Patras University (Greece): collaboration with Nikolaos Karanikolas (formerly postdoc in the team) [16].

8.2.5. International Research Visitors

- David Carral (postdoc, TU Dresden, Germany) visited the group between 19-21 Dec. 2018.
- Joshua Sohn (PhD, DTU, Denmark) visited the group for a month in October 2018.
- Prof. Guillermo Simari (U. Nacional del Sur, Argentina) visited the group for a week in July 2018.

8.2.6. Visits to International Teams

- One-year stay (academic year 2017-2018) of Meghyn Bienvenu at University of Toronto, Computer Science Department, collaboration with Sheila McIlraith and KR group, focusing mainly on program synthesis with linear temporal logic (LTL) specifications, in particular, taking into account environment assumptions and user preferences.
- Marie-Laure Mugnier visited the Knowledge-Based Systems research group at TU Dresden (Markus Kroetzsch), mid July 2018.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

- Co-chair of the Doctoral Consortium for the KR conference, Tempe, Arizona, October 27th 2018. http://reasoning.eas.asu.edu/kr2018/.
- Co-chair of the Tutorial Track for the IJCAI conference, Stockholm, Sweden, 13th July 2018. https://www.ijcai-18.org/.
- Scientific co-chair of the international Workshop "Reasoning on Data" associated with the international conference The Web 2018, April 24, 2018. https://sites.google.com/site/2018rod/
- Co-organization of a one-day meeting of the group "Reasoning on Data", common to GDR MaDICS and IA, October 4, 2018. http://www.lirmm.fr/rod/rod3.html

9.1.1.2. Member of the Conference Program Committees

We are regularly program committee members for the major conferences in AI (i.e., IJCAI, AAAI, ECAI, AAMAS), and more focused conferences and workshops (such as RuleML+RR, Description Logics, COMMA etc.). We also take part in the animation of the national community (JIAF, EGC, IC, BDA). For 2018, we served in the following program committees:

International

- IJCAI / ECAI 2018 (International Conferences on Artificial Intelligence): Senior PC and PC
- AAAI 2018 (AAAI Conference on Artificial Intelligence): Senior PC
- AAMAS 2018 (International Conference on Autonomous Agents and Multiagent Systems): PC
- RuleML+RR 2018 (International Joint Conference on Rules and Reasoning): PC
- Description Logics 2018: PC
- KR 2018 (Knowledge Representation and Reasoning): PC

National

- IC 2018 (Ingénierie des Connaisances) : PC
- EGC 2018 (Conférence sur l'Extraction et Gestion de Connaissances): PC
- JIAF (Journées d'Intelligence Artificielle Fondamentale): PC

9.1.2. Invited Talks

- Invited tutorial, Reasoning on data: the ontology-mediated query answering problem, 6th World Congress and School on Universal Logic (in association with UNILOG 2018), Vichy, 16-20 June, 2018 (Marie-Laure Mugnier)
  https://www.uni-log.org/start6s.html
- Invited Seminar, Answering Conjunctive Regular Path Queries over Existential Rule Knowledge Bases, Quantitative Logics and Automata Seminar, TU Dresden, July 10, 2018 (Marie-Laure Mugnier)
- Invited Talk, L'interrogation de données en présence d'ontologies : Exploiter les connaissances pour mieux tirer parti des données, Journées Nationales du GDR Informatique Mathématiques (IM), April 2018 (Meghyn Bienvenu)
- Invited Talk, Accès aux données médiatisé par des ontologies, Journées plénières du GDR IA, October 2018 (Meghyn Bienvenu)
- Invited Talk, Ontology-Mediated Query Answering and Heterogeneous Data, Séminaire INRA du réseau IN-OVIVE, June 2018 (Federico Ulliana)
- Invited talk, Ontology-mediated query answering: Harnessing knowledge to get more from data, Annual Meeting of GT ALGA (GDR IM), October 2018 (Meghyn Bienvenu)
- Invited talk, Difficultés posées par les prédicats calculés en Ontology Mediated Query Answering, Meeting of GT RoD (GDR IA), October 2018 (Jean-François Baget)

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 2018, Jean-François Baget gave Master courses (40 h) and Meghyn Bienvenu gave a 3-hour tutorial at the international conference KR 2018 on "Inconsistency-Tolerant Ontology-Mediated Query Answering".

Moreover, faculty members have some specific responsibilities in the Computer Science Licence and Master. Madalina Croitoru is the head of Special Conversion Year at IUT (since 2014) and the head of international relations for the computer science department at IUT (since 2018). 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 Leclere is deputy head of the computer science department of the faculty (since 2015). He is also in charge of the Information Systems of the faculty. 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: Abdelraouf Hecham, Defeasible Reasoning for Existential Rules, University of Montpellier, 9th of July 2018, P. Bisquert and M. Croitoru.

PhD in progress: Stathis Delivorias. Supervisors: Federico Ulliana, Michel Leclère and Marie-Laure Mugnier. "Boundedness and Module extraction in Existential Rules KBs". Started Oct. 2015.

PhD in progress: Bruno Yun. Supervisors: Madalina Croitoru, Rallou Thomopolous, Srdjan Vesic (CRIL). "Decision Making and Ranking Semantics in Logical Argumentation Frameworks". Started October 2016.

PhD in progress: Maxime Buron (CEDAR Inria team). "Efficient reasoning on large heterogeneous graphs",Supervisors: François Gaosdoué (IRISA/CEDAR) Ioana Manolescu (CEDAR), Marie-Laure Mugnier. Started October 2017.

9.2.4. Juries

- Marie Laure Mugnier was a PhD reviewer for Duc Minh TRAN, University of Nice, July 2018.
- Marie Laure Mugnier was a PhD jury member for Jieying CHEN, University Paris Sud, November 2018.
- Meghyn Bienvenu was a PhD jury member for Christos Rantsoudis, University of Toulouse / IRIT, December 2018.

9.3. Popularization

9.3.1. Articles and contents

- M. Chein, Sur la science informatique et son installation à Montpellier, Conf. Association française pour l'avancement des sciences, Montpellier avril 2017 /Bull. Acad. Sc. Lett. Montp., vol. 48, suppl. C1 (2017), p.89-102/
- M. Chein, L'informatique : la science au coeur du numérique , Conf. Académie des Sc ; et Lett. De Montpellier, mai 2017, /Bull. Acad. Sc. Lett. Montp., vol.48 (2017), p.203-214/

9.3.2. Interventions

- M. Chein, Intelligence artificielle : Mythes et Réalités, Médiathèque, La Boissière, mars 2018
- M. Chein, La complexité en Informatique. Complexité spatio-temporelle des programmes, des algorithmes et des problèmes. Pierre Rouge Sciences, Assas, janvier 2018

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[5] M. BIENVENU, S. KIKOT, R. KONTCHAKOV, V. V. PODOLSKII, M. ZAKHARYASCHEV.*Ontology-Mediated Queries: Combined Complexity and Succinctness of Rewritings via Circuit Complexity*, in "Journal of the ACM (JACM)", September 2018, vol. 65, n^o 5, p. 1-51 [*DOI :* 10.1145/3191832], https://hal-lirmm.ccsd.cnrs.fr/lirmm-01892661

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[11] A. HECHAM.*Defeasible reasoning for existential rules*, Université de Montpellier, July 2018, https://tel.archives-ouvertes.fr/tel-01904558

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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

Keywords:

Computer Science and Digital Science:

A2.3. - Embedded and cyber-physical systems
A5.1. - Human-Computer Interaction
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
A8.11. - Game Theory
A9.5. - Robotics

Other Research Topics and Application Domains:

B2.1. - Well being
B2.5. - Handicap and personal assistances
B2.7. - Medical devices
B2.8. - Sports, performance, motor skills
B3.1. - Sustainable development
B5.2. - Design and manufacturing
B5.6. - Robotic systems
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]
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External Collaborator

Ting Wang [ESIEE, from May 2018]

Technical Staff

Alain Coulbois [Inria, until Oct 2018]
Artem Melnyk [Inria, until Nov 2018]

Visiting Scientists

Hiparco Lins Vieira [University Sao Paulo, from Nov 2018]
Maysa Tome [Escola Superior de Agricultura "Luiz de Queiroz", Piracicaba, from Dec 2018]

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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
- **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.

[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, ...)

- **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 [16].

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 8.1.1), game theory, interval analysis and robotics (see section 7.1). 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 [0.5,0.6] 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 than 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 [18]. 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. Application Domains

4.1. Domains: a transversal approach

While the methods developed in the project can be used for a very broad set of application domains (for example we have an activity in CO2 emission allowances, it is clear that the size of the project does not allow us to address all of them. Hence we have decided to focus our applicative activities on *mechanism theory*, where we focus on *modeling*, *optimal design* and *analysis* of mechanisms. Along the same line our focus is *robotics* and especially *service robotics* which includes rescue robotics, rehabilitation and assistive robots for elderly and handicapped people. Although these topics were new for us when initiating the project we have spent two years determining priorities and guidelines by conducting about 200 interviews with field experts (end-users, praticians, family and caregivers, institutes), establishing strong collaboration with them (e.g. with the CHU of Nice-Cimiez) and putting together an appropriate experimental setup for testing our solutions. A direct consequence of setting up this research framework is a reduction in our publication and contract activities. But this may be considered as an investment as assistance robotics is a long term goal. It must be reminded that we are able to manage a large variety of problems in totally different domains only because interval analysis, game theory and symbolic tools provides us the methodological tools that allow us to address completely a given problem from the formulation and analysis up to the very final step of providing numerical solutions.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Science

- strong advances on the analysis of cable-driven parallel robots (section 7.1.1)
- collaboration with lawyers on the ethical and legal aspects of assistance robotics
- strong collaboration with the medical community on walking analysis, rehabilitation (section 7.2.1) and activities detection (section 7.3)

5.1.2. Experimentation

- completion of the first version of our immersive environment for rehabilitation (section 7.2.1)
- continuation of the daily activities monitoring in a day hospital (section 7.3)

5.1.3. Awards

J-P. Merlet has received the best paper award at the Eucomes conference .
BEST PAPERS AWARDS :
[15]
J.-P. MERLET.*Some properties of the Irvine cable model and their use for the kinematic analysis of cable-driven parallel robots*, in "EUCOMES", Aachen, Germany, 2018, https://hal.archives-ouvertes.fr/hal-01965230

6. New Software and Platforms

6.1. 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

6.2. PALGate

KEYWORDS: Health - Home care - Handicap

- Contact: David Daney

6.3. Platforms

6.3.1. 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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6.3.2. Hardware platforms

We describe here only the new platforms that have been developed or improved in 2018 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 or our experimental flat).

6.3.2.1. 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. For example we have developed an active treadmill whose slope change according to the user place in the virtual world while the lateral inclination may be changed in order to regulate the load between the left and right leg. Such a system may be used in rehabilitation to simulate a walk in the mountain while increasing on-demand the load on an injured leg (that is usually avoided by the user) for a shorter rehabilitation time. At the same time the walking pattern is analyzed by using lidar, kinect and distance sensor in order to assess the efficiency of the rehabilitation exercise.

The motion system is composed of two vertical columns whose height may be adjusted (they are used for actuating the treadmill), a 6 d.o.f motion base and a cable-driven parallel robot which may lift the user (in the walking experiment this robot may be used to support partly the user while he is walking allowing frail people to start the rehabilitation earlier). We intend to develop sailing and ski simulators as additional rehabilitation environment. Currently the columns and instrumented treadmill are effective and we have completed at the end of this year the coupling between the subject motion and the 2D visualization of a walk in a nice-looking environment, including basic sound (figure 1). Walking analysis is performed using a lidar, a kinect and a distance sensor at the head of the treadmill.

6.3.2.2. Activities detection platform

For non intrusive activities detection we use low cost distance and motion sensors that are incorporated in a 3D printed box and constitute a detection station. Several such station are implemented at appropriate place in the location that has to be monitored. Currently we have 15 such stations deployed at Valrose EHPAD since end of 2016 and 17 (which amount to 77 different sensors) deployed at Institut Claude Pompidou since the end of 2017.

7. New Results

7.1. Robotics

7.1.1. Analysis of Cable-driven parallel robots

Participants: Alain Coulbois, Artem Melnyk, 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 [19]. This is a non algebraic planar model with the upper attachment

Figure 1. Our rehabilitation station in a configuration with a treadmill, 2 columns for changing its slope and inclination and lidar and kinect for motion analysis

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 [15] (best paper award of the Eucomes conference) 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. For that purpose it is of interest to add sensors on the robot beside the measurement of cable lengths in order to improve the solving time by using additional constraints and possibly ending up with a single solution. But these measurements are uncertain although we may assume that the measurement errors are bounded. It is necessary to determine these error bounds for a practical use of these measurement and we have conducted an experimental investigation of various additional measurements [12]: a mechanical system for measuring the angle of the cable plane with respect to a reference axis, cable angulation with accelerometers glued on the cable, a “poor man lidar” on the platform for optically determining several cables angulation, accelerometers on the platform and cable tensions with strain gauges while the pose of the platform was estimated accurately by using a metrology arm and laser range-meters. This investigation has shown that:

- the friction in the mechanical system leads to large errors for the cable plane angle (up to 30 degrees). For later measure we have bypassed this system
- even for small and medium-sized CDPRs the sagging effect cannot be neglected for estimating cable angulation
- accelerometers on the cable and the lidar system have a good accuracy (between 1 and 5 degrees)
- cable tension measurement is very approximate even with high accuracy strain gauges and cannot be used for control purposes.

We have also continued to investigate calculation of planar cross-sections of the workspace for CDPR with sagging cables, i.e. when 4 of the 6 platform pose parameters are fixed leaving only 2 free parameters. Brand new algorithms have been developed, based on a continuation approach [12],[13]. The main idea is that almost everywhere the workspace border is a one-dimensional variety so that if one of the free parameters is fixed, then a pose on the border should satisfy a square equation system constituted of the kinematic equations and the constraints equations (e.g. that a cable length is equal to a given maximum limit). Pose on the border are obtained by choosing an arbitrary pose that has an inverse kinematic solution that satisfy the constraints in the workspace and then moves incrementally along one of the free axis using a certified Newton scheme for finding the inverse kinematics solution until the constraint equations are almost satisfied in which case the certified Newton scheme is used to determine exactly (i.e with an arbitrary accuracy) a pose that lies on the border. Then a continuation scheme is used to find new poses on the border until we reach a pose at which a new set of constraints is satisfied i.e. a starting point for a new border arc. The border is then composed of several polygonal arcs that approximate the real border. The scheme is devised so that we completely master the difference between the real workspace area and the region defined by the polygonal approximation of the border. If necessary we may reduce this difference by adding new vertices on the border polygon. An important point is that the constraints define border arcs but also singularity curves (i.e. pose at which the direct kinematics equations are singular) and a specific continuation scheme has been developed to determine those arcs. Indeed the cancellation of the determinant of the jacobian of the direct kinematic equations is part of the equations that are satisfied on this type of border arc but this determinant cannot be obtained in closed-form. Consequently we have devised a certified Newton scheme that just require to evaluate the determinant and its derivatives at a given pose. A consequence of the existences of such arcs is that the workspace may have several *aspects* i.e. workspace region that can be reached only for a given inverse kinematics solution and is unreachable for the other one(s).

7.1.2. 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 this year by artists interested in mimicking the 3D additive manufacturing process on a large scale with glass micro-beads for a live art performance to be held in 2019 (www.lestanneries.fr/exposition/monuments-larmes-prince). We have been working on the design of the robotics system, namely a cables parallel robots with autonomous refilling capabilities.

7.1.3. Robotized ultrasound probe

Participant: Jean-Pierre Merlet.

In collaboration with the EPIONE project we have started investigation the development of a portable robotized cardiac ultrasound probe that may be used while performing an effort test. A first step, somewhat surprising was the necessity to instrument an existing probe in order to determine what are the forces that the doctor exert on the probe during an investigation and the maximal angulation of the probe (apparently this data has not been measured beforehand). We add an accelerometer (for measuring the angle) and a force sensor in a 3D-printed covering of the probe and recorded the data during several experiments. We were then planing to develop a small, portable 3 d.o.f. rotational parallel robot whose range of motion was within the maximum angles that has been determined experimentally and was able to sustain the force exerted by the doctor. Unfortunately there was not a general consensus between the doctors and the company manufacturing the probe on the number of d.o.f. that was requested for the robot (which clearly have a drastic influence on the mechanical design and on the dimensional synthesis of the robot) so that the project is on stand-by.

7.1.4. Parallel robot performances and uncertainties

Participants: Jean-Pierre Merlet, Hiparco Lins Vieira [correspondant].

The purpose of this study, which is the PhD subject of H. Lins Vieira, is to develop interval analysis-based algorithm for determining if some performance requirements for parallel robots (e.g. on workspace, accuracy, load lifting ability) can be guaranteed in spite of the unavoidable manufacturing and control uncertainties of the system.

7.2. Assistance

We are still going on in building a framework for customizable and modular assistive robotics including hardware, software and communication and medical monitoring. The development of our platforms shows that we are now able to identify problematic issues for end-users, helpers and the medical community and to propose appropriate hardware/software solutions. But the most time consuming part of our work is related to evaluation and therefore experimentation: this involves legal/ethical issues (for which we have contributed [5]), participation of the medical community (for evaluation and recruitment) and heavy administrative management. Clearly we are lacking of permanent staff as we have long term objectives that cannot be fulfilled only with PhD or post-doc students. We need also engineers during specific periods (for hardware development and experimentation) but over a longer time than the one or two years currently proposed by Inria.

7.2.1. Rehabilitation in an immersive environment

Participants: Artem Melnyk, Jean-Pierre Merlet, Yves Papegay [correspondant], Ting Wang.

Rehabilitation is a tedious and painful process and it is difficult to assess its trend. Using an immersive environment has shown to increase the patient motivation but is not sufficient regarding rehabilitation efficiency. First the visual feedback (event 3D) is not sufficient to provide a full immersive feeling as body motion is not involved. Controlling body motion is also very important for therapists that currently must continuously correct the patient pose so that the rehabilitation exercise is the most efficient. We propose to add motion generators in the environment to reinforce realism (thereby increasing patient motivation) but also to allow therapists to use these generators to control the body pose so that they will be able to repeat rehabilitation exercises in a controlled context. Furthermore these generators are instrumented to provide information on the body pose and additional external sensors complete these measurements for rehabilitation assessment. We have developed 3 types of motions generators: one 6 d.o.f. motion base, a CDPR that is able to lift a patient and 2 multipurpose lifting columns.

When starting this project we were planning to use Inria-Sophia immersive room , hence allowing us to focus on the rehabilitation station. Unfortunately this room is no more available. This year we have developed a 2D renderer that has been connected to a flexible software platform allowing the various agents to exchange messages. We have been able to build a first version of our rehabilitation platform using a treadmill as exercise tool and columns to animate the treadmill (figure 1). For measuring the gait pattern we are using a planar lidar for detecting the leg motions, a kinect for detecting the motion of a skeleton and a distance sensor that measure the body motion with respect to the head of the treadmill. Figures 2 and 3 show an extract of the measurements obtained during a typical walk. It may be seen that the lidar data are very clean and allows one to estimate the mean position of the leg as a function of time (from which we will be able to deduce the number of steps, velocities of the leg, ...). Kinect data are much more noisy although that a fusion with the lidar data and the distance data will allows us to detect significant trunk motion. A typical walk of 3mn provides approximately 20 Mo of data.

Note that we are not using wearable sensors (although they are available: accelerometers for the arms and legs, shoes with pressure sensor and accelerometers): this is voluntary as our contacts with the medical community have indicated that many patients will not be comfortable with wearable sensors. In the same manner we have experimented having a headset instead of the screen but it appears that visualization is very disturbing and uncomfortable. Subject safety is ensured: during the exercise the subject must keep a push button pressed and

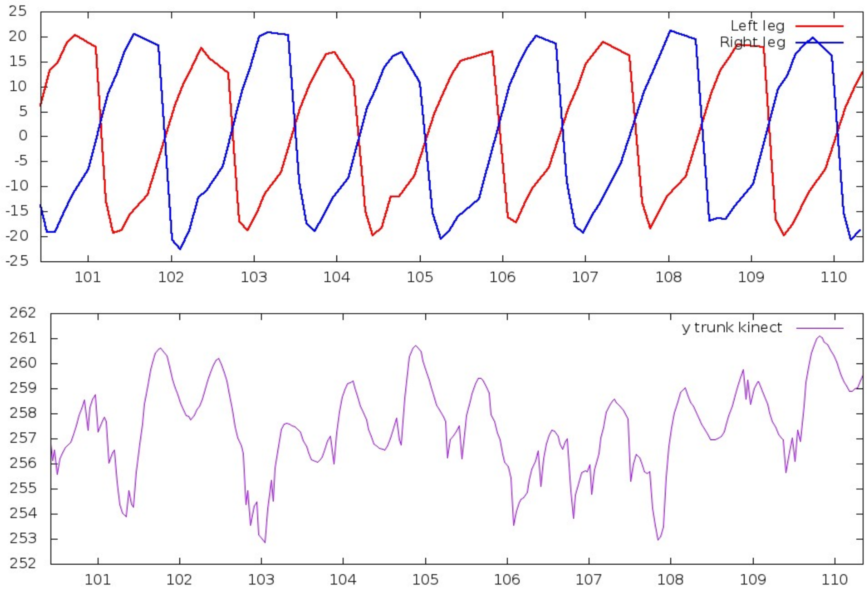

Figure 2. An extract of the legs motions in the walking direction as measured by the lidar and the trunk forward/backward motion estimated by the kinect

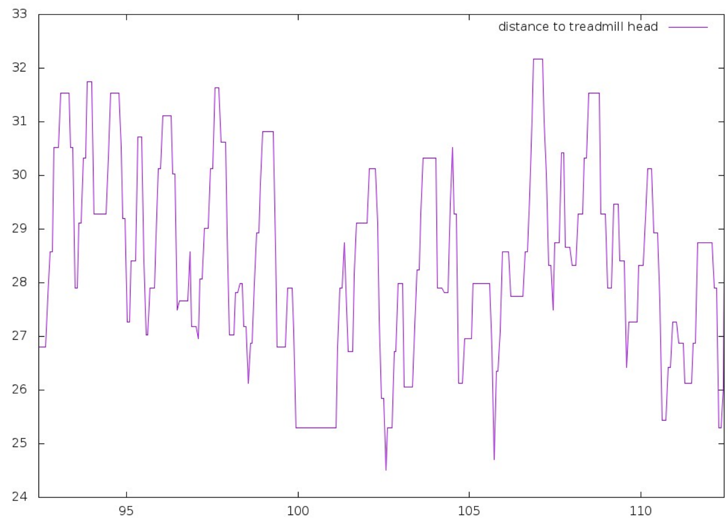

Figure 3. An extract of the trunk forward/backward motions as measured by the distance sensor in the head of the treadmill

when released the treadmill stop immediately. An emergency stop button is also available for the operator. Furthermore the system has been designed to provide various supports for avoiding fall and is surrounded by soft carpets.

The rehabilitation station for walking analysis on a treadmill in various walking condition is now almost fully functional and reliable. The next step will start of the beginning of 2019 with an experiment involving a cohort of voluntary subjects of Inria in order to obtain a significant amount of data. A statistical analysis of these data will then be performed in order to examine if synthetic and medically pertinent indicators (besides classical indicators such a number of steps, velocity, ...) may be obtained. The next step will involve repeating this experiment with pathological patients from Centre Héliomarin de Vallauris, most probably at the end of 2019. Meanwhile we will integrate our motion base as another element of the rehabilitation station with the purpose of equilibrium analysis, using a sea landscape as virtual environment with fans providing a realistic simulation of winds.

7.3. Smart Environment for Human Behaviour Recognition

Participants: Alain Coulbois, Aurélien Massein, 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 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.

This year we have focused our attention in several aspects : improvement of the hardware of the experimental monitoring system and tools for handling and analyzing the data gathered.

The PhD work about optimal location of sensors in a smart environments has been defended in november, defining new metrics on set of sensors and new methods [0].

7.3.1. Hardware

Two monitoring systems have been installed. The first one in the first floor of EHPAD Valrose in Nice, and a second one in Institut Claude Pompidou in Nice. Both systems are composed of multi sensors barriers that provide raw data from which we deduce the time and direction of its crossing by a person.

For the second experimental system the analysis of the first data have shown that the system was not reliable enough while the data themselves were not satisfactory because of the specificity of the building (large corridors, large waiting room, picture windows and the number of sensors installed (77). We have worked on the hardware of the system (redundant power supply, better orientation of barriers, better communication system) to improve the gathered data.

[0] Design of Instrumented Environment for Human Monitoring, defended on 12/26/2018

7.3.2. Tools for handling data and data analysis

We have developed a simulation program, written in C and using the GTK library, that generates barrier-events (i.e. crossing time, direction of crossing, speed of crossing). This program is based on Monte Carlo procedures simulating the displacement of both elderly and caregivers in the EHPAD environment equipped with movement detectors. The code can simulate up to 20 persons and randomly draws room-to-room movements according to the walking speed of each individual (caregivers walk at a faster pace than elderly), and counts the locations and time coordinates of each movement event identified by the detectors. The figure 4 gives a view of the graphic interface. Such a simulation program, and the results produced, will provide basic training data to reconstruct patient movements from the information collected by the activity detectors.

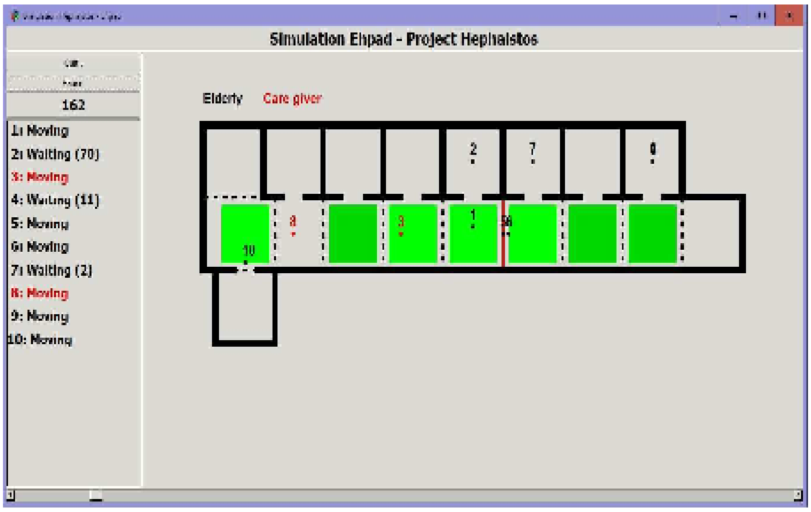

Figure 4. Simulation tool for event detection analysis

Another scientific activities were based on the development of diagnostic tools (also written in C) to visualize (and thus to check and to interpret) events identified by each detector in such equipped environment. Finally, another activity – that is still under development – is to analyze statistically gait data obtained through the event detection. In this case, the goal is to build a series of relevant statistical descriptive parameters that will be used to describe, identify and compare gait features and pathology in medically assisted environments. This last part is developed used the R software.

In the two installed system data are collected continuously during the all day and a large number of barrier crossing is observed. We are currently comparing raw and simulated data before moving on with a statistical analysis.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. 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.

9. Partnerships and Cooperations

9.1. Regional Initiatives

- the HEPHAISTOS and CHORALE teams together with I3S have organized the 2-days workshop *Robopaca* supported by Inria and UCA. The purpose was to organize a meeting between academics, industry and end-users to examine together the possibility of structuring the robotic activities in PACA

9.2. 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

9.2.1. FHU

- the team has been involved for the FHU *INOVPAIN : Innovative Solutions in Refractory Chronic Pain* that has been labeled in December 2016

9.3. International Initiatives

9.3.1. Inria International Partners

9.3.1.1. 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: 2 joint PhD student, publications
- University Innsbruck: joint conference organization
- Fraunhofer IPA, Stuttgart: joint conference organization
- Duisburg-Essen University: joint conference organization
- University of New-Brunswick: 1 joint PhD student
- University Laval, Québec: joint book
- University of Tokyo: joint conference organization
- Tianjin University, China: joint book

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation, Steering committees

- 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,
- Y. Papegay is a permanent member of the International Steering Committee of the International Mathematica Symposium conferences series.

10.1.2. Reviewing

- The members of the team reviewed numerous papers for numerous international conferences and journals

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- J-P. Merlet is board member of the Journal of Behavorial Robotics
- E. Wajnberg is Editor-in-Chief of the journal BioControl, a board member of the journals Entomologia Experimentalis et Applicata, Neotropical Entomology, Applied Entomology and Zoology and Journal of Economical Entomology

10.1.4. Invited Talks

- J-P. Merlet has given a talk on parallel robots at the workshop "Rigidity theory for multi-agent systems meet parallel robototics", Nantes, a talk on interval analysis at SCAN, Tokyo and a talk on bibliometric indicators at the SIF workshop
- E. Wajnberg has been invited for talks by the University of Palermo (Italy, February), the University of Haifa (Israel, March), the conference "l'Ere du Temps" (Nice, June), the European Congress of Entomology, Naples (Italy, July), and the University dell'Insubria (Varese, Italy, November).

10.1.5. 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. J-P. Merlet is an IEEE Fellow, doctor honoris causa of Innsbruck University and IFToMM Awards of Merits
- Y. Papegay is a member of the OpenMath Society, building an extensible standard for representing the semantics of mathematical objects.

10.1.6. 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).

10.1.7. Research Administration

- J-P. Merlet is an elected member of the Academic Council of UCA COMUE, 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 CUMIR (the committee managing the interaction between researchers and the computer support staff)
- O. Pourtallier is a board member of SeaTech, an Engineering School of University of Toulon. She is responsible of the NICE committee (long term invited scientists and post-doctoral student selection) and a member of the CGL AGOS

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

In February, Y. Papegay has been visiting lecturer of University of French Polynesia, where he gave an object oriented programming course.

O. Pourtallier lectured 6 hours on game theory to Master OSE (M2), at École des Mines de Paris, Sophia Antipolis, France

E. Wajnberg has taught one week course (about 30 h) about the use of the R program and statistics for PhD students and senior scientists in Rehovot (Israel, March), and another week with the same teaching program in Piracicaba (Brazil, July).

10.2.2. Supervision

PhD : A. Massein, Design of Instrumented Environment for Human Monitoring, defended in november 2018, supervisor: Y.Papegay.

PhD in progress: W. Plouvier. Improving pest control efficiency: a modelling approach (2015-2019). Supervisor: E. Wajnberg.

10.2.3. Juries

- J-P. Merlet has been a member of four PhD juries. He was also president of the jury for the Best PhD thesis award of the robotics GDR. He is a member of the “Comité de Suivi Doctoraux” (preliminary evaluation committee of PhD students) of Dayan Hassan (project team Chorale) and of Matheuse Laranjeira (Toulon University).
- E. Wajnberg has been a member of one PhD jury.

10.3. Popularization

10.3.1. Articles and contents

- J-P. Merlet has given two interviews at Nice-Matin and is a member of the scientific committee for the preparation of a permanent robotics exhibition at Cité des Sciences et de l’Industrie, Paris

10.3.2. Education

- Y.Papegay is actively participating to the Math.en.Jeans initiative for Mathematics teaching for undergraduate students. He is developing several pedagogical resources based on small robotics devices at high-school level. He has 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.

10.3.3. Interventions

- J-P. Merlet and Y. Papegay have meet several schoolchildren (3ème)
- J-P. Merlet has given a talk during the Art'DI (a meeting between handicapped people and artists) day at Cannes
- J-P. Merlet and E. Wajnberg have given two talks in the framework of “Science pour tous”

10.3.4. Internal action

- J-P. Merlet has given a talk at Café Techno and at Café ADSTIC (for local PhD students), has invited Nathalie Rochet, a member of south-east CPP to give a talk at a Café-In

10.3.5. Creation of media or tools for science outreach

- the Hephaistos team proposes simple cable-driven parallel robots that are used to illustrate scientific concepts such as showing what is a sinus, instantiating the geometrical definition of an ellipse

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[13] J.-P. MERLET.*Computing cross-sections of the workspace of a cable-driven parallel robot with 6 sagging cables having limited lengths*, in "ARK", Bologna, Italy, 2018, https://hal.archives-ouvertes.fr/hal-01965231

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Project-Team INDES

Secure Diffuse Programming

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Distributed programming and Software engineering

Table of contents

Project-Team INDES

Creation of the Team: 2009 January 01, updated into Project-Team: 2010 July 01

Keywords:

Computer Science and Digital Science:

A1.3. - Distributed Systems
A2. - Software
A2.1. - Programming Languages
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
A2.1.12. - Dynamic languages
A2.2.1. - Static analysis
A2.2.5. - Run-time systems
A2.2.9. - Security by compilation
A4. - Security and privacy
A4.3.3. - Cryptographic protocols
A4.6. - Authentication
A4.7. - Access control
A4.8. - Privacy-enhancing technologies

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]

External Collaborators

Marc Feeley [University of Montréal, Aug 2018]
Gérard Berry [Collège de France, HDR]

PhD Students

Imane Fouad [Inria]
Jayanth Krishnamurthy [Inria, from Sep 2018]
Heloise Maurel [Inria, from Oct 2018]
Bertrand Petit [Inria]
Doliere Some [Inria, until Oct 2018]

Colin Vidal [Inria, until Jun 2018]

Post-Doctoral Fellows

Yoon Seok Ko [Inria, from Oct 2018]

Nguyen Nhat Minh Ngo [Inria]

Doliere Some [Inria, from Nov 2018]

Visiting Scientists

Mauricio Cano [University of Groningen, from Feb 19, 2018 until Apr 21, 2018]

Paola Giannini [University of Piemonte Orientale, from Feb 19, 2018 until Mar 3, 2018]

Administrative Assistant

Nathalie Bellesso [Inria]

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 and functional 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.

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. New Software and Platforms

4.1. 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/

4.2. 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

4.3. 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/

4.4. iflowsigs.js

KEYWORDS: Compilers - Monitoring
FUNCTIONAL DESCRIPTION: iflowsigs.js is a JavaScript library designed to inline an information flow monitor into JavaScript code. iflowsigs.js support is able to track information flow even in programs that interact with arbitrary Web APIs.

- Participants: José Fragoso Santos and Tamara Rezk
- Contact: Tamara Rezk
- URL: http://j3fsantos.github.io/PersonalPage/IFMonitor/

4.5. iflowTYPES.js

FUNCTIONAL DESCRIPTION: iflowtypes.js is a JavaScript library designed to type secure information flow in JavaScript. iflowtypes.js has two main modes of operation: fully static and hybrid. In the hybrid mode, the program to be typed is instrumented with runtime assertions that are verified at runtime. By deferring rejection to runtime, the hybrid type system is able to type more programs than fully static mechanisms.

- Contact: Tamara Rezk
- URL: http://j3fsantos.github.io/PersonalPage/TypeSystem/

4.6. Mashic

KEYWORD: Security
FUNCTIONAL DESCRIPTION: The Mashic compiler is applied to mashups with untrusted scripts. The compiler generates mashups with sandboxed scripts, secured by the same origin policy of the browsers. The compiler is written in Bigloo.

- Contact: Tamara Rezk
- URL: http://web.ist.utl.pt/~ana.matos/Mashic/mashic.html

4.7. 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

4.8. 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: Doliere Some
- URL: http://www-sop.inria.fr/members/Doliere.Some/essos/

4.9. BELL

Browser fingerprinting via Extensions and Login-Leaks
KEYWORDS: Browser Extensions - Security and Privacy in Web Services - Social Networks Security and Privacy
FUNCTIONAL DESCRIPTION: Recent studies show that users can be tracked based on their web browser properties. This software is designed to conduct an experiment on such kinds of user tracking. In this experiment, we demonstrate that a Web user can also be tracked by

- her browser extensions (such as AdBlock, Pinterest, or Ghostery), and

- the websites she has logged in (such as Facebook, Gmail, or Twitter).

In the experiment, we collect user's browser fingerprint, together with the browser extensions installed and a list of websites she has logged in. We only collect anonymous data during the experiment (more details in our Privacy Policy [0]), we will securely store the data on an Inria server, use it only for research purposes and not share it with anyone outside of Inria.

- Contact: Gabor Gulyas
- URL: https://extensions.inrialpes.fr/

4.10. webstats

Webstats
KEYWORDS: Web Usage Mining - Statistic analysis - Security

[0] https://extensions.inrialpes.fr/privacy.php

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: Doliere Some
- URL: https://webstats.inria.fr

4.11. Platforms

4.11.1. Skini

Skini is a distributed system for composing and producing live performances with audience participation using HTML5 devices. Skini is developed in Hop and HipHop. It proposes a framework for composing music based on patterns and dynamic control of the orchestration for either synthesizers or musicians.

The system has two basic concepts, "Pattern" and "Orchestration" which can be modulated as much as the composer wants in terms of complexity, duration, etc. The platform is meant for interaction with the audience during the show. Each participant can interact with the platform as well as with other participants. According to our experience during the Golem show in MANCA 2017, we implemented five levels of interaction, which allowed theoretically 120 possible combinations.

5. New Results

5.1. Information Flow Security

We have pursued our study on information flow security policies and enforcements. We have followed two main axes.

Impossibility of Precise and Sound Termination Sensitive Security Enforcements An information flow policy is termination sensitive if it imposes that the termination behavior of programs is not influenced by confidential input. Termination sensitivity can be statically or dynamically enforced. On one hand, existing static enforcement mechanisms for termination sensitive policies are typically quite conservative and impose strong constraints on programs like absence of while loops whose guard depends on confidential information. On the other hand, dynamic mechanisms can enforce termination sensitive policies in a less conservative way. Secure Multi-Execution (SME) , one of such mechanisms, was even claimed to be sound and precise in the sense that the enforcement mechanism will not modify the observable behavior of programs that comply with the termination sensitive policy. However, termination sensitivity is a subtle policy, that has been formalized in different ways. A key aspect is whether the policy talks about actual termination, or observable termination.

We have proved that termination sensitive policies that talk about actual termination are not enforceable in a sound and precise way. For static enforcements, the result follows directly from a reduction of the decidability of the problem to the halting problem. However, for dynamic mechanisms the insight is more involved and requires a diagonalization argument.

In particular, our result contradicts the claim made about SME. We correct these claims by showing that SME enforces a subtly different policy that we call indirect termination sensitive noninterference and that talks about observable termination instead of actual termination. We construct a variant of SME that is sound and precise for indirect termination sensitive noninterference. Finally, we also show that static methods can be adapted to enforce indirect termination sensitive information flow policies (but obviously not precisely) by constructing a sound type system for an indirect termination sensitive policy.

This study is described in [16].

A Better Facet of Dynamic Information Flow Control

Multiple Facets (MF) is a dynamic enforcement mechanism which has proved to be a good fit for implementing information flow security for JavaScript. It relies on multi executing the program, once per each security level or view, to achieve soundness. By looking inside programs, MF encodes the views to reduce the number of needed multi-executions.

In this year, we have published a paper [15], where we have extended Multiple Facets in three directions. First, we propose a new version of MF for arbitrary lattices, called Generalised Multiple Facets, or GMF. GMF strictly generalizes MF, which was originally proposed for a specific lattice of principals. Second, we propose a new optimization on top of GMF that further reduces the number of executions. Third, we strengthen the security guarantees provided by Multiple Facets by proposing a termination sensitive version that eliminates covert channels due to termination.

5.2. JavaScript Implementation

We have pursued the development of Hop.js and our study on efficient JavaScript implementation. We have followed three main axes.

Implementing Hop.js

Hop.js supports full ECMAScript 5 but it still lack many of the new features ECMAScript 2016 has introduced and now that are now well established in ECMAScript 2017. During the year, we have implemented many of these features (iterators, destructuring assignments, modules, etc.). Few constructs remain missing and hopefully will be added to the system by the end of the year (map, set, and proxies). Completing full ECMAScript 2017 is important as we now see more and more packages using these new features being made available and we consider that maintaining the ability to use all these publicly available resources is a prerequisite to a wide Hop.js adoption. We also consider that this is an important asset for Hop.js users, in particular, for the Denimbo company, an Inria startup using Hop.js extensively.

Ahead-of-time JavaScript compilation

Hop.js differs from most JavaScript implementations by many aspects because contrary to all fast and popular JavaScript engines that use just-in-time compilation, Hop.js relies on static compilation, *a.k.a.,* ahead-of-time (AOT) compilation. It is an alternative approach that can combine good speed and lightweight memory footprint, and that can accommodate read-only memory constraints that are imposed by some devices and some operating systems. Unfortunately the highly dynamic nature of JavaScript makes it hard to compile statically and all existing AOT compilers have either gave up on good performance or full language support.

Indeed, JavaScript is hard to compile, much harder than languages like C, Java, and even harder than Scheme and ML two other close functional languages. This is because a JavaScript source code accepts many more possible interpretations than other languages do. It forces JavaScript compilers to adopt a defensive position by generating target codes that can cope with all the possible, even unlikely, interpretations because general compilers can assume very little about JavaScript programs. The situation is worsened further by the *raise as little errors as possible* principle that drives the design of the language. JavaScript functions are not required to be called with the declared number of arguments, fetching an unbound property is permitted, assigning undeclared variables is possible, etc.

All these difficulties are considered serious enough to prevent classic static compilers to deliver efficient code for a language as dynamic and as flexible as JavaScript. We do not share this point of view. We think that by carefully combining classical analyses, by developing new ones when needed, and by crafting a compiler where the results of the high-level analyses are propagated up to the code generation, it is possible for AOT compilation to be in the same range of performance as fast JIT compilers. This is what we attempt to demonstrate with this study. Of course, our ambition is not to produce a compiler strictly as fast as the fastest industrial JavaScript implementations. This would require much more engineering strength than what we can afford. Instead, we only aim at showing that static compilation can have performances reasonably close to those of fastest JavaScript implementations. *Reasonably close* is of course a subjective notion, that everyone is free to set for himself. For us, it means a compiler showing half the performances of the fastest implementations.

The version of the Hop.js AOT compiler we have developed during the year contains new typing analyses and heuristics that compensate for the lack of information JavaScript source codes contain. A first analysis, named *occurrence typing*, that elaborates on top of older techniques developed for the compilation of the Scheme programming language, extracts as much as possible syntactic information directly out of the source code. This analysis alone would give only rough approximations of the types used by the program but its main purpose is to feed the compiler with sufficient information so that it can deploys more efficient supplemental analyses. Probably the most original one is the analysis that we have named *hint typing* or *which typing* that consists in assigning types to variables and to function arguments according to the efficiency of the generated code. In other words, the *which typing* assign types for which the compiler will be able to deliver its best code instead of assigning types that might denote all the possible values variables and arguments may have during all possible executions. We have shown that these *whiched* types correspond very frequently to the implicit *intentional* types programmers had in mind when they wrote their programs. These analyses and the optimizations they enable are implemented in Hop.js version 3.2.0 available on the Inria pages and from Github. They are described in [17] paper.

Property caches: Property caches are a well-known technique invented over 30 years ago to improve dynamic object accesses. They have been adapted to JavaScript, which they have greatly contributed to accelerate. However, this technique is applicable only when some constraints are satisfied by the objects, the properties, and the property access sites. We have started a study to try to improve it on two common usage patterns: *prototype accesses* and *megamorphic accesses*. We have built a prototypical implementation in Hop.js that has let us measure the impact of the technique we propose. We have observed that they effectively complement traditional caches and that they reduce cache misses and consequently accelerate execution. Moreover, they do not cause a slowdown in the handling of the other usage patterns. We are now at completing this study by polishing the implementation and by publishing a paper exposing and evaluating the new techniques.

5.3. Web Reactive Programming

During the year, we have continued our effort in designing and implementing the HipHop.js programming language, we have applied it to interactive music composition, and we have studied security of reactive systems.

HipHop.js

Web applications react to many sort of events. Let them be GUI events, multimedia events, or network events on client code or IO and system events on the server, they are all triggered asynchronously. JavaScript, the hegemonic programming language of the Web, handles them using low level constructs based on *listeners*, a synonym for *callback*. To improve on the so-called *callback hell*, the recent versions of the language have proposed new constructs that raise the programming abstraction level (promises and `async/await`). They enable a programming style, closer to traditional sequential programming, which helps developing and maintaining applications. However, the improvements they propose rely exclusively on syntactic extensions. They do not change the programming model. For that reason, complex orchestration problems that imply all sorts of synchronization, preemption, and parallelism remain as complex to program as before. We think that orchestration should be reconsidered more globally and from the ground. The solution we propose consists in embedding a DSL specialized on orchestration inside the traditional Web development environment, in our case, Hop.js, the Web programming language that the team develop.

The orchestration DSL we propose is called HipHop.js. It is a reactive synchronous language. More precisely, it is an adaptation of the Esterel programming language to the Web. The motivations for choosing Esterel are diverse. First, and most important, Esterel is powerful enough to handle all the orchestration patterns we are considering. Second, the team, via its partnership with Colège de France, has high expertise in the design and development of Esterel-like languages, which constitutes a highly valuable asset for our development.

Esterel is powerful enough to handle all the orchestration patterns we are considering but Esterel has been designed and developed in a context baring no resemblance with the Web. Esterel was considering static execution models while the Web assumes permanent evolutions and modifications of the running programs. Esterel was considering sequential imperative languages for its embedding, while the Web is considering dynamic functional languages (i.e., JavaScript). Esterel was assuming static execution contexts where *a-priori* validity proof were enforced before hand while the Web assumes highly dynamic runtime executions so that only dynamic verifications are doable. For all these reasons, adapting Esterel and transforming it to form HipHop.js has needed a deep revamping and a deep paradigm shift.

During the year of 2018, we have finalized and completed the design of the language that is now almost stabilized. It follows previous version developed in C. Vidal's PhD studies [13], [18]. The version 0.3.x has been made available at the URL http://hop-dev.inria.fr. It has been used to implement our first orchestration demanding applications, in particular, an interactive music composition application. Our next steps will consist in completing the design and implementation of the language and a minimal development environment without which only experts can use the system. We of course also need to publicize the system and describe its design and internal in various academic publications.

Interactive music composition: the Skini platform

In the sixties, the philosopher Umberto Eco, and musicians such as K. Stockausen, K. Penderescki, L. Berio questioned about the relationship between composers, musicians, and the way we perceive music. Eco used the wording "Open Work", and showed that, the vision of the world evolved from a static world to a more blurred perception. According to this new perception and in a shift comparable to the evolution of physics from Copernic to Einstein, some contemporary artists tried to express this complexity through works where the performer and the audience have a concrete impact on the work. Since the sixties, the development of audience participation for collaborative music production has become a more and more active field. Thanks to the large device market and web based technology development such as web audio API, "Open Work" got a broader meaning with systems allowing individual interaction. Nevertheless it is still difficult to find systems proposing frameworks dedicated to music composition of interactive performances with a clear composition scheme and ease of use. This is our motivation for developing a framework, called Skini, designed for composing, simulating, and executing interactive performances. Skini is based on elementary music patterns, automatic control of the patterns activation made possible thanks to Hop and Hiphop. Skini was first used for a concert that took place at the very end of 2017 in the contemporary Musical Festival of Nice (MANCA) followed in 2018 by performances during the "Portes ouvertes" of Inria, the "Fête de la Science" and the Synchron conference.

In 2018: The Skini's user interface has been revamped. We have tried several interfaces for the pattern activation and focused on a simple one in order to make the interface more intuitive and fluid. We have added an important feature called the "distributed sequencer", which allows the audience not only to activate patterns but also to create them. We have added a new level of interaction, the scrutator, which allows global actions by the audience on the orchestration. The complete system is now synchronized with an external Midi clock. We have developed a first version of stand alone Midi control of the pattern. The system has followed the evolution of the Hiphop syntax and now implements the last version for the control of orchestration. We improved the synchronisation system and the processes for implementing the orchestration.

5.4. Session Types

Session types describe communication protocols between two or more participants by specifying the sequence of exchanged messages, together with 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 now been embedded into a range of functional, concurrent, and object-oriented programming languages.

We have pursued our work on session types along three main directions.

Multiparty Reactive Sessions

Ensuring that communication-centric systems interact according to an intended protocol is an important but difficult 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 reactive systems. *Session-based concurrency* is the model of concurrent computation induced by session types, a rich typing discipline designed to specify the structure of interactions.

In this work, we propose a process calculus for multiparty sessions enriched with features from SRP. In this calculus, protocol participants may broadcast messages, suspend themselves while waiting for a message, and also react to events.

Our main contribution is a session type system for this calculus, which enforces session correctness in terms of communication safety and protocol fidelity, and also ensures a time-related property, which we call input timeliness, which entails livelock-freedom. Our type system departs significantly from existing ones, specifically as it captures the notion of "logical instant" typical of SRP. This work is currently under submission.

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 has the ability to 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 CCS, then for the π-calculus, and only recently for session calculi.

Following up on our previous work on concurrent reversible sessions [29], 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 the choice. This operator is inspired by the notion of *connecting action* recently introduced by Hu and Yoshida to describe protocols with optional participants. We argue that this choice operator allows for a natural description of typical communication protocols. Our calculus also 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. We present a session type system for the calculus and show that it enforces the expected properties of session fidelity, forward progress and backward progress. This work has been accepted for journal publication.

Multiparty sessions with Internal Delegation

We have investigated a new form of delegation for multiparty session calculi. Usually, delegation 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 sessions. As a consequence, properties such as deadlock-freedom or lock-freedom are difficult to ensure in the presence of delegation. Here 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 (internal delegation) and may be captured by its global type. To increase flexibility in the use of delegation, our calculus uses connecting communications, which allow optional participants in the branches of choices. By these means, we are 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 is under submission.

5.5. Measurement and Detection of Web Tracking

Detecting Web Trackers via Analyzing 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 [23] and EasyPrivacy [24] (EL&EP) are the most popular publicly maintained blacklist of know advertising and tracking domains, used by the popular browser extensions AdBlock Plus [20] and uBlockOrigin [28]. Disconnect [22] is another very popular list for detecting domains known for tracking, used in Disconnect browser extension [21] and in integrated tracking protection of Firefox browser [25]. 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.

In this work, to detect trackers, we propose a new technique based on the analysis of invisible pixels [0]. These images are routinely used by trackers in order 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 HTML tag into a webpage. Since invisible pixels do not provide any useful functionality, we consider them *perfect suspects for tracking*.

By using an Inria cluster and setting up a distributed crawler, we have collected a dataset of invisible pixels from 829,349 webpages. By analyzing this dataset, we observed that invisible pixels are widely used: more than 83% of pages incorporate at least one invisible pixel.

Overall, we made the following key contributions:

- We define a new classification of Web tracking behaviors based on the analysis of invisible pixels. By analyzing behavior associated to the delivery of invisible pixels, we propose a new fine-grained classification of tracking behaviors, that consists of 8 categories of tracking. To our knowledge, *we are the first to analyse tracking behavior based on invisible pixels that are present on 83% of the webpages*.
- We apply our classification to a full dataset and uncover new collaborations between third-party domains. We detect new relationships between third-party domains beyond basic cookie syncing detected in the past. In particular, we discovered that *first to third party cookie syncing* is the most prevalent tracking behavior performed by 50,812 distinct domains. Finally, we find that 76.23% of requests responsible for tracking originate from loading other resources than invisible images. To our knowledge, *we are the first to discover a highly prevalent first to third party syncing behavior detected on 51.54% of all crawled domains*.
- We show that the consumer protection lists cannot be considered as ground truth to identify trackers. We find out that the browser extensions based on EasyList and EasyPrivacy (EL&EP) and Disconnect each miss 22% of tracking requests we detect. Moreover, if we combine all the lists, 238,439 requests originated from 7,773 domains are unknown to these lists and hence still track users on 5,098 webpages even if tracking protection is installed. We also detect instances of cookie syncing in domains unknown to these lists and therefore likely unrelated to advertising. To our knowledge, *we are the first to detect that EL&EP and also Disconnect lists used in majority of Web Tracking detection literature are actually missing tracking requests to 7,773 distinct domains.*

This working paper [19] is currently under submission at an international conference.

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] By "invisible pixels" we mean 1x1 pixel images or images without content.

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.

Measuring Uniqueness of Browser Extensions and Web Logins

Web browser is the tool people use to navigate through the Web, and privacy research community has studied various forms of *browser fingerprinting*. Researchers have shown that a user's browser has a number of inherent "physical" characteristics that can be used to uniquely identify her browser and hence to track it across the Web. Fingerprinting of users' devices is similar to physical biometric traits of people, where only physical characteristics are studied.

Similar to previous demonstrations of user uniqueness based on their behavior, *behavioral characteristics*, such as browser settings and the way people use their browsers can also help to uniquely identify Web users. For example, a user installs web browser extensions she prefers, such as AdBlock, LastPass, or Ghostery to enrich her Web experience. Also, while browsing the Web, she logs in her preferred social networks, such as Gmail, Facebook or LinkedIn. In this work, we study *users' uniqueness* based on their behavior and preferences on the Web: we analyze how unique are Web users based on their *browser extensions and logins*.

In this work, we performed the first large-scale study of user uniqueness based on browser extensions and Web logins, collected from more than 16,000 users who visited our website https://extensions.inrialpes.fr/. Our experimental website identifies installed Google Chrome extensions via Web Accessible Resources. and detects websites where the user is logged in by methods that rely on URL redirection and CSP violation reports. Our website is able to detect the presence of 13K Chrome extensions (the number of detected extensions varied monthly between $12,164$ and $13,931$), covering approximately 28% of all free Chrome extensions [0] . We also detect whether the user is connected to one or more of 60 different websites. Our main contributions are:

- A large scale study on *how unique users are based on their browser extensions and website logins*. We discovered that 54.86% of users that have installed at least one detectable extension are unique; 19.53% of users are unique among those who have logged into one or more detectable websites; and 89.23% are unique among users with at least one extension and one login. Moreover, we discover that 22.98% of users could be uniquely identified by web logins, even if they disable JavaScript.

[0] The list of detected extensions and websites are available on our website: https://extensions.inrialpes.fr/faq.php

- We study the privacy dilemma on Adblock and privacy extensions, that is, *how well these extensions protect their users against trackers and how they also contribute to uniqueness*. We evaluate the statement "the more privacy extensions you install, the more unique you are" by analyzing how users' uniqueness increases with the number of privacy extensions she installs; and by evaluating the tradeoff between the privacy gain of the blocking extensions such as Ghostery [26] and Privacy Badger [27].

We furthermore show that browser extensions and web logins can be exploited to fingerprint and track users by only checking a limited number of extensions and web logins. We have applied an advanced fingerprinting algorithm [30] that carefully selects a limited number of extensions and logins. For example, we show that 54.86% of users are unique based on all 16,743 detectable extensions. However, by testing 485 carefully chosen extensions we can identify more than 53.96% of users. Besides, detecting 485 extensions takes only 625ms.

Finally, we give suggestions to the end users as well as website owners and browser vendors on how to protect the users from the fingerprinting based on extensions and logins.

This paper has been published at at WPES international workshop affiliated with ACM CCS 2018 [14].

6. Bilateral Contracts and Grants with Industry

6.1. 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. 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. Yoonseok Ko was hired to work on this project as a postdoc.

7. Partnerships and Cooperations

7.1. Inria internal funding

7.1.1. 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.

Tamara Rezk coordinates this project.

7.1.2. 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 from INDES team is part of this project.

7.2. National Initiatives

7.2.1. ANR AJACS

The AJACS project (Analyses of JavaScript Applications: Certification & Security) is funded by the ANR for 42 months, starting December 2014. The goal of the AJACS project is to provide strong security and privacy guarantees on the client side for web application scripts. The Indes members Tamara Rezk and Nataliia Bielova are involved in the tasks WP2 Certified Analyses and WP3 Security of JavaScript Applications. The partners of this project include Inria teams Celtique (coordinator), Toccata, and Prosecco.

7.2.2. 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.

7.2.3. ANR PrivaWeb

The PrivaWeb project (Privacy Protection and ePrivacy Compliance for Web Users) is funded by the ANR JCJC program for 42 months, starting 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.

7.2.4. FUI UCF

The 3 years long UCF project aims at developing a reactive Web platforms for delivering multimedia contents. The partners of the project are the startups Alterway, OCamlPro, and XWiki, and the academic research laboratories of University Pierre et Marie Curie, and Denis Diderot. Manuel Serrano participates in this project.

7.3. European Initiatives

7.3.1. Collaborations in European Programs, Except FP7 & H2020

7.3.1.1. 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 is the first European network of excellence aimed at coordinating research on reversible computation.

7.3.1.2. *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 is 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 project started in June 2016 and is due to end in June 2019. The objective of the project is to study formal models for reliable distributed communication-centric software systems. The project focusses on analysis and validation techniques based on behavioural types, aimed at enforcing various properties (safety, liveness, security) of structured communications.

7.4. International Initiatives

7.4.1. Inria International Partners

7.4.1.1. *Informal International Partners*

- We are initiating a new collaboration with Prof. Robby Findler and his group from Northwestern University of Chicago. We are studying reactive synchronous programming languages and their applications.
- 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. 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 initiating a new collaboration 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. Alejandro Russo from Chalmers University of Technology and Prof. Cormac Flanagan from University of California Santa Cruz, that resulted in a joint publication at WWW conference [15].
- We have been collaborating with Prof. Benoit Baudry from KTH Royal Institute of Technology, Sweden on the survey of browser fingerprinting technologies.

7.4.2. Participation in Other International Programs

7.4.2.1. *International Initiatives*

DAJA

Title: Detection strategies based on Software Metrics for Multitier JavaScript

International Partners (Institution - Laboratory - Researcher):

Universidad de Chile (Chile), DDC Alexandre Bergel

Universidad Nacional del Centro de la Provincia de Buenos Aires (Argentina) - ISISTAN Research Insitute - 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.

7.5. International Research Visitors

7.5.1. Visits of International Scientists

- We are collaborating with Prof. Marc Feeley from University of Montréal. For the second consecutive year, M. Feeley has visited us for studying implementation of dynamic languages.
- As part of our ongoing collaboration on session types, Prof. Paola Giannini from the University of Piemonte Orientale visited our team for two weeks, funded by the COST Action on Reversibility.
- Our team, together with Cinzia Di Giusto's team at I3S, hosted Mauricio Cano, a PhD student from the University of Groningen, for a 2-month visit. This was part of our collaboration with the University of Groningen within the project PICS SuCCeSS. The visit was funded for the most part by Academy 1 of Université Côte d'Azur.

7.5.1.1. Internships

- Tamara Rezk supervised the intern Sadry Fievet for 6 months
- Tamara Rezk supervised - as "tuteur" - the internship of El Mehdi Regragui for 6 months
- Bertrand Petit and Manuel Serrano supervised the internship of Thibaud Ardoin who studied and implemented the Skini distributed sequencer.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. General Chair, Scientific Chair

- Nataliia Bielova was the co-chair (together with Claude Castelluccia) of the Francophone workshop on Privacy Protection " l'Atelier sur la Protection de la Vie Privée" (APVP), which took place in Porquerolles (France) from 3 to 6 June 2018. https://project.inria.fr/apvp2018/
- Manuel Serrano was the general chair of the Programming'18 conference that took place in Nice in April 2018, https://2018.programmingconference.org/.
- Tamara Rezk was co-chair and co-organizer (together with Sébastien Bardin and Stéphanie Delaune) of the yearly event of the Working Group "Méthodes formelles pour la sécurité" (GT-MFS) in the context of the Pré-GDR Sécurité meeting in Paris (May 30, 2018).
- Ilaria Castellani was the co-chair (together with Mohammad Reza Mousavi) of the workshop TRENDS 2018, which took place in Beijing on September 8, in association with the CONCUR 2018 conference. https://concurrency-theory.org/events/workshops/trends

8.1.1.2. Member of the Organizing Committees

- Tamara Rezk was the local chair of the Programming'18 conference that took place in Nice in April 2018 https://2018.programmingconference.org/.

8.1.2. Scientific Events Selection

8.1.2.1. Chair of Conference Program Committees

- Nataliia Bielova was the PC co-chair (together with Claude Castelluccia) of the Francophone workshop on Privacy Protection " l'Atelier sur la Protection de la Vie Privée" (APVP), which tool place in Porquerolles (France) from 3 to 6 June 2018. https://project.inria.fr/apvp2018/
- Manuel Serrano was the co-chair together with Sukyong Ryu from Kaist University of the WWW'18 alternate Programming Track, https://www2018.thewebconf.org/call-for-papers/web-programming-cfp/, which took place in April in Lyon.

8.1.2.2. Member of the Conference Program Committees

- Nataliia Bielova served in the Program Committees of IEEE SecDev'18, POST'18, ProWeb'18, eCrime'18, APVP'18. She also is a member of the Steering Committee of the PLAS workshop.
- Manuel Serrano served in the Program Committee of ProWeb'18 workshop.
- Tamara Rezk served in the Program Committees of NDSS'18, Euro S&P'18, APLAS'18, POST'18, WWW'18, PriSC'18, CSF'18, SEC@SAC'18. She is also a member of the Steering Committee of the POST conference at ETAPS.
- Ilaria Castellani served in the Program Committee of the conference FORTE'18.

8.1.2.3. Reviewer

- The team members have been reviewers for the following conferences and workshops: PoPETs'18, CONCUR'18, FORTE'18, EXPRESS/SOS'18.

8.1.3. Journal

8.1.3.1. Member of the Editorial Boards

- Ilaria Castellani is a member of the editorial board of *Technique et Science Informatiques*.
- Tamara Rezk is a member of editorial Board of Interstices and blog Binaire du Le Monde.

8.1.3.2. Reviewer - Reviewing Activities

- The team members have been reviewers for the following journals: JCS, Acta Informatica, JLAMP, TCS, JOT.

8.1.4. Invited Talks

- Nataliia Bielova was an invited speaker at the workshop "Transparence et opacité des systèmes d'information" in April http://transparence.conf.citi-lab.fr/. She gave a talk at the Journées Scientifiques Inria in June https://journees-scientifiques2018.inria.fr/francais-programme/. She gave a tutorial on Web Tracking Technologies at TheWeb'18 conference in April https://www2018.thewebconf.org/program/tutorials-track/tutorial-203/ and gave a keynote talk at the Journée scientifique RISE/DS4H of Université Cote d'Azur in September. Nataliia was an invited speaker at Harvard University where she gave a talk on Web tracking technologies in October 2018. She also gave an invited lecture on "Online tracking and privacy protection", at Master 2 course, Carnegie Mellon University in October and an invited lecture on "Ethics and Internet Security" in Master in Digital Business course at SKEMA Business school in March.
- Manuel Serrano gave an invited talk on on Web Programming at the Programming ProWeb'18 workshop in April, https://2018.programming-conference.org/track/proweb-2018-papers. He gave a two hours talk on Reactive Web Programming during the Synchron'18 workshop https://project.inria.fr/synchron2018/fr/. He also was an invited speaker at Brown University where he gave a talk on JavaScript implementation.

- Tamara Rezk was an invited speaker at the seminar in the context of Inaugural lecture of Marieke Huisman, University of Twente, January 2018. She also gave a talk in the Dagstuhl Seminar on Secure Compilation of May 2018 and at Harvard University in October 2018.

8.1.5. Leadership within the Scientific Community

- Ilaria Castellani is the chair of the IFIP TC1 WG 1.8 on Concurrency Theory since June 2014. In 2018 she has been reelected for a second term.
- Ilaria Castellani is a Management Committee member of the COST Action IC1405 on Reversible Computation (November 2014-April 2019).

8.1.6. Research Administration

- Nataliia Bielova is a member of “Comité du Suivi Doctoral (CSD)” (Supervision of PhD students) of the Inria Sophia Antipolis Mediterranée research center. She was a member of the Inria “Master Transverse” evaluation committee.
- Manuel Serrano was the "Délégué scientifique" (head of research) of the Inria Sophia Antipolis Mediterranée research center until end of August. He was member of the Inria Evaluation Committee until that time.
- Tamara Rezk is a member of " Commission de Développement Technologique (CDT)" of the Inria Sophia Antipolis Mediterranée research center.
- 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 Scientific Committee of the Morgenstern Colloquium. She is also a member of the Réseau Parité of Université Côte d’Azur, and of the Scientific Committee of the Forum Numerica Seminar of Academy 1 of Université Côte d’Azur.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Master : Nataliia Bielova, Security of Web Applications, 18ETD, niveau M2, University of Pierre et Marie Curie, France

Master : Nataliia Bielova, Foundations of Privacy, 1.5ETD, niveau M2, Carnegie Mellon University, USA

Master: Nataliia Bielova, Ethics and Internet Security, 1.5ETD, M2, SKEMA Business school, France.

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

Master : Tamara Rezk, Security of Web Applications, 36ETD, niveau M2, University of Pierre et Marie Curie, France

Doctorat : Nataliia Bielova, Apprentissage et fouille de données sur les Réseaux, 2.25ETD, École de Recherche ResCom, France

Doctorat : Nataliia Bielova, Ecole de Cybersécurité, 3ETD, UCA, France

Doctorat : Nataliia Bielova, Web Privacy, 30ETD, University of Trento, Italy

E-learning

MOOC: Nataliia Bielova, “Protection de la vie privée dans le monde numérique”, 1 Module, 8 sequences, FUN-MOOC, Inria, grande public, formation continue, 8900 inscrit au 18 Decembre 2018.

8.2.2. Supervision

HdR :Tamara Rezk, *Secure Programming* [11], Université Côte d'Azur, 03/04/2018

PhD : Dolière Francis Somé, *Web Applications Security and Privacy* [12], Université Cote d'Azur, 29/10/2018, Nataliia Bielova and Tamara Rezk

PhD: Colin Vidal, *Programmation Web réactive* [13], University of Nice, 1/07/2015-1/09/2018, Manuel Serrano and Gérard Berry.

PhD in progress : Imane Fouad, Web tracking detection and measurement, 1/01/2018, Nataliia Bielova and Arnaud Legout

PhD in progress : Jayanth Krishnamurthy, Privacy policy enforcement in IoT applications, 12/09/2018, Nataliia Bielova and 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

Postdoc: Yoonseok Ko, Subsets of secure JavaScript, 1/10/2018-, Tamara Rezk

Postdoc: Minh Ngo, TSNI enforcement mechanisms, 1/01/2018-31/12/2018, Tamara Rezk

Postdoc: Francis Somé, IoT secure broadcasting, 1/11/2018-, Tamara Rezk

8.2.3. Juries

- Nataliia Bielova was a member of the PhD jury of Oleksii Starov, Stony Brook University.
- Nataliia Bielova was a member of the PhD jury of Daniel Schoepe, Chalmers University of Technology.
- Manuel Serrano was a member of the PhD jury of Remy El-Sibaie, Paris-Sorbonne University.
- Manuel Serrano was a member of the PhD jury of Pierre Talbot Ircam, Paris-Sorbonne University.
- Tamara Rezk was "rapporteur" for the PhD thesis of Nadim Kobeissi, ENS
- Tamara Rezk was "rapporteur" for the PhD thesis of Gurvan Cabon, Université de Rennes
- Tamara Rezk was a member of the Licenciate jury of Iulia Bastys, Chalmers University of Technology
- Tamara Rezk was a member of the jury "soutenance stage" of the CASPAR master of University of Nice Sophia Antipolis
- Tamara Rezk was a member of the jury for the ACM Student Research Competition of April 2018

8.3. Popularization

8.3.1. Internal or external Inria responsibilities

Tamara Rezk is member of the editorial board of Interstices and Blog Binaire Le Monde

8.3.2. Articles and contents

Tamara Rezk published the article "Est-ce que mon programme est bien protégé ?" in blog binaire Le Monde in February 2018. The article with some minor modifications was retaken by Interstices and published in December 2018. http://binaire.blog.lemonde.fr/2018/02/09/est-ce-que-mon-programme-est-bien-protege-contre-les-cyberattaques/.

Nataliia Bielova was interviewed by Sophie Casals, "Comment mieux protéger sa vie privée en naviguant sur internet? Les conseils d'une spécialiste" in Nice Matin, June 2018. https://www.nicematin.com/faits-de-societe/comment-mieux-proteger-sa-vie-privee-en-naviguant-sur-internet-les-conseils-dune-specialiste-239166

8.3.3. Education

8.3.3.1. Skini and the Fabrique à Musique

Skini is currently used with a class of secondary school in order to create a musical show in collaboration with the Conservatory of Nice and the CIRM (National Center for Music Creation). A group of 25 children, 12 year old, are creating together a story, and use the distributed sequencer of Skini to design basic musical patterns using tablets. The next step is to organize with them the orchestration of the piece which is coded in HipHop. The activation of the piece will be done in real time by the children using the tablet and the Skini plateform. This project is funded by SACEM (Société des auteurs, compositeurs et éditeurs de musique). The project will end in May 2019 with a public concert in the Conservatory of Nice.

8.3.3.2. MOOC Protection de la vie privée dans le monde numérique

Nataliia Bielova has participated to the MOOC “Protection de la vie privée dans le monde numérique” (Session 2) that was shooted in July 2018 under the guidance of Inria Learning Lab and was open to general public between 5 November 2018 and 7 January 2019, https://www.fun-mooc.fr/courses/course-v1:inria+41015+session02/about.

8.3.4. Interventions

- Nataliia Bielova held a stand at Portes ouvertes (Fête de la science) of Inria Sophia Antipolis explaining how to protect privacy on the Web, October 2018.
- Ilaria Castellani and Héloïse Maurel held the stand “Science au féminin” together with Carine Antico from CNRS at the Fête de la Science in Antibes Juan-les-Pins, October 2018.

8.3.5. Internal action

- Nataliia Bielova gave a talk at the PhD seminar special edition on “Tracking technologies and protection of your privacy on the Web”, March 2018.
- Nataliia Bielova gave a talk at the Data Science meetup Nice on “How companies track you as you browse the web and how to protect yourself?”, https://www.meetup.com/Data-Science-Meetup-Nice-Sophia-Antipolis/events/255546602/, October 2018.

9. Bibliography

Major publications by the team in recent years

[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

[2] G. Boudol, I. Castellani. *Noninterference for Concurrent Programs and Thread Systems*, in "Theoretical Computer Science", 2002, vol. 281, n^{o} 1, p. 109-130

[3] G. Boudol, Z. Luo, T. Rezk, M. Serrano. *Reasoning about Web Applications: An Operational Semantics for HOP*, in "ACM Transactions on Programming Languages and Systems (TOPLAS)", 2012, vol. 34, n^{o} 2

[4] S. Capecchi, I. Castellani, M. Dezani-Ciancaglini. *Information Flow Safety in Multi-party Sessions*, in "Mathematical Structures in Computer Science", 2015, vol. 26, n^{o} 8, 43 [*DOI :* 10.1017/S0960129514000619], https://hal.inria.fr/hal-01237236

[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

[6] C. FOURNET, T. REZK.*Cryptographically sound implementations for typed information-flow security*, in "Proceedings of the 35th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, POPL 2008, San Francisco, California, USA, January 7-12, 2008", 2008, p. 323-335

[7] M. NGO, F. PIESSENS, T. REZK.*Impossibility of Precise and Sound Termination-Sensitive Security Enforcements*, in "SP 2018 - IEEE Symposium on Security and Privacy", San Francisco, United States, IEEE, May 2018, p. 496-513 [*DOI :* 10.1109/SP.2018.00048], https://hal.inria.fr/hal-01928669

[8] M. SERRANO, G. BERRY.*Multitier Programming in Hop - A first step toward programming 21st-century applications*, in "Communications of the ACM", August 2012, vol. 55, n^{o} 8, p. 53–59 [*DOI :* 10.1145/2240236.2240253], http://cacm.acm.org/magazines/2012/8/153796-multitier-programming-in-hop/abstract

[9] M. SERRANO, V. PRUNET.*A Glimpse of Hopjs*, in "21th ACM Sigplan Int'l Conference on Functional Programming (ICFP)", Nara, Japan, September 2016, p. 188–200, http://dx.doi.org/10.1145/2951913.2951916

[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

Publications of the year

Doctoral Dissertations and Habilitation Theses

[11] T. REZK.*Secure Programming*, Université de Nice - Sophia Antipolis, April 2018, Habilitation à diriger des recherches, https://hal.inria.fr/tel-01941697

[12] D. F. SOMÉ.*Web applications Security and Privacy*, Université Côte D'Azur, October 2018, https://hal.inria.fr/tel-01925851

[13] C. VIDAL.*Reactive Web Programming*, Université Côte d'Azur, July 2018, https://tel.archives-ouvertes.fr/tel-01900619

International Conferences with Proceedings

[14] G. G. GULYÁS, D. F. SOMÉ, N. BIELOVA, C. CASTELLUCCIA.*To Extend or not to Extend: On the Uniqueness of Browser Extensions and Web Logins*, in "WPES'18 - Workshop on Privacy in the Electronic Society", Toronto, Canada, ACM Press, October 2018, p. 14-27 [*DOI :* 10.1145/3267323.3268959], https://hal.inria.fr/hal-01921863

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Other Publications

[19] I. FOUAD, N. BIELOVA, A. LEGOUT, N. SARAFIJANOVIC-DJUKIC.*Tracking the Pixels: Detecting Web Trackers via Analyzing Invisible Pixels*, December 2018, working paper or preprint, https://hal.inria.fr/hal-01943496

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[26] *Ghostery Official website*, 2018, https://www.ghostery.com/

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[28] *uBlock Origin - An efficient blocker for Chromium and Firefox. Fast and lean*, 2018, https://github.com/gorhill/uBlock

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Team KAIROS

Logical Time for Formal Embedded System Design

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
Embedded and Real-time Systems

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Team KAIROS

Creation of the Team: 2017 January 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]

Faculty Members

Julien Deantoni [Univ. Nice - Sophia Antipolis, Associate Professor]
Frédéric Mallet [Team Vice-Leader, Univ. Nice - Sophia Antipolis, Professor, HDR]
Marie-Agnès Peraldi-Frati [Univ. Nice - Sophia Antipolis, Associate Professor]
Sid Touati [Univ. Nice - Sophia Antipolis, Professor, HDR]

External Collaborators

Paul Bouche [Institut de recherche technologique Saint-Exupery, from Jun 2018]
Amin Oueslati [Institut de recherche technologique Saint-Exupery]

Technical Staff

Luc Hogie [Ingénieur de recherche, CNRS]

PhD Students

Carsten Bruns [Univ Côte d'Azur, from Oct 2018]
Giovanni Liboni [Safran Tech, from Apr 2018]
Claude Stolze [Univ. Nice - Sophia Antipolis]
Hui Zhao [Inria, Labex]
Dongdong An [East China Normal University, until Apr 2018]
Marwa Hami [Univ. Sousse, until Jul 2018]

Visiting Scientists

Tengfei Li [East China Normal University, from Mar 2018 until Oct 2018]
Jing Liu [East China Normal University, until Jan 2018]

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 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.

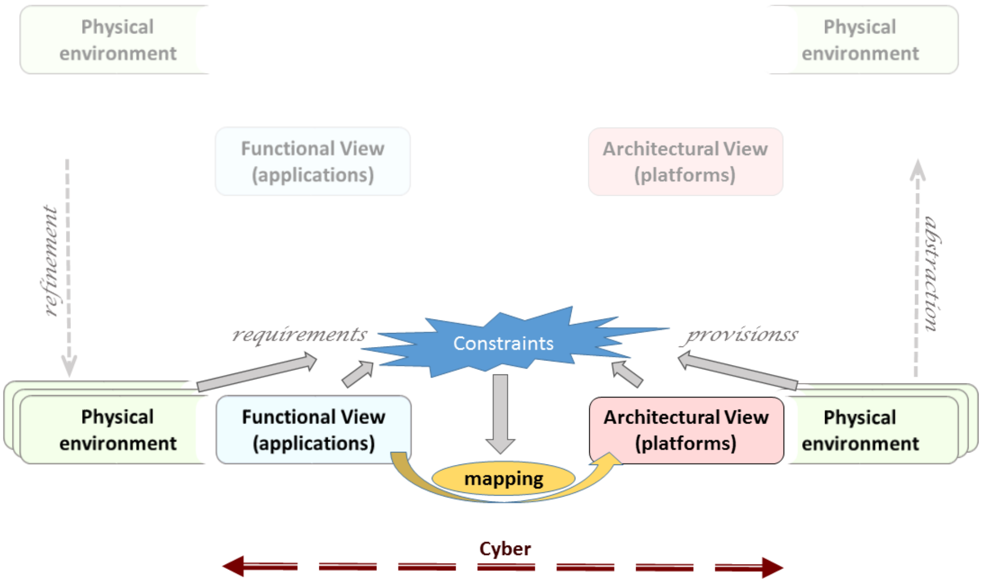

Figure 1. Cyber-Physical generic architectural features

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 discovery and 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 to Code and Optimization

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. 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 of A is less than the timestamp of B). We hope to extend 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 CCSL constraints needed to formalize logical clocks (in particular CCSL expressions like subclock, clock union, intersection and concatenation) and provide opportunities for an *ad hoc* polymorphic type theory. Logical time constraints seen as property types can be beneficially 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.

3.6. Object-oriented programming and logical time

We formalize in the past object-oriented programming features, like e.g. delegation-based and trait inheritance. We view our logical time model as a mean to enhance the description of timing constraints and properties on top of existing specification formalism. When considering general purpose object-oriented languages like Java, type-theory is a natural way to provide such properties. Currently, such languages do not have constructs nor special types to manage instants, time structures and instant relations like subclocking, precedence, causality, equality, coincidence, exclusion, independence, etc. CCSL provide 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 consider logical time constraints as behavioral type properties, and the design of programming language constructs and *ad hoc* type systems.

3.7. 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.

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

Our local collaborations on handheld, smartphone-like appliances have come to a close with the disappearance of most industrial partners at Sophia Antipolis (Texas Instruments mostly) and the end of the CIM PACA Design platform association. We are renewing collaborations with other local partners, with a focus on Smart Contract applied to connected objects in a IoT environment, and special concern for cloud/fog/edge allocation of computations, expressed with logical time modeling constraints. A speculative european consortium is put up under coordination by Easy Global Market (Sophia-based), and other initiatives with companies such as Symag, Accenture Labs Sophia, and Renault are also being developed.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

BEST PAPERS AWARDS :
[16]
A. SCHULZ-ROSENGARTEN, R. VON HANXLEDEN, F. MALLET, R. DE SIMONE, J. DEANTONI.*Time in SCCharts*, in "Forum on specification & Design Languages", Munich, Germany, September 2018, p. 5-16, Best Paper Award [*DOI :* 10.1109/FDL.2018.8524111], https://hal.inria.fr/hal-01898285

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.

Experimental version (2018) also includes algorithm for computing the symbolic semantics of Open Systems

- Participants: Antonio Cansado, Bartlomiej Szejna, Eric Madelaine, Ludovic Henrio, Marcela Rivera, Nassim Jibai, Oleksandra Kulankhina and Siqi Li
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- 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.

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- 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

Framework for building social networks executable on web browsers, android and apple platforms
KEYWORDS: Framework - Peer-to-peer. - NoSQL - Mobile application - Social network - Publish-subscribe
SCIENTIFIC DESCRIPTION: [EN] myMed : an ad hoc framework to execute homogeneous social networks. The explosion of different Open Social Networks (OSN) "running" in the internet arena has changed the habits of mostly all of us. There are OSN almost for everything, from cooperative work, car pooling, healthcare, friendship, love, affairs, healthcare, information, gaming, etc. In almost all of the cases, there are no two OSN that are built by the same software producer, and - quite often - mostly of them work on a competitive basis, and - for many different reasons (business, privacy, politics, etc.) - they are not open source and they are hosted by their private servers. The interactions between those OSN is very little, since the Application Programming Interfaces (API) - if existing - are very weak and limited to access to the friends lists or to access OSN X with the password of OSN Y. Even worst, the possibility of programming or at least interconnecting common features (e.g. search on different data bases, link user names and passwords, chat, access to common data bases etc.) between different OSN advance slowly. The most used practice of interconnecting OSN is based on a form of "asymmetric viral communication" where one can relay (or post or publish) a duplicated copy or a pointer of a record published by user A in OSN X into another OSN Y, provided user A have also an account on OSN Y, and de facto forbidding in mostly cases the inverse operation, aka subscribing for a different user B on OSN Y to any publication of user A on OSN X even if user B does not have an account on OSN X. As such, the well know paradigm of Publish/Subscribe at the basis of many CSCW applications cannot be fully exploited inter social networks, leaving only their use intra social network, the latter use being of less impact in coordination and cooperation. Beside of the "business needs" of OSNs, the myMed (www.mymed.fr) meta-social network represents an important step toward the natural interconnections of social applications. This paper introduce the concept and the original structure of the myMed experimental system, as it was conceived as a common effort between five academic sites (Inria, Polytechnic of Turin, University of Turin, University of Piedmont Oriental, University of Nice Sophia Antipolis) and few local startups. myMed is an open source project, which facilitate and accelerate the development of ad hoc social applications (called in myMed jargon "sociapps") running over an heterogeneous "Plateau" of platforms, such as PCs, Smartphones and Tablets running iOS and Android. myMed provides a rich framework for publishing, searching and subscribing to content: the engine is built on top of a distributed noSQL database. In its current version, it provides high scalability and fault tolerance. The myMed framework allows you to easily build social web applications: it features geolocalization, points of interest in charts, buddy lists, profile management, content/user reputation, built-in cooperation and coordination among different OSN running on it, proto OSN store, etc. A short description of the framework can be found in the appendix of this paper. In a nutshell the myMed framework is composed of: • a Software Development Kit (SDK) to develop fixed and mobile web sociapps, running on many Web browsers but also natively on Smartphones and Tablets equipped with Android or iOS. Sociapps, by their name, must have a strong social flavor (open social networks, closed social networks, enterprise social networks, micro/nano social networks and so on). Thanks to the rich, general-purpose, catalog of modules in the framework, every module can be freely used without interfering with other sociapps, in a true "Lego" fashion. The program is distributed under the Apache V2 free license. The TTM ("Time To Market") envisaged to develop a sociapp using the myMed SDK can be estimated from 1 to 3 months employing 1 or 2 senior programmers. • A "cloud" to execute the "sociapps" represented by a "backbone" of 50PCs, distributed through the "AlpMed" EuroRegion following some precise efficiency criteria (as example the presence of Internet running on optical fibers). Part of those PCs have a double function: o ensure the good behavior of all the running sociapps, and o offer services other than those offered by myMed, such as a web browser, an

open-source Office suite, a private disk of little size, logically separated from the noSQL space that can be used by others users (we call this "an elastic usage of the myMed cloud PC"). Those PCs can be accessed via a private login and password generated by the framework on demand. The operating systems running on those PC (Ubuntu myMed Edition, UME) is also open source and it is based on a customized version of the Ubuntu operating system. To guarantee the quality of the execution of the sociapps, we require that all machines belonging to the backbone are constantly running (on state). • A little collection of "proof of concept" sociapps to validate, experiment, and testing the development kit and the execution cloud. These sociapps have been conceived with the precious help of the "Civil society" of the EuroRegion "AlpMed" (States, Regions, Prefectures, Associations, Chambers of Commerce, Municipalities, Universities, etc.) that have played a role of "maitre d'oeuvre" (or experts) in a given "applicative domain". The quasi totality of the sociapps are available on the myMed web platform at the address http://www.mymed.fr/?action=login but also on the most common mobile application stores, such as the Apple Store and the Google Play Store Markets. The myMed system is naturally divided into a backend and a frontend permitting a natural separation of concerns. The present and the future features of the myMed architecture together with the many open questions left open are: • myMed is distributed by construction and could be decentralized. The myMed backbone is 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. • myMed (should be) Easy to use. Start from the template, add or remove features, play with the design and the interface and you have an application ready to deploy on the myMed cloud and accessible to all myMed users via the proto store. • myMed is Extensible. myMed provides a modular architecture, since developers can easily install new modules and users can add or remove all the sociapps they like using the proto store. • myMed as a distributed Social Operating system? for many aspects myMed looks like an social operating system installed on a distributed and decentralize pull of PCs. Modifications of internal myMed modules would not affect the behavior of all sociapps using those modules. • myMed promotes collaboration and cooperation between OSN. The sharing of all social modules have the positive effect of greatly facilitate OSN interconnection • myMed users feature a two level profile. Having a myMed "basic profile" just give access to the store and to a "read only view" of each OSN X. For a full experience the user must fill the, so called, "extended profile" for OSN X which allows a full read/write access. • myMed and myMed sociapps can feature an ad hoc economical model? It is well know that economical models for OSN are quite often related to advertising, or buying intra OSN features. The myMed interconnectivity by construction, open a way to novel business models, like "the more you open the more you earn?" • myMed should feature an unique Human Computer Interface? a common template is provided to expert users that want to implement a proper OSN. Do they need to be compliant with some graphical chart? • myMed can run on different instances. Can different instances cooperate? As in higher-order languages, the same cooperation level featured between different OSNs running on one myMed instance can be applied on different myMed instances running on different hardware. This would be subject of a further evolution of inter-cooperation and connection of myMed instances and their OSN running inside it. A lot of care must be given in building coherent "meta basic profiles".

FUNCTIONAL DESCRIPTION: myMed is an experimental framework for implementing and deploying, on the top of a built-in cloud platform, many Open Social Networks (OSN) that could take advantage of sharing common software modules, hardware resources, making inter-communication and inter-interaction simpler and improving rapid development and deployement. myMed OSN are either accessible on web browsers and mobile platforms (android, ios). myMed is based on a peer-to-peer architecture and noSQL database technology. A number of experimental OSN are experimentally implemented and deployed to validate the framework : among them we mention myRiviera, myPaysduPaillon, mioConsolato, myBenevolat, myFondationSophiaAntipolis, myEurocin, myEurope, myAngel, ...

- Participants: Claudio Casetti, Luigi Liquori, Mariangiola Dezani and Mino Anglano
- Partners: Politecnico di Torino - Université de Nice Sophia Antipolis (UNS) - Università di Torino - Università del Piemonte Orientale
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- 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.

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7. New Results

7.1. Schedulability of CCSL specifications via SMT

Participants: Frédéric Mallet, Robert de Simone.

The full expressive power of the CCSL language makes it very complex, if not impossible, to also find good, or even optimal, schedules as results of solving the CCSL constraints. Nevertheless, important subclasses can be devised, or efficient heuristics can be attempted. The study of CCSL scheduling decidability and efficient is a long-term source of theoretical developments in the team, here is a record of this year advances, split in two parts.

We have made progress on the inherent complexity of finding a schedule with a general CCSL specification. We have proved that the schedulability problem of CCSL is NP-hard. Then it makes sense to find whether there are still some practical ways to find solutions in specific cases. It turns out that in many cases, we can still find solutions in a reasonable duration. To do so, we have proposed [8] an encoding of CCSL specifications as an SMT (Satisfiability Modulo Theory) specification and we use Z3 and CVC4 as solvers for our experiments. Using a pure SAT solver is not possible for CCSL, as CCSL combines Boolean operations with arithmetics on unbounded integers. Using SMT allows to combine both. This encoding uses a sublogic called UFLIA that relies on quantified variables (boolean or integer), undefined functions on boolean and integers, and linear integer arithmetics. This logics is undecidable in the general case and the use of quantified variables makes it difficult to deal with, but we have found some interesting examples where we still get some results in a reasonable amount of time. We have also tried to identify subdomains where we get interesting results and we have focused on pure real-time schedulability problems. In that context, we showed that the schedulability problem for a set of real-time tasks reduces to the schedulability problem of CCSL specifications with a specific form (to be published).

The Clock Constraint Specification Language (CCSL) is a clock-based specification language for capturing causal and chronometric constraints between events in Real-Time Embedded Systems (RTESs). Due to the limitations of the existing verification approaches, CCSL lacks a full verification support for 'unsafe CCSL specifications' and a unified proof framework. In this paper [18], we propose a novel verification approach based on theorem proving and SMT-checking. We firstly build a logic called CCSL Dynamic Logic (CDL), which extends the traditional dynamic logic with 'signals' and 'clock relations' as primitives, and with synchronous execution mechanism for modelling RTESs. Then we propose a sound and relatively complete proof system for CDL to provide the verification support. We show how CDL can be used to capture RTES and verify CCSL specifications by analyzing a simple case study.

7.2. Logical Time for the semantics of Reactive Languages

Participants: Frédéric Mallet, Robert de Simone.

This work was initiated during the sabbatical period of Reihard von Hanxleden, on leave from the University of Kiel (Germany), funded by the the UMR I3S laboratory.

The results won Best Paper Award at the Federated Design Languages (FDL) conference edition of 2018 [16]. The paper abstract follows:
Synchronous languages, such as the recently proposed SCCharts language, have been designed for the rigorous specification of real-time systems. Their sound semantics, which builds on an abstraction from physical execution time, make these languages appealing, in particular for safety-critical systems. However, they traditionally lack built-in support for physical time. This makes it rather cumbersome to express things like time-outs or periodic executions within the language. We here propose several mechanisms to reconcile the synchronous paradigm with physical time. Specifically, we propose extensions to the SCCharts language to express clocks and execution periods within the model. We draw on several sources, in particular timed automata, the Clock Constraint Specification Language, and the recently proposed concept of dynamic ticks. We illustrate how these extensions can be mapped to the SCChart language core, with minimal requirements on the run-time system, and we argue that the same concepts could be applied to other synchronous languages such as Esterel, Lustre or SCADE.

7.3. Dealing with uncertainty in logical time

Participants: Frédéric Mallet, Robert de Simone.

When uplifting the target of models to heterogeneous Cyber-Physical Systems, the relations from physical time (which governs Physical components) to logical time becomes an issue for proper abstraction in the design. Often, the other engineering discipline may know of "proto-logical" timing abstraction, but involving probabilistic/stochastic ingredients to link the declared logical clocks/events. As a results, several attempts have been made at extending the language to allow perceptive probabilistic structuring operators, that may link (unreachable) physical rhythms with their discretized, manageable counter-parts. Of course the feasibility of constraint solving remains the key issue for allowing extensions scarcely. Nevertheless, it should be noted that the focus on relevancy of relations between physical and logical times may in some case be an important concerns for non-IT scientists.

The reports on how early attempts can be found in [6], [10], [12]. The topic is far from closed, but as such these are valuable starts.

In the future, we plan to exploit these model extensions on practical application fields, including car trajectory computation with Renault Software Lab, security properties "with Time"in the ILP SPAI with other Inria teams, and micro-satellites in the ATIPPIC IRT Saint-Exupery project with Thales Alenia Space.

7.4. Behavioral semantics and equivalence notions for Open Systems

Participants: Eric Madelaine, Tengfei Li, Zechen Hou.

Model-Based Design 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. Following last year results we have published an experience paper [23] showing the applicability of this approach to show properties of a piece of the control software of a nano-satellite, specified using BIP architectures. Our work now turns on designing specific symbolic algorithms for model checking and equivalence checking (bisimulation) of such open systems, and also, as a specific application domain, to formalize the encoding of BIP architecture, extended with data constraints, into open pNets, aiming at a full approach for compositional verification of such systems. This work is done in collaboration with researchers from ENS Lyon and Inria Lille, and from ECNU Shanghai [23].

7.5. Logical Time for Safety Analysis and dependability

Participants: Paul Bouche, Amin Oueslati, Robert de Simone.

We have studied in the past the relevance of Logical Time for modeling of dynamic Non-Functional Properties (NFP) aspects of functional applications and/or execution platforms. In this setting, any recurring events may be seen as generating its own "rythm", as a logical clock. The most obvious NFP aspects to consider were performance and power consumption, as important concerns of Real-Time Embedded systems. Recently we have turned towards fault tolerance and availability/dependability aspects. This was motivated by demands from industrial partners inside IRT Saint-Exupery, who tried to design in real terms the digital computing structure of micro-satellites using ordinary processor components from the Shelf (COTS), extremely sensible to solar radiations (creatings faults). We have put up a full model-based design of the proposed use case, which includes modeling of the fault-tolerant features, but also the independent modeling of waterfall propagation schemes from incidental faults to fully recognized dysfunctions, where the system is no longer operational. Current results are encouraging, as they build up natural specification styles using logical time on top of existing formalisms such as AltaRica, widely used in industry. Methodological advances are proposed to industrial partners in IRT Saint-Exupery, and primarily Thales Alenia Space. We plan to comfort our approach next year with dedicated tools for modeling and analysis, as well as translation towards existing formalisms such as AltaRica, seen as lower level in our context.

7.6. Co-Simulation of Cyber-Physical Systems

Participants: Julien Deantoni, Giovanni Liboni, Robert de Simone.

While we continued to study and envision the past, present and future of co-simulation in [11], we already obtained promising results. In [14], we highlighted the current problems of the FMI co-simulation standards and more generally of existing coordination between actors of the co-simulation. We also shown that providing appropriate mean to communicate with the actors according to their internal semantics allows for dedicated coordinator providing better results than existing ones (speed up can reach 25 with a perfect accuracy). As shown in [14], the functional correctness of co-simulation can be violated by a non appropriate coordination of co-simulation actors. To avoid such phenomenon, we explored in [17] the possibility to formally prove the correctness of a coordinator according to properties defined by the actors. This last work is greatly exploratory but Julien Deantoni did a Short Term Scientific Mission (in the context of the MPM4CPS cost action [0]) in the MSDL Lab in Antwerp to understand more deeply the problem and potential solutions. Preliminary interesting results have been obtained [0] and may be published in 2019.

7.7. Early Interconnect Contention Analysis

Participants: Amin Oueslati, Julien Deantoni.

In the context of the Atippic project, industrial partners are using the Capella system engineering language (http://polarsys.org/capella) to migrate a satellite control software on a totally new architecture platform based on "COTS" dual core processors. In order to better deal with the potential contention on the interconnect between the different cores, it was required to help for contention analysis. In this context and based on one of our software (GEMOC Studio: http://eclipse.org/gemoc) we developed an executable extension to Capella, from which simulation of Capella model can be used to obtain bus latency and bandwidth.

We are currently extending this simulation approach to ease Design Space Exploration based on variation of some parameters (typically parameters of the tasks that create traffic like for instance, periods or consumed/produced data size). First results have already been demonstrated to the IRT Saint-Exupery and should be published early 2019.

[0] http://mpm4cps.eu/
[0] http://mpm4cps.eu/STSM/reports/material/STSM_DeantoniJulien_Report_527.pdf

7.8. Process network models with explicit data size handling

Participants: Amin Oueslati, Robert de Simone.

We concluded our activities in the definition of a process network, inspired from established formalisms such as Ptolemy's SDF, StreaMIT, and Thales Array-OL task graph languages. Our next formalisms described accurately how regular data structures (2-dimensional arrays or matrices mostly) get assembled or deassembled in actual data-flow computations for streaming intensive data/signal processing. This allows to allocate these computations to similar dedicated architectures (GPUs, TPUs) while making all kinds of parallelism (data-, task-, streaming) explicit. The resulting forms of specification are intently very close to representations that may be expressed in OpenMP or MPI, and cover the important class of Deep Networks filter stream models, which have raised tremendous interest lately in Artificial Intelligence.

7.9. Union and Intersection constraints

Participants: Luigi Liquori, Claude Stolze.

In [21], we introduced an explicitly typed λ-calculus with strong pairs, projections and explicit type coercions. The calculus can be parameterized with different intersection type theories, producing a family of calculi with related intersection typed systems. We proved the main properties like Church-Rosser, unicity of type, subject reduction, strong normalization, decidability of type checking and type reconstruction. We stated the relationship between the intersection type assignment systems and the corresponding intersection typed systems by means of an essence function translating an explicitly typed Delta-term into a pure λ-term one. We finally translated a term with type coercions into an equivalent one without them; the translation is proved to be coherent because its essence is the identity. The resulting generic calculus can be parametrized to take into account other intersection type theories as the ones in the Barendregt *et al.* book.

7.10. Logical frameworks with Union and Intersection constraints and Oracles

Participants: Luigi Liquori, Claude Stolze.

In [13], we introduced the Δ-framework, DLF, a dependent type theory based on the Edinburgh Logical Framework LF, extended with the *strong proof-functional connectives*, i.e. strong intersection, minimal relevant implication and strong union. Strong proof-functional connectives take into account the shape of logical proofs, thus reflecting polymorphic features of proofs in formulæ. This is in contrast to classical or intuitionistic connectives where the meaning of a compound formula depends only on the truth value or the provability of its subformulæ. Our framework encompasses a wide range of type disciplines. Moreover, since relevant implication permits to express subtyping, DLF subsumes also Pfenning's refinement types. We discuss the design decisions which have led us to the formulation of DLF, study its metatheory, and provide various examples of applications. Our strong proof-functional type theory can be plugged in existing common interactive proof assistants.

Moreover, in [7], we introduced two further extensions of LF, featuring monadic *locks*. A lock is a monadic type construct that captures the effect of an *external call to an oracle*. The oracle can be invoked either to check that a constraint holds or to provide a suitable witness. Such calls are the basic tool for *plugging-in*, i.e. gluing together, different type theories and proof development environments.

7.11. Object reclassification

Participant: Luigi Liquori.

In [19], we investigated, in the context of *functional prototype-based languages*, a calculus of objects which might extend themselves upon receiving a message, a capability referred to by Cardelli as a *self-inflicted* operation. We introduced a sound type system for this calculus which guarantees that evaluating a well-typed expression will never yield a *message-not-found* run-time error. The resulting calculus is an attempt towards the definition of a language combining the safety advantage of static type checking with the flexibility normally found in dynamically typed languages.

7.12. Object discovery

Participant: Luigi Liquori.

In [20], we proposed a Content Name System (CNS) discovery service, extending the current TCP/IP hourglass Internet architecture, that provides a new network aware content discovery service. Contents are addressed using "hypernames", whose rich syntax allow to specify hosts, PKI, fingerprint and optional logical attributes (tags) attached to the content name, such as e.g. mutable vs. immutable contents, digital signatures, owner, availability, price, etc. The CNS behavior and architecture is, partly, inspired by the Domain Name Service (DNS), and whose discovery process logic uses the Border Gateway Protocol (BGP) information allowing Internet to route between different Autonomous Systems (AS). The service registers and discovers object names in each Autonomous System (AS), and the content discovery process is inspired to the so called "valley-free" property. In the routing among different ASes (i.e., the BGP protocol) this is a property that avoids unjustified AS transit costs.

7.13. Code optimization for HPC and CPS programs

Participants: Sid Touati, Carsten Bruns, Robert de Simone.

Optimising HPC applications is a classical research area in computer science, complementary to intensive computation (which is an adjacent research community to HPC). Since decades, the most used languages are imperative ones (FORTRAN, C, etc). These languages are the closest to formal algorithms and low-level assembly codes. In intensive computing area, other kinds of languages and programming paradigms are used (interpreted languages for instance), but are far from HPC challenges, which tackle low level optimization (close to back-end compilation and processor micro-architectures).

We started a while ago to work on optimisation of HPC applications at C++ program level, where code and data are mixed in the same objects, allowing sophisticated programming methods that were not traditionally tackled in classical HPC programming (such as virtual classes, exception handling, etc). Currently, we are working on performance analysis and optimisation of linear algebra codes (BLAS) programmed with classes: this allows to extend BLAS computation to any kind of data (such as complex numbers) not only floating points. Our final aim is to apply and adjust this type of general C++ code optimization, to cover the spectrum of typical Kairos applications expressed from in C++ from high level formal specifications.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Safran: Desir/Glose

Participants: Julien Deantoni, Giovanni Liboni, Robert de Simone.

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 HyComes, and DiverSE Inria project teams. Technically, the goal of this project is to elaborate on the (under development) Safran's system engineering method to make it simulable at different steps of the development, possibly early in the design process and possibly mixing models at different maturity level. This project is strongly connected to results depicted in Section 7.6.

8.1.2. IRT Saint-Exupery ATIPPIC

Participants: Paul Bouche, Amin Oueslati, Robert de Simone, Julien Deantoni.

In an attempt to build an extension of IRT Saint-Exupery from Occitanie to PACA region, the Thales Alenia Space company promoted the ATIPPIC project, to build the computing digital electronic structure of micro-satellites on ordinary, "COTS" processors. The project was accepted for 30 months, funds two temporary research engineers working under our own supervision, while exchanging extensively with the rest of the ATIPPIC project, which is actually hosted by Inria. The technical content of our contributions is described in Section 7.5 and 7.7.

8.1.3. Renault Software Lab

Participants: Frédéric Mallet, Marie-Agnès Peraldi-Frati, Robert de Simone.

We have just 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 will start at the beginning of 2019.

8.1.4. Accenture Labs, Sophia

Participant: Luigi Liquori.

We started in 2018 a collaboration with Accenture Labs, Sophia on the following topics:

- Smart Contract languages for permissioned blockchains. We saw in the recent years the development of different platforms that focuses on the so-called private (or permissioned) blockchain(s) and digital ledgers. Almost the totality of private blockchain(s) 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. Both public and private blockchain often lack maturity and a formal semantic as they have been under pressure of the sudden and rapid explosion of blockchain popularity. A CIFRE PhD will start in 2019.
- Oracles in Smart Contract for IoT and and CPS. Oracles are third party services which are not part of the blockchain consensus mechanism. The main challenge with oracles is that people need to trust these sources of information. Whether a website or a sensor, the source of information needs to be trustworthy. The main challenges for oracles are dealing with small computation power, mobility, security and dealing with time. A CIFRE PhD is planned to start in 2019.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. Université Côte d’Azur Academy 1

In the context of the UCA Jedi IDEX, associated with the UCA ComUE, we have applied to a number of funding initiatives. The project Smart IoT for Mobility has been funded for three years by the Academy RISE. This project is lead by the LEAT and Kairos is building a formal language for the design of smart contracts in the context of a mobility project with Renault Software Labs. The smart contracts are persisted in a secured distributed ledgers (through blockchain technology). The SyMag company, a subsidiary of BNP Paribas, is providing the technology to access block chain with a ledger-agnostic API. A PhD (at LEAT) and a Post-doc (within Kairos) positions are funded by this project. A complementary funding has been asked to the ANR with the generic call 2019.

9.2. National Initiatives

9.2.1. Investissements d’Avenir: PIA Clarity

Participants: Julien Deantoni, Robert de Simone, Amin Oueslati, Frédéric Mallet, Marie-Agnès Peraldi-Frati.

This project was funded by the LEOC Call (*Logiciel Embarqué et Objets Connectés*) of the national support programme *Investissements d’Avenir*. It ended in January 2018. Partners were: Thales (several divisions), Airbus, Areva, Altran, All4Tec, Artal, the Eclipse Fondation, Scilab Enterprises, CESAMES, U. Rennes, and Inria. The purpose of the project is to develop and promote an open-source version of the ARCADIA Melody system design environment from Thales, renamed CAPPELLA for that purpose. In this project we investigated extensions of Capella to enable simulation and analysis of mode automata in the context of model based system engineering.

9.2.2. 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,con Programming and Software Engineering (LaHMA group), LTP, Langages, Types et Preuves.

9.3. International Initiatives

9.3.1. Inria International Labs

The SACCADES LIAMA project came to a conclusion with the ending of the related Associated Team with ECNU Shanghai. We are actively working on a renewal of this colaboration, integrating the new generation of Professors there.

9.3.2. Inria International Partners

9.3.2.1. Declared Inria International Partners

- Luigi Liquori has a steady collaboration with researchers from University of Udine, and Turin, Italy.
- We collaborate with the University of Verona on topics of CPS co-simulation. This partly funds a support engineer on their side.
- M.A Peraldi-Frati participates in an international cooperation between University Côte d'Azur, University of Danang (Vietnam) and AUF. This collaboration crystallized through the DNIIT excellence initiative between Univ of Danang and UCA. M.A Peraldi-Frati is involved in the SLEGO project (Specific domain Language for Experience Global Orchestration)[22].

9.3.2.2. TuMuLT

Title: Trustworthy Modeling using Logical Time

International Partner (Institution - Laboratory - Researcher):

ECNU (China) - Software Engineering Institute - Min Zhang

Duration: 2018 - 2022

Start year: 2018

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

We have four main research directions:

- Modeling the Uncertain Environments of Cyber-Physical Systems (CPS): Logical Time was one of the main scientific foundations of the AOSTE 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 CPS means widening those assumptions to consider the external environment as part of the design. The environment obeys the law of physics that usually depend on physical time consideration with models that are approximation of the reality and that necessarily introduce a wide uncertainty on the behavior. 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 [25].
- 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, Solving a system of logical-time constraints is NP-complete but we strive to find efficient algorithms to solve sub-classes of well defined systems. In that context, SMT is a promising solution to combine and solve systems that combine several theories. We had first results on this aspect [8] 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. In addition to the temporal factor omni-present in real-time and embedded systems, a physical location plays also a central role. Functions of the system (like a train) must be done both at the right time AND at the right location. This task focuses 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).
- Open pNets: 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 satisfiability checking engines (SAT and SMT). We are working on novel methods combining classical verification paradigms (state-space construction and minimization, model-checking) with SMT approaches to create symbolic and compositional verification methods and tool platforms. We have interesting preliminary results [26], and collaborate actively on both fundamental results and prototype development.

9.3.3. Participation in Other International Programs

- PHC Xu Quangqi funded by ANR for International collaborations with China in 2008.
  - PI: Frédéric Mallet (France) and Zhang Min (China)
  - Title: SMT FOR LOGICAL TIME
  - Description: The main goal of the project was to build an efficient encoding of logical time in SMT solvers. This goal has been achieved (see New Result in Section 7.1).

9.4. International Research Visitors

- Xue-Yang ZHU, assistant research professor at Institute of Software, Chinese Academy of Science, Beijing.
- Zhang Min, Assistant Professor, ECNU Shanghai, 2 weeks in August 2018,
- Changbo Wang, Professor, Dean of Computer Science Department, ECNU Shanghai, 2 weeks in August 2018.

9.4.1. Internships

Zechen HOU benefited from an Inria International Internship Grant.

9.4.2. Visits to International Teams

9.4.2.1. Explorer programme

Julien Deantoni has spent one week visiting the Modelling, Simulation and Design Lab (MSDL) in Antwerp, funded by the MPM4CPS European cost action.

9.4.2.2. Research Stays Abroad

Eric Madelaine has spent 1 month visiting the Software engineering and computer Science department at ECNU Shanghai (2 weeks in May, 2 week in October).

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

- Robert de Simone organized the Scientific Program for the yearly Synchron seminar, held in November in Saint-Raphaël. He is also Steering Committee member of IEEE/ACM EmSoft a conference part of Embedded System Week.
- Eric Madelaine is chair of the steering committee of the Int. Symposium on Formal Aspects of Component Software (FACS: http://sevlab.postech.ac.kr/facs18/committees/)
- Frédéric Mallet was track co-chair for DATE 2018.
- Julien Deantoni was track co-chair for IEEE-RIVF (http://rivf2019.udn.vn/).

10.1.1.2. Member of the Organizing Committees

M-A. Peraldi-Frati and R. de Simone organized the Open Workshop Synchron 2018 in Saint-Raphaël.

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

- M.A Peraldi-Frati is member of the IEEE-RIVF 2019 Program Committee.
- E. Madelaine is member of the PC of FACS'2018, VECoS'2018.
- R. de Simone is PC member for the conference MeMoCode, FDL, and EmSoft.
- Frédéric Mallet. Member of program committee for DATE'18, Euromicro DSD'18, FTSCS'18, FDL'18, TASE'18, Modelsward'18.
- Julien Deantoni is PC member RIVF'19, EXE'18, GEMOC'18, MDebug'18, DSD'18, MoMo'18.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- Eric Madelaine is Guest Editor of the Science of Computer Programming special issue for selected papers of the FACS'2014 symposium.
- Frédéric Mallet. Managing Guest Editor for a special issue of Elsevier Science of Computer Programming (SCP).

10.1.3.2. Reviewer - Reviewing Activities

- Eric Madelaine is reviewer for the journals: Science of Computer Programming (SCP), and Journal of Logical and Algebraic Methods in Programming (JLAMP).
- Marie-Agnès Peraldi-Frati : ACM Transactions on CPS, Forte2018.
- Luigi Liquori. Journal reviewer : Fundamenta Informaticae. Conference TPC: NICS'18, ICCE'18
- Frédéric Mallet. Journal reviewer for IEEE Transactions on Computer Aided Design of Integrated Circuits (TCAD), ACM Transactions on Embedded Computing Systems (TECS), ACM Transactions on Design Automation of Electronic Systems (TODAES), Elsevier Computers In Industry.
- Julien Deantoni. Journal reviewer for Software and Systems Modeling (http://www.i3s.unice.fr/~deantoni/SoSyM-review-certificate-Julien-DeAntoni.pdf) and for Computer Languages, Systems & Structures.

10.1.4. Research Administration

- F. Mallet is Deputy Director of UMR I3S Laboratory and as such, member of the 'comité de direction', 'conseil de laboratoire', 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

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.

M.A Peraldi-Frati teaches Web security (20h), Security of connected objects (20h), IoT Infrastructure deployment (20 H) and Large scale plateform for IoT (20h) in a licence cursus dedicated to Internet of Objects, Infrastructure and Applications.

Licence : Luigi Liquori, Peer-to-peer systems, 32 eq TD, Université Côte d'Azur.

Winter School on Theoretical Foundations of Computer Science, 4-9 February 2019, Georgia. Luigi Liquori. Peer-to-peer and reklated systems, International Black Sea University and Shota Rustaveli National Science Foundation of Georgia.

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, 24h eq TD, Polytech'Nice.

Master: Julien Deantoni, Language Interpreter, 24h eq TD, Polytech'Nice.

10.2.2. Teaching Administration

- Sid Touati was the responsible of first year of computer science licentiate since 2011 till 2018.
- Sid Touati is a vice-director of the computer science department since 2017, in charge of the graduate students (licence).
- Frédéric Mallet is the coordinator of the International track of the Master of Computer Science since 2015.
- Frédéric Mallet is a member of the steering committee of the Graduate School DS4H (EUR DS4H).
- Master: Julien Deantoni, computer science internship management.

10.2.3. Supervision

- PhD in progress : Claude Stolze, A proof-functional type theory for intersection and union types, Université Côte d'Azur, end 2019, Luigi Liquori.
- PhD in progress : Carsten BRUNS, Performance analysis and optimisation of C++ applications, Université Côte d'Azur, 2021, Sid TOUATI.
- PhD in progress : Hui Zhao, Multiview System Integration for Cyber Physical Systems, Université Cote d'Azur, end 2019, Frédéric Mallet
- PhD in progress : Giovanni Liboni, Coordination of discrete (Cyber) Models, Université Cote d'Azur, end 2021, Frédéric Mallet, Julien DeAntoni

10.2.4. Juries

Robert de Simone was reviewer of the PhD thesis of Amaury Greillat (VERIMAG, Grenoble), and of the Habilitation thesis of Katell Morin-Allaury (TIMA, Grenoble).

M.A Peraldi-Frati : Examinator Thesis jury Slim Medimegh - CentraleSupélec University- Dec 2018.

Frédéric Mallet : Reviewer for the PhD thesis of NGuyen Van Hai - Université Paris Saclay - Central/Supélec, 27/09/2018

Frédéric Mallet : Reviewer for the PhD thesis of Martial Chabot - Université Grenoble Alpes - TIMA, 30/10/2018

11. Bibliography

Major publications by the team in recent years

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[2] B. COMBEMALE, J. DEANTONI, B. BAUDRY, R. B. FRANCE, J.-M. JÉZÉQUEL, J. GRAY.*Globalizing Modeling Languages*, in "Computer", June 2014, p. 10-13, https://hal.inria.fr/hal-00994551

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[5] M. ZHANG, F. DAI, F. MALLET.*Periodic scheduling for MARTE/CCSL: Theory and practice*, in "Science of Computer Programming", March 2018, vol. 154, p. 42-60 [*DOI :* 10.1016/J.SCICO.2017.08.015], https://hal.inria.fr/hal-01670450

Publications of the year

Articles in International Peer-Reviewed Journal

[6] D. DU, P. HUANG, K. JIANG, F. MALLET.*pCSSL: A stochastic extension to MARTE/CCSL for modeling uncertainty in Cyber Physical Systems*, in "Science of Computer Programming", November 2018, vol. 166, p. 71 - 88 [*DOI :* 10.1016/J.SCICO.2018.05.005], https://hal.inria.fr/hal-01898202

[7] F. HONSELL, L. LIQUORI, P. MAKSIMOVIC, I. SCAGNETTO.*Plugging-in Proof Development Environments using Locks in LF*, in "Mathematical Structures in Computer Science", 2018, vol. 28, n^{o} 9, p. 1578–1605, https://hal.inria.fr/hal-01272647

[8] M. ZHANG, F. DAI, F. MALLET.*Periodic scheduling for MARTE/CCSL: Theory and practice*, in "Science of Computer Programming", March 2018, vol. 154, p. 42-60 [*DOI :* 10.1016/J.SCICO.2017.08.015], https://hal.inria.fr/hal-01670450

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Invited Conferences

[10] F. MALLET.*Model-Based Systems Engineering for Cyber-Physical Systems: a (possible) roadmap for MARTE*, in "3rd International workshop on TIming Performance engineering for Safety critical systems CONFESTA/TIPS", Beijing, China, September 2018, https://hal.inria.fr/hal-01898291

International Conferences with Proceedings

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Team LEMON

Littoral, Environnement : Méthodes et Outils Numériques

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).

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THEME
Earth, Environmental and Energy Sciences

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Team LEMON

Creation of the Team: 2014 January 01, updated into Project-Team: 2019 January 01

Keywords:

Computer Science and Digital Science:

A6.1.1. - Continuous Modeling (PDE, ODE)
A6.1.2. - Stochastic Modeling
A6.1.4. - Multiscale modeling
A6.1.5. - Multiphysics modeling
A6.2.1. - Numerical analysis of PDE and ODE
A6.2.2. - Numerical probability
A6.2.3. - Probabilistic methods
A6.3.4. - Model reduction

Other Research Topics and Application Domains:

B3.3.2. - Water: sea & ocean, lake & river
B3.3.3. - Nearshore
B3.3.4. - Atmosphere
B3.4.1. - Natural risks
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B4.3.2. - Hydro-energy
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B8.3. - Urbanism and urban planning
B9.11.1. - Environmental risks

1. Team, Visitors, External Collaborators

Research Scientist

Antoine Rousseau [Team leader, Inria, Researcher, HDR]

Faculty Members

Carole Delenne [Univ de Montpellier, Associate Professor, HDR]
Vincent Guinot [Univ de Montpellier, Professor, HDR]
Gwladys Toulemonde [Univ de Montpellier, Associate Professor]

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Joao Guilherme Caldas Steinstraesser [Inria, from Sep 2018]
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Annie Aliaga [Inria]

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 and HSM, we collaborate with **several local academic research partners**. To mention but a few examples, we are in close contact 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).

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.

[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).

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 [44]. 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 [67]. While the research on porosity-based shallow water models has accelerated over the past decade [61], [80], [84], [56], [55], [67], [96], [97], [91], [92], 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 [80], [58], 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 consistency issues [58]. Secondly, the flux and source term models fail to reproduce the alignment with the main street axes in a number of situations [57]. 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, 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 [67]. It has led to the development of the Dual Integral Porosity model [59]. 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.

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. [72] 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, [93] 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 [30], [69], that are not adapted to generate extreme rainfall events. Recent advances in spatio-temporal extremes modelling based on generalized Pareto processes [48], [87] and semi-parametric simulation techniques [36] 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) project, led by Gwladys Toulemonde, is funded by the action MANU (MAthematical and Numerical methods) of the LEFE program. It aims 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.

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 [51], for example: to characterize the flood dynamics of great rivers [73], to monitor temporary ponds [85], but also to calibrate hydrodynamics models and assess roughness parameters [82], [62], [95].

Upscaled models developed in LEMON (see 3.2.1) embed new parameters that reflect the statistical properties of the medium geometry. Two types of information are needed: the directional properties of the medium and its flow connectivity properties. New methods are thus to be developed to characterize such statistical properties from 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. In developed countries, it is intended to extract information on the porosity parameters and their principal directions from National geographical survey databases. 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). However, such level of detail in vector format is still not available in many countries. Moreover, vector data for the street network does not provide all the relevant information. In suburban areas, lawns, parks and other vegetated areas may also contribute to flood propagation and storage. In this context, it is intended to extract the necessary information from aerial and/or satellite images, that are widely available and the spatial resolution of which improves constantly. A research line will consist in deriving the information on street preferential orientation using textural analysis techniques. Such techniques have been used successfully in the field of agricultural pattern identification during Carole Delenne's PhD thesis [46], [77]. However, their application to the urban environment raises a number of issues. One of them is the strongly discontinuous character of the urban medium, that makes textural analysis difficult.

Moreover, in order to achieve a correct parametrization, identifying areas with homogeneous porosity properties is necessary. Algorithms identifying the shape and extension of such areas are still to be developed.

In wetlands applications, the flow connectivity is a function of the free surface elevation. 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

3.2.3.4. *External collaborations*

- The methodologies concerning geographical databases in vector form will be developed in strong collaboration with C. Dieulin at HSM in the framework of the PoroCity Associate International Laboratory cited above.
- Research on topography reconstruction in wetlands begun in collaboration with J.-S. Bailly (LISAH) in 2016 [45] and will continue in the coming years.

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 [79], [70] 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 [68]. They embed dispersive terms that allow for shoaling and other bathymetry effects. Since the pioneering works of Green and Naghdi (see [52]), 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.

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 [32]).

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.

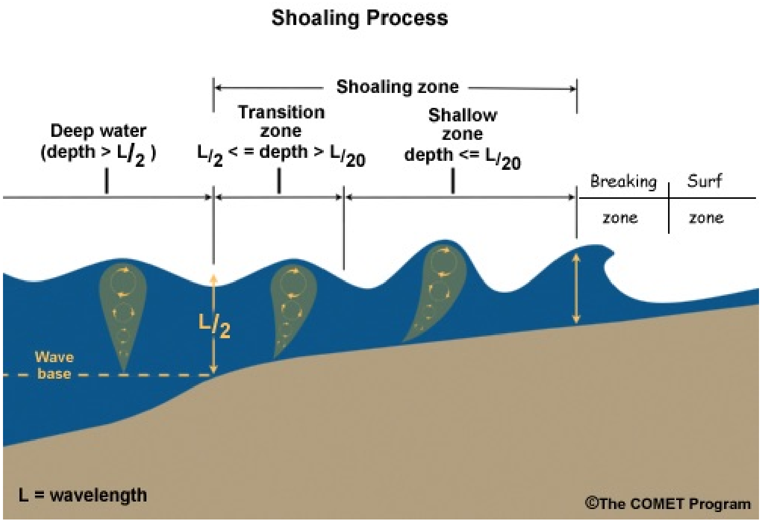

Figure 1. Deep sea, shoaling, and breaking zones.

- **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. [36] proposed such an approach. They first produced and studied a 52-year hindcast using the WW3 wave model [34], [37], [35], [88]. Then stemming from parts of the original work of [33], [53], [48], [36] 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 [36] and the Pareto Processes [48]. This will allow the work of [36] 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

- 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 [36].

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 [83], [81], [65], [41], [74] 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 [43]. 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 [48], [87]. 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 [42], [86]. This has motivated the development of more flexible dependence models such as max-mixtures of max-stable and asymptotically independent processes [94], [28] for maxima data, and Gaussian scale mixture processes [75], [64] 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 [89] . 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 [39], [40], [63]) 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 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 [78]. Now local authorities are confronted with the task of combining data produced by different parts, having distinct formats, variable precision and granularity [38].

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 [76]. 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. 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 [66] 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.

In collaboration with J.S. Bailly (LISAH), it is intended to extend the application field of the Cart'Eaux project to rainwater collection systems, involving free surface ditches. These are particularly present in peri-urban areas and are integral part of the green corridor by playing a crucial environmental role of pollution retention and ecological continuity. Multiple-point geostatistics methods [54] will be explored, especially the Direct Sampling approach [71], efficient to simulate spatial heterogeneities by combining continuous and categorized data. When a variable is observed at a given location, the method uses it as conditional information to guide the simulation of another variable of interest in the whole spatial field.

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).

- A new project lead by N. Chahinian (HSM) has recently been funded concerning data mining and text analysis, in collaboration with linguists of URM Praxiling. Carole Delenne will have a slight implication in this project.
- A phd thesis will be submitted to the French Association of Research and Technology (ANRT) in co-funding with Berger-Levrault company concerning data fusion.
- The problematic of inferring a connected network from scarce or uncertain data is common to several research topics in LEMON such as sewage or drainage systems, urban media and wetlands. A generic methodology will be developed in collaboration with J.-S. Bailly (LISAH).

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 [59]. This source term is not active in all situations but takes effect only when positive waves are involved [56], [57]. 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 [67], [80]. 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 [47] 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

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. External collaborations

3.4.4.1. Inland hydrobiological systems

3.4.4.1.1. 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 [49], 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 [50], [31] and to the improvement of ODE models in order to account for space-heterogeneity of bioremediation processes in water resources [29].

3.4.4.1.2. 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 will be 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.

3.4.4.1.3. People

Céline Casenave (INRA Montpellier), Antoine Rousseau, Vincent Guinot, Joseph Luis Kahn Casapia, PhD student (march 2018)

3.4.4.1.4. 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. Application Domains

4.1. Simulation of extreme events

The models and methods developed within this research line aim to support decision-making in the field of flood crisis management. This concerns various types of floods.

- rainfall-induced floods, stemming from intense rainfall events (see 3.2.3, 3.4.1, 3.4.2),
- fluvial floods
- fast rising flood waves induced by dam/dike break or tsunami waves (see 3.3.1, 3.2.2),
- coastal submersion (storm surges).

The aforementioned models and methods can be used at the three stages of the flood crisis.

- Before the crisis, models can be run offline to assess the vulnerability and resilience of alternative urbanization schemes, rescue actions and mitigation policies to various meteorological/coastal scenarios. This includes the simulation of extreme forcings (wind, wave and/or rainfall fields) from a limited set of available records, see subsection 3.3.2.
- During the crisis, either fast-running porosity models or pre-computed scenarios may be used to support real-time decision-making for rescue actions.
- After the crisis, data and experience collected at the crisis stage may be used to enrich the simulation database, better parametrize the models and methods.

4.2. Marine and coastal systems

LEMON will consider interactions between various processes (and the corresponding models) in coastal oceanography. Our guideline is the design and implementation of accurate numerical methods to simulate physical and/or ecological processes involving various time and space scales:

- modelling of waves in several regimes of the coastal area (shoaling, breaking, running, etc.) implies the implementation of numerical models involving various physical regimes (2D, 3D, hydrostatic, dispersive, etc.) which cannot be studied independently (in particular in the framework of marine energies). Each of the corresponding models has its own specificity, requirements and experts. Hence the difficulty to build a multiphysics (coupled) global ocean system at the coastal scale.
- for most coastal marine organisms, including algae, invertebrates and fish, dispersal, genetic connectivity and the replenishment of coastal populations depend on the character of the coastal ocean. Modelling this dispersal process and larval transport across the surfzone is at the foremost of marine conservation ecology and requires advanced ocean modelling (in addition to the specific biological processes).

LEMON has a strong expertise on mathematical modelling and coupling techniques (borrowed from domain decomposition models) that will be intensely used in these frameworks. As far as extreme events are concerned, we want to build a data generator which will allow the study of the effects of various scenarios on impact measures. To do so, we will first analyze data simulated from a physical system and detect extreme events. The latter will be used to generate and calibrate as many realistic extreme events as necessary.

5. Highlights of the Year

5.1. Highlights of the Year

- Undoubtedly the most important highlight is the "go" decision of Inria's Project Committee for the creation of the LEMON team. This decision was made at the end of 2018 and the team will officilly exist as "Equipe Projet" as of 2019.
- 3 new members joined the team in 2018: Fatima Palacios Rodrigouez (funding source: Inria) started a PostDoc as of November 2018. Joao Guilherme Caldas Steinstraesser (funding source: Inria) and Joseph Luis Kahn Casapia (funding sources: ANR/Inria) started their PhD in October and November this year.
- The publication of the depth-dependent porosity model [4] is the result of a three year, joint research effort carried out by the team. With Vincent Guinot , Carole Delenne and Antoine Rousseau from LEMON and Olivier Boutron from Tour du Valat as co-authors, this publication is emblematic of the team's activities in the field of porosity model development.

6. New Software and Platforms

6.1. 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.

- Participant: Vincent Guinot
- Contact: Vincent Guinot

6.2. 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

6.3. 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

6.4. 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

7. New Results

7.1. Inland flow processes

7.1.1. Shallow water models with porosity

7.1.1.1. DDP model.

A new porosity model was published in 2018. The Depth-Dependent Porosity (DDP) model [4] was developed to account for subgrid-scale topographical features in shallow water models. The purpose is to allow flows to be modelled using coarse grids in the presence of strongly contrasted topography (e.g. ditches, narrow channels, submerged obstacles). Applications range from the modelling of lagoon/wetland dynamics to the submersion of urban areas by dambreak or tsunami waves. The development is the result of a team work in cooperation with the Tour du Valat research institute (O. Boutron). The developments are incorporated in the SW2D code.

7.1.1.2. Porosity model validation.

The first experimental results validating the Dual Integral Porosity (DIP) model were presented at the RiverFlow 2018 International conference [9]. This work was carried out in collaboration with S. Soares-Frazão at Université Catholique de Louvain (UCL). Two stays of Carole Delenne and Vincent Guinot at UCL to participate in the experimental campaign in 2017 had been supported financially by the LEMON budget. A journal article presenting these experiments in detail has been submitted to the Journal of Hydraulic Research and is currently awaiting the final decision.

7.1.2. Forcing

Stochastic approaches can be used to generate forcing scenarios randomly. To this end, an accurate characterization of the spatio-temporal variability and rainfall intensity distribution must be obtained from available data. So we have deeply studied a gridded hourly rainfall dataset in a region in Mediterranean France and proposed a semiparametric method to simulate spatio-temporal scenarios for extreme events. Our work was presented in the following international conferences: METMA 2018 - 9th Workshop on Spatio-temporal modelling (June 2018, Montpellier) [11] and SWGEN 2018 - Stochastic Weather Generators Conference (October 2018, Boulder, United States)[10]. Moreover we have invited P. Naveau (CNRS, LSCE) during two weeks and we have begun a collaboration concerning the construction of a unique temporal model permitting to deal with both ordinary and extreme events.

7.1.3. Inland hydrological systems

The PhD of Joseph Luis Kahn Casapia (co-advised by Antoine Rousseau and Céline Casenave from INRA) has just started (Oct. 2018). The objective of the thesis is the modelling of cyanobacteria blooms in shallow water lakes such as TaiHu, in China. This work is done in the framework of the ANSWER research project funded by ANR, with a co-funding by labex NUMEV in Montpellier.
A publication presenting the KarstMod modelling platform was accepted in Environmental Modelling & Software [6]. KarstMod incorporates a number of developments by Vincent Guinot, including the Hysteretic [90] and the infinite characteristic time [60] transfer functions.
A family of multi-region transport models in heterogeneous porous media have been derived and validated experimentally [5]. The publication with Carole Delenne and Vincent Guinot as co-authors presents not only experimental results, but also a theoretical analysis of the transport and dispersion properties of a variety of models, depending on the structure of the flow field.

7.1.4. Parametrization

With an objective of assessing flood hazard at large scale, the CASACADE project has been funded by the Luxembourg National Research Fund and provides for a phD (started in November 2018 by Vita Ayoub) concerning assimilation of satellite derived flood information for better parameterizing and controlling large scale hydraulic models over data scarce areas. One of the model used will be the DDP model [4]. The effective integration of remote sensing-derived flood information into this model will be investigated in this project for retrieving uncertain model parameters and boundary conditions. The PhD is co-directed by Carole Delenneand Renaud HOSTACHE from the Luxembourg Institute of Sciences and Technologies (LIST).

7.2. Marine and coastal systems

7.2.1. Multi-scale ocean modelling

We proposed in [2] a Schwarz-based domain decomposition method for solving a dispersion equation consisting on the linearized KdV equation without the advective term, using simple interface operators based on the exact transparent boundary conditions for this equation. An optimization process is performed for obtaining the approximation that provides the method with the fastest convergence to the solution of the monodomain problem.
We also moved towards more complex equations and derived in [13], [12] 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 used the derived transparent boundary conditions as interface conditions in a domain decomposition method, where they become local in time. We analyzed numerically their efficiency thanks to comparisons made with other interface conditions. A paper [19] is submitted for publication in addition to the aforementioned talks.

7.2.2. Data-model interactions

To go further with what have been explained in subsection Forcings, there are clear advantages of thresholding techniques in stochastic approaches aiming to simulate extreme events. They permit to exploit information from more data (compared to the block-maxima approach) and to explicitely model the original event. Pareto processes have been mostly used in a parametric framework, thereby using assumptions on the choce of the underlying dependence structure that may be strong. We have proposed a semi-parametric approach ([10], [11]) and we have shown the links between this semi-parametric method and the Pareto processes. A key benefit of the proposed method is to allow the generation of an unlimited number of realizations of these extreme fields. This work will be submitted for publication during the first trimester of 2019.

7.3. Methodological developments

7.3.1. Stochastic models for extreme events

In extreme value theory, there is two main approaches. The first one is based on block maxima and involve max-stable models. Indeed the use of extreme value copula for extreme events is justified by the theory of multivariate extreme. The most accessible models are too simplistic when they are used in a high-dimensional framework. That is why we have proposed in a spatial context to combine two Gumbel copulas. By doing that, we reduce the complexity considering the weight parameter as a function depending on covariates. Moreover interpolation becomes straightforward and enable the interpretation of the parameters with distances between sites. Properties of the proposed model such as the possible extremal dependencies varying in space are studied and inference relies on ABC techniques. This work will be submitted for publication during the first quarter of 2019 (see also [14]).

The second approach is based on high threshold exceedances. We have proposed a novel hierarchical model for this kind of data 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 been presented in two invited talks in 2018 ([16], [17]) and is under revision in JASA [27].

7.3.2. Integrating heterogeneous data

In the framework of the Cart'Eaux project, a stochastic algorithm has been set up to provide a set of probable wastewater networks geometries, obtained from manhole covers positions and cost functions based on general guidelines for such networks construction. The methodology and results are presented in a publication submitted to Computers, Environment and Urban Systems Journal.

Meanwhile, the MeDo project led by N. CHAHINIAN in collaboration with linguists, aims at identifying thematic entities related to wastewater networks in automatically collected documents on the web. This project has been presented in [8].

A PhD thesis has just been funded by ANRT and Berger-Levrault company concerning the fusion of the heterogeneous and uncertain data collected. This PhD (Yassine BEL-GHADDAR) will starts at the beginning of 2019 and will be co-directed by Carole Delenne and Ahlame BEGDOURI from the LSIA laboratory of FST Fes (Maroc).

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

LEMON has been collaborating for a while with Olivier Boutron (La Tour du Valat) and we had a specific contract in 2018 to adapt our software SW2D to specificities of Camargue lakes and lagoons. This has lead to a common paper.

9. Partnerships and Cooperations

9.1. Regional Initiatives

Cart'Eaux project (European Regional Development Fund (ERDF)): in partnership with colleagues of LIRMM and HSM (Montpellier) and with Berger-Levrault company, Carole Delenne and Benjamin COMMANDRE are developing a methodology that will collect and merge multi-sources data in the aim of mapping urban drainage networks for hydraulic modeling purpose. This chain of treatment includes: i) detection of manhole covers from remote sensing data (aerial images, numerical elevation models...), 2) development of an algorithm to retrieve the network from the detected points and other information such as roads or topography, 3) data manning to extract useful characteristics for the hydraulic model, from various databases available or from documents automatically gathered from the web. A confidence index will be given to each characteristic assessed and a sensitivity analysis will enable the software to propose a hydraulic model together with an associated uncertainty.

The GeRIMU project (Gestion du Risque d'Inondation en Milieu Urbain) will be based on the SW2D computational code. The purpose is to optimize and implement the commercial version of the code into a complete software chain for the forecasting and scenario appraisal for rainfall-generated urban floods on the scale of the urban area. The test and application site is the entire urban area of Montpellier.

9.2. National Initiatives

Antoine Rousseau is member of the ANR project ANSWER (PI Céline Casenave), 2016-2019

Gwladys Toulemonde is head of a project (2016-2018) funded by INSU via the action MANU (MAthematical and NUmerical methods) of the LEFE program. This project, called Cerise, aims to propose methods for simulating scenarii integrating spatio-temporal extremes fields with eventual asymptotic independence for impact studies in environmental sciences. Fatima PALACIOS-RODRIGUEZ is also a member of this project.

9.3. International Initiatives

9.3.1. Inria International Labs

Antoine Rousseau collaborates with Inria Chile through the partnership with MERIC in Chile. Two visits every year.

9.3.1.1. Associated team 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: - design and implementation of domain decomposition and coupling techniques for coastal modeling - high resolution ocean simulation (including nesting) thanks to the software ROMS-CROCO, applied to biological tracers tracking.

9.3.2. Inria International Partners

9.3.2.1. Declared Inria International Partners

In 2015, the *Marine Energies Research International Center* (MERIC) was launched in Chile by CORFO. Antoine Rousseau is the scientific coordinator for Inria, and several members of LEMON, CARDAMOM and TOSCA research teams will be involved in this 8 years project driven by DCNS. Antoine Rousseau is involved in the research line *advanced modeling for marine energy*.

9.3.2.2. Informal International Partners

Vincent Guinot collaborates with B.F. Sanders (University of California Irvine, USA)

Carole Delenne and Vincent Guinot collaborate with S. Soares-Frazao (Unité de Génie Civil, Université catholique de Louvain, Belgium)

Gwladys Toulemonde collaborates with C. Gaetan (Università Ca' Foscari - Venezia)

9.3.3. Participation in Other International Programs

Antoine Rousseauwas member of a successfull application to the REDES (Conicyt, Chile) program with H. Ramirez (CMM, Santiago) and P. Gajardo (UTFSM, Valparaiso).

9.4. International Research Visitors

Rodrigo Cienfuegos (PUC Santiago, Chile) visited Paris for two weeks in June (collaboration around TsunamiLab).

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Event Organisation

10.1.1.1. Member of Organizing Committee

Gwladys Toulemonde is chair of the organizing committee of the international conference METMA IX (June 2018, Montpellier).

10.1.2. Journal

10.1.2.1. Member of Editorial Board

Antoine Rousseau is member of DCDS-S editorial board

Gwladys Toulemonde is guest editor (with L. Bel, AgroParisTech) of the Special Issue entitled "Space-time modeling of rare events and environmental risks" which will be published in Spatial Statistics.

10.1.2.2. Reviewer - Reviewing Activities

Carole Delenne is a reviewer for Journal of Hydraulic Research, Water (2 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 (2 manuscripts/year)

10.1.3. 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).

10.1.4. Scientific Expertise

Antoine Rousseau is member of the scientific board of Fondation Blaise Pascal

Carole Delenne was reviewer for the STIC-AmSud Program

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

Gwladys Toulemonde is member of the scientific committee of Spatial Statistics 2019 (Sitges, Spain)

10.1.5. 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,

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*)

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*)

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*)

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Three LEMON permanent members (out of four) 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. Carole Delenne is also teaching manager of the department EGC at Polytech. The teaching load is summarized in Table 1.

Table 1. Teaching

Antoine	Teaching M1 level: 0 to 30 hrs/year Student supervision: 50 hrs/year
Carole	Teaching L1-M2 level: 200-250 hrs/year hydraulics, applied mathematics, informatics Student tutorship and supervision: 50-100 hrs/year
Gwladys	Teaching L3/M1/M2 level: 200-250 hrs/year mathematics, probability, statistics, data mining Student tutorship and supervision: 50-100 hrs/year
Vincent	Teaching L3/M1/M2 level: 290 hrs/year Student tutorship and supervision: 50-100 hrs/year

10.2.2. Supervision

Gwladys Toulemonde is responsible for student recruitment at the IG department (Polytech Montpellier).

Gwladys Toulemonde co-supervises a PhD thesis in an established collaboration with Sanofi and is also involved in two other industrial collaborations (BALEA, Twin Solutions)

Gwladys Toulemonde advises a post-doctoral fellow since october 2017 on spatio-temporal extreme processes to assess flood hazards (NUMEV funding until Oct 2018)

10.2.3. Juries

Antoine Rousseau was appointed internal member of a recruitment campaign at Inria (CR2 at Inria CRI-SAM)

10.3. Popularization

Antoine Rousseau is member of the editorial board of Interstices and the Binaire Blog in Le Monde.

10.3.1. Internal or external Inria responsibilities

Antoine Rousseau is member of "Bureau du Comité des Équipes-Projet" in the research center of Sophia-Antipolis Méditerranée.

10.3.2. Interventions

Antoine Rousseau has given lectures in the following events:

- Fête de la Science (Genopolys Montpellier) and Semaine des maths (Collège Les Fontanilles, Castelnaudary)
- FUTUR·E·S in La Villette (Paris) for a demo of Tsunamilab
- another Tsunamilab demo for Region Occitanie (November 30th, Port Barcarrès)
- Centre d'Alembert (Orsay-Saclay)
- public schools of Aubais (Gard) and Castelnaudary (Aude)

10.3.3. Internal action

- Antoine Rousseau gave a talk in the Café des Sciences at Inria Rocquencourt, March 20th.

10.3.4. Creation of media or tools for science outreach

- Antoine Rousseau has contributed to the development of Tsunamilab in collaboration with Inria Chile
- Antoine Rousseau is a co-administrator of the association Le Calendrier Mathématique

11. Bibliography

Major publications by the team in recent years

[1] V. GUINOT, C. DELENNE, A. ROUSSEAU, O. BOUTRON.*Flux closures and source term models for shallow water models with depth-dependent integral porosity*, in "Advances in Water Resources", September 2018, vol. 122, p. 1-26 [*DOI :* 10.1016/J.ADVWATRES.2018.09.014], https://hal.archives-ouvertes.fr/hal-01884110

Publications of the year

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Invited Conferences

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International Conferences with Proceedings

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Project-Team MARELLE

Mathematics, Reasoning, and Software

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Proofs and Verification

Table of contents

Project-Team MARELLE

Creation of the Project-Team: 2006 November 01

Keywords:

Computer Science and Digital Science:

A2.1.11. - Proof languages
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
A8.10. - Computer arithmetic

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]
José Grimm [Inria, Researcher]
Benjamin Grégoire [Inria, Researcher]
Laurence Rideau [Inria, Researcher]
Enrico Tassi [Inria, Researcher]
Laurent Théry [Inria, Researcher]

External Collaborators

Gilles Barthe [IMDEA Madrid, HDR]
Loïc Pottier [Ministère de l'Education Nationale, HDR]

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Maxime Dénès [Inria Foundation, until Nov 2018, Inria since then]

PhD Students

Cécile Baritel-Ruet [Ecole Normale Supérieure Cachan]
Sophie Bernard [Univ de Nice - Sophia Antipolis]
Boris Djalal [Inria, until Sep 2018]
Mohamad El Laz [Inria]
Damien Rouhling [Ministère de l'Enseignement Supérieur et de la Recherche]

Post-Doctoral Fellow

Frank Florian Steinberg [Inria, until Sep 2018]

Visiting Scientists

Sunjay Cauligi [University of California San Diego, from Sep 2018 until Nov 2018]
Joshua Gancher [Cornell University, from Sep 2018 until Nov 2018]
Vincent Laporte [IMDEA Madrid, until Jun 2018]

Administrative Assistant

Nathalie Bellesso [Inria]

2. Overall Objectives

2.1. Overall Objectives

We want to concentrate on the development of mathematical libraries for theorem proving tools. This objective contributes to two main areas of application: tools for mathematicians and correctness verification tools for software dealing with numerical computation.

In the short term, we aim for mathematical libraries that concern polynomials, algebra, group theory, floating point numbers, real numbers, big integers, probabilities and geometrical objects. In the long run, we think that this will involve any function that may be of use in embedded software for control or robotics (in what is called hybrid systems, systems that contain both software and physical components) and in cryptographical systems. We want to integrate these libraries in theorem proving tools because we believe they will become important tools for mathematical practice and for engineers who need to prove the correctness of their algorithms and software.

We believe that theorem proving tools are good tools to produce highly dependable software, because they provide a framework where algorithms and specifications can be studied uniformly and often provide means to mechanically derive programs that are correct by construction.

We also study the extensibility of interactive theorem proving tools based on decision procedures that free designers from the burden of verifying some of the required properties. We often rely on “satisfiability modulo theory” procedures, which can be connected to theorem proving tools in a way that preserves the trustability of the final results.

3. Research Program

3.1. Type theory and formalization of mathematics

The calculus of inductive constructions is a branch of type theory that serves as a foundation for theorem proving tools, especially the Coq proof assistant. It is powerful enough to formalize complex mathematics, based on algebraic structures and operations. This is especially important as we want to produce proofs of logical properties for these algebraic structures, a goal that is only marginally addressed in most scientific computation systems.

The calculus of inductive constructions also makes it possible to write algorithms as recursive functional programs which manipulate tree-like data structures. A third important characteristic of this calculus is that it is also a language for manipulating proofs. All this makes this calculus a tool of choice for our investigations. However, this language still is the object of improvements and part of our work focusses on these improvements.

3.2. Verification of scientific algorithms

To produce certified algorithms, we use the following approach: instead of attempting to prove properties of an existing program written in a conventional programming language such as C or Java, we produce new programs in the calculus of constructions whose correctness is an immediate consequence of their construction. This has several advantages. First, we work at a high level of abstraction, independently of the target implementation language. Secondly, we concentrate on specific characteristics of the algorithm, and abstract away from the rest (for instance, we abstract away from memory management or data implementation strategies). Therefore, we are able to address more high-level mathematics and to express more general properties without being overwhelmed by implementation details.

However, this approach also presents a few drawbacks. For instance, the calculus of constructions usually imposes that recursive programs should explicitly terminate for all inputs. For some algorithms, we need to use advanced concepts (for instance, well-founded relations) to make the property of termination explicit, and proofs of correctness become especially difficult in this setting.

3.3. Programming language semantics

To bridge the gap between our high-level descriptions of algorithms and conventional programming languages, we investigate the algorithms that are present in programming language implementations, for instance algorithms that are used in a compiler or a static analysis tool. When working on these algorithms, we usually base our work on the semantic description of the programming language. The properties that we attempt to prove for an algorithm are, for example, that an optimization respects the meaning of programs or that the programs produced are free of some unwanted behavior. In practice, we rely on this study of programming language semantics to propose extensions to theorem proving tools or to verify that compilers for conventional programming languages are exempt from bugs.

4. Highlights of the Year

4.1. Highlights of the Year

4.1.1. Awards

The paper by Barthe, Grégoire, and Laporte at *Computer Security Foundations* on cryptographic constant-time was awarded a distinguished paper award.
BEST PAPERS AWARDS :
[16]
G. BARTHE, B. GRÉGOIRE, V. LAPORTE.*Secure Compilation of Side-Channel Countermeasures: The Case of Cryptographic "Constant-Time"*, in "CSF 2018 - 31st IEEE Computer Security Foundations Symposium", Oxford, United Kingdom, July 2018, https://hal.archives-ouvertes.fr/hal-01959560

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 8.8.2 contains the result of refinements and stabilization of features and deprecations, cleanups of the internals of the system along with a few new features.

Summary of changes:

Kernel: fix a subject reduction failure due to allowing fixpoints on non-recursive values (#407), by Matthieu Sozeau. Handling of evars in the VM (#935) by Pierre-Marie Pédrot.

Notations: many improvements on recursive notations and support for destructuring patterns in the syntax of notations by Hugo Herbelin.

Proof language: tacticals for profiling, timing and checking success or failure of tactics by Jason Gross. The focusing bracket { supports single-numbered goal selectors, e.g. 2:{, (#6551) by Théo Zimmermann.

Vernacular: cleanup of definition commands (#6653) by Vincent Laporte and more uniform handling of the Local flag (#1049), by Maxime Dénès. Experimental Show Extraction command (#6926) by Pierre Letouzey. Coercion now accepts Prop or Type as a source (#6480) by Arthur Charguéraud. Export modifier for options allowing to export the option to modules that Import and not only Require a module (#6923), by Pierre-Marie Pédrot.

Universes: many user-level and API level enhancements: qualified naming and printing, variance annotations for cumulative inductive types, more general constraints and enhancements of the minimization heuristics, interaction with modules by Gaëtan Gilbert, Pierre-Marie Pédrot and Matthieu Sozeau.

Library: Decimal Numbers library (#6599) by Pierre Letouzey and various small improvements.

Documentation: a large community effort resulted in the migration of the reference manual to the Sphinx documentation tool. The new documentation infrastructure (based on Sphinx) is by Clément Pit-Claudel. The migration was coordinated by Maxime Dénès and Paul Steckler, with some help of Théo Zimmermann during the final integration phase. The 14 people who ported the manual are Calvin Beck, Heiko Becker, Yves Bertot, Maxime Dénès, Richard Ford, Pierre Letouzey, Assia Mahboubi, Clément Pit-Claudel, Laurence Rideau, Matthieu Sozeau, Paul Steckler, Enrico Tassi, Laurent Théry, Nikita Zyuzin.

Tools: experimental -mangle-names option to coqtop/coqc for linting proof scripts (#6582), by Jasper Hugunin. Main changes:

Critical soundness bugs were fixed between versions 8.8.0 and 8.8.2, and a PDF version of the reference manual was made available. The Windows installer also includes many more external packages that can be individually selected for installation.

On the implementation side, the dev/doc/changes.md file documents the numerous changes to the implementation and improvements of interfaces. The file provides guidelines on porting a plugin to the new version.

More information can be found in the CHANGES file. Feedback and bug reports are extremely welcome.

Distribution Installers for Windows 32 bits (i686), Windows 64 bits (x8_64) and macOS are available. They come bundled with CoqIDE. Windows binaries now include the Bignums library.

Complete sources of the files installed by the Windows installers are made available, to comply with license requirements.
NEWS OF THE YEAR: Version 8.8.0 was released in April 2018 and version 8.8.2 in September 2018. This is the third release of Coq developed on a time-based development cycle. Its development spanned 6 months from the release of Coq 8.7 and was based on a public road-map. It attracted many external contributions. Code reviews and continuous integration testing were systematically used before integration of new features, with an important focus given to compatibility and performance issues.

The main advances in this version are cleanups and fixes in the many different components of the system, ranging from low level kernel fixes to advances in the support of notations and tacticals for selecting goals. A large community effort was made to move the documentation to the Sphinx format, providing a more accessible online ressource to users.

- Participants: Abhishek Anand, C. J. Bell, Yves Bertot, Frédéric Besson, Tej Chajed, Pierre Courtieu, Maxime Denes, Julien Forest, Emilio Jesús Gallego Arias, Gaëtan Gilbert, Benjamin Grégoire, Jason Gross, Hugo Herbelin, Ralf Jung, Matej Kosik, Sam Pablo Kuper, Xavier Leroy, Pierre Letouzey, Assia Mahboubi, Cyprien Mangin, Érik Martin-Dorel, Olivier Marty, Guillaume Melquiond, Pierre-Marie Pédrot, Benjamin C. Pierce, Lars Rasmusson, Yann Régis-Gianas, Lionel Rieg, Valentin Robert, Thomas Sibut-Pinote, Michael Soegtrop, Matthieu Sozeau, Arnaud Spiwack, Paul Steckler, George Stelle, Pierre-Yves Strub, Enrico Tassi, Hendrik Tews, Laurent Théry, Amin Timany, Vadim Zaliva and Théo Zimmermann
- Partners: CNRS - Université Paris-Sud - ENS Lyon - Université Paris-Diderot
- Contact: Matthieu Sozeau
- Publication: The Coq Proof Assistant, version 8.8.0
- URL: http://coq.inria.fr/

5.2. Easycrypt

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/

5.3. 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: First public release
NEWS OF THE YEAR: First public release

- Participant: Claudio Sacerdoti Coen
- Contact: Enrico Tassi
- Publications: ELPI: fast, Embeddable, λProlog Interpreter - Implementing Type Theory in Higher Order Constraint Logic Programming
- URL: https://github.com/lpcic/elpi/

5.4. 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: The library includes 16 more theory files, covering in particular field and Galois theory, advanced character theory, and a construction of algebraic numbers.

- 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/

5.5. 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

5.6. Ssreflect

FUNCTIONAL DESCRIPTION: Ssreflect is a tactic language extension to the Coq system, developed by the Mathematical Components team.

- Participants: Assia Mahboubi, Cyril Cohen, Enrico Tassi, Georges Gonthier, Laurence Rideau, Laurent Théry and Yves Bertot
- Contact: Yves Bertot
- URL: http://math-comp.github.io/math-comp/

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

6. New Results

6.1. Extension language for Coq

Participants: Enrico Tassi, Feruccio Guidi [University of Bologna], Claudio Sacerdoti Coen [University of Bologna].

We continued our work on the design of a language mixing λ-prolog and constraint programming. This year, we redesigned and provided a new implementation of the constraint handling rules, leading to a first public release of the software. We are starting to have users beyond our own team:

- (Inria/Parsifal) MLTS https://github.com/voodoos/mlts
- (Inria/Parsifal) proofcert https://github.com/proofcert/checkers
- (UML.eu) Lang-n-play https://github.com/mcimini/lang-n-play

In an article submitted for publication [24], we showed that Elpi could be used to give a short implementation of Type Theory.

We are also starting a collaboration to construct an elaborator for HOL-Light using Elpi.

6.2. Deriving equality tests

Participant: Enrico Tassi.

In type theory, for most inductive types, it is possible to construct a two-argument boolean function that tests when two terms of the type are equal. When inductive types have constructors containing sub-components from another inductive, this needs to be done in a modular way. This year, we studied how this problem could be solved in a modular way using Elpi. It turns out that the unary parametricity translation can serve as a tool to make the derivation compositional. This is described in a pre-print [25].

6.3. Parametricity proofs

Participants: Cyril Cohen, Abishek Anand [Cornell University], Simon Boulier [Inria Gallinette], Matthieu Sozeau [Inria Pi.r2], Nicolas Tabareau [Inria Gallinette], Robert Y. Lewis [Vrije Universiteit Amsterdam], Johannes Hölzl [CMU, Pittsburgh, USA and Vrije Universiteit, Amsterdam, the Netherlands].

After our previous experiment using Elpi to develop a tool that produces parametricity proofs, we investigated the use of the *Template-Coq* framework to implement this kind of algorithm. This work is described in [11]. A similar experiment has been performed using the Lean theorem prover.

6.4. Proving Expected Sensitivity of Probabilistic Programs

Participants: Benjamin Grégoire, Gilles Barthe [IMDEA], Thomas Espitau [UPMC Paris 6], Justin Hsu [University of Pennsylvania], Pierre-Yves Strub [Ecole Polytechnique].

Program sensitivity, also known as Lipschitz continuity, describes how small changes in a program's input lead to bounded changes in the output. We propose an average notion of program sensitivity for probabilistic programs—expected sensitivity—that averages a distance function over a probabilistic coupling of two output distributions from two similar inputs. This work is described in [8].

6.5. An Assertion-Based Program Logic for Probabilistic Programs

Participants: Benjamin Grégoire, Gilles Barthe [IMDEA], Thomas Espitau [UPMC Paris 6], Marco Gaboardi [University at Buffalo, SUNY], Justin Hsu [University of Pennsylvania], Pierre-Yves Strub [Ecole Polytechnique].

We have developed Ellora, a sound and relatively complete assertion-based program logic, and demonstrate its expressivity by verifying several classical examples of randomized algorithms using an implementation in the EasyCrypt proof assistant. Ellora features new proof rules for loops and adversarial code, and supports richer assertions than existing program logics. We also show that Ellora allows convenient reasoning about complex probabilistic concepts by developing a new program logic for probabilistic independence and distribution law, and then smoothly embedding it into Ellora. This is described in article [14].

6.6. Vectorizing Higher-Order Masking

Participants: Benjamin Grégoire, Kostas Papagiannopoulos [Radboud University], Peter Schwabe [Radboud University], Ko Stoffelen [Radboud University].

The cost of higher-order masking as a countermeasure against side-channel attacks is often considered too high for practical scenarios, as protected implementations become very slow. At Eurocrypt 2017, we have proposed the bounded moment leakage model to study the (theoretical) security of parallel implementations of masking schemes. In this work we show how the NEON vector instructions of larger ARM Cortex-A processors can be exploited to build much faster masked implementations of AES based on the bounded moment model. This work is described in publication [18].

6.7. Masking the GLP Lattice-Based Signature Scheme at Any Order

Participants: Benjamin Grégoire, Gilles Barthe [IMDEA], Sonia Belaïd [CryptoExpert], Thomas Espitau [UPMC Paris 6], Pierre-Alain Fouque [Université Rennes 1], Mélissa Rossi [ENS Paris], Mehdi Tibouchi [NTT].

Recently, numerous physical attacks have been demonstrated against lattice based schemes, often exploiting their unique properties such as the reliance on Gaussian distributions, rejection sampling and FFT-based polynomial multiplication. In this work, we describe the first masked implementation of a lattice-based signature scheme. Since masking Gaussian sampling and other procedures involving contrived probability distribution would be prohibitively inefficient, we focus on the GLP scheme. This work is described in [13].

6.8. Symbolic Proofs for Lattice-Based Cryptography

Participants: Benjamin Grégoire, Gilles Barthe [IMDEA], Xiong Fan [Cornell], Joshua Gancher [Cornell], Charlie Jacomme [LSV], Elaine Shi [Cornell].

Symbolic methods have been used extensively for proving security of cryptographic protocols in the Dolev-Yao model, and more recently for proving security of cryptographic primitives and constructions in the computational model. However, existing methods for proving security of cryptographic constructions in the computational model often require significant expertise and interaction, or are fairly limited in scope and expressivity. In this work we introduce a symbolic approach for proving security of cryptographic constructions based on the Learning With Errors assumption. This work is described in [15].

6.9. Formal Security Proof of CMAC and Its Variants

Participants: Benjamin Grégoire, Cécile Baritel-Ruet, François Dupressoir [University of Surrey], Pierre-Alain Fouque [Université Rennes 1].

The CMAC standard, when initially proposed by Iwata and Kurosawa as OMAC1, was equipped with a complex game-based security proof. Following recent advances in formal verification for game-based security proofs, we have formalized a proof of unforgeability for CMAC in EasyCrypt. This work is described in [12].

6.10. Secure Compilation of Side-Channel Countermeasures: The Case of Cryptographic "Constant-Time"

Participants: Benjamin Grégoire, Gilles Barthe [IMDEA], Vincent Laporte [IMDEA].

Software-based countermeasures provide effective mitigation against side-channel attacks, often with minimal efficiency and deployment overheads. Their effectiveness is often amenable to rigorous analysis: specifically, several popular countermeasures can be formalized as information flow policies, and correct implementation of the countermeasures can be verified with state-of-the-art analysis and verification techniques. However, in absence of further justification, the guarantees only hold for the language (source, target, or intermediate representation) on which the analysis is performed. We consider the problem of preserving side-channel counter-measures by compilation for cryptographic “constant-time”, a popular countermeasure against cache-based timing attacks. We have presented a general method, based on the notion of constant-time-simulation, for proving that a compilation pass preserves the constant-time countermeasure. This work was described in [16]. At the conference, this work received the “distinguished paper” award.

6.11. Hypotheses of Decisional Diffie-Hellmann

Participants: Benjamin Grégoire, Mohamad El Laz, Tamara Rezk [Inria, Indes project team].

In the thesis work of Mohamad El Laz, co-supervised by Benjamin Grégoire and Tamara Rezk (Indes project-team), we studied the cryptographic hypothesis of DDH (Decisional Diffie-Hellman) and implementations that would break this hypothesis. We focused on ElGamal encryption cryptosystem implementations to assess they use the DDH hypothesis correctly. We analyzed a number of implementations including Botan, Belenios and Libgcrypt. The lessons learned from this analysis are that the hypotheses are not always well understood.

In a second stage we considered message encoding methods. We investigated several approaches such as DCDH (Decisional Class Diffie-Hellman) in Encoding-Free ElGamal Encryption.

6.12. Proving the domain management protocol

Participants: José Bacelar Almeida [INESC TEC], Manuel Barbosa [INESC TEC], Gilles Barthe [IMDEA], Benjamin Grégoire, Vitor Pereira [INESC TEC], Bernardo Portela [INESC TEC], Benedikt Schmidt [Google Inc.], François-Xavier Standaert [Université Catholique de Louvain], Pierre-Yves Strub [Ecole Polytechnique].

We have performed 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 KMS; it governs the long-term keys that anchor the security of encryption services at AWS. Informally, we show that the protocol securely implements a distributed encryption mechanism. Formally, the proof shows that the domain management protocol is indistinguishable from an ideal encryption functionality under standard cryptographic assumptions.

6.13. Formalized graph theory algorithms

Participants: Cyril Cohen, Laurent Théry, Ran Chen [Chinese Academy of Science], Jean-Jacques Lévy [Inria Pi.r2], Stephan Merz [Inria Veridis].

We formalise the correctness proof of Tarjan's algorithm for computing strongly connected components using the Mathematical Component Library. This leads to a comparison of formalisation between various systems described in [22].

6.14. Formal study of a triangulation algorithm

Participant: Yves Bertot.

In work from 2010, a formal description of Delaunay triangulations was presented where the input was a triangulation not satisfying the Delaunay criterion and where the output was a triangulation satisfying this criterion.

In this work, we wish to complete the previous work by describing an algorithm that produces the initial triangulation. We plan this work in several phases, where the first phase only uses simple data-structures, more advanced structures being introduced only later. This work was presented partially in an invited talk at the ICTAC conference [10].

6.15. Formalizing Bourbaki-style mathematics

Participant: José Grimm.

Most of the work described here is inspired by the experiment of giving formal proofs in Coq of the exercises found in Bourbaki's exposition of set theory. However, some of the results go beyond what can be found in Bourbaki.

We implemented a paper of Sierpinski about properties of continuous ordinal functions and limits of such functions.

We implemented a paper on sums of sequences of ordinals, showing that the value obtained (which depends on the order) lies in a finite set. We also showed that this result does not hold when replacing ordinals by order types.

We implemented a paper by Tarski that says if every infinite cartinal is equal to its square, then every set can be well-ordered (this is the axiom of choice). We had to modify our library to make the use of the axiom of choice more explicit.

We continued implementing in Coq the Exercises of Set Theory of Bourbaki. We solved two of them, and proved by a counter example that three of them are false.

6.16. Formal study of double-word arithmetic algorithms

Participants: Laurence Rideau, Jean-Michel Muller [CNRS and ENS Lyon], Valentina Popescu [CNRS and ENS Lyon], Mioara Joldes [CNRS LAAS].

As part of the ANR Fastrelax project, we are formalizing double-word arithmetic algorithms, in particular the sum of a double-word and a floating point number and the sum of two double-word numbers described in the article " Tight and rigourous error bounds for basic building blocks of double-word arithmetic" [27]. The formalization is progressing, moving from addition to multiplication. The progress is slowed down because minor errors in the informal proofs are regularly uncovered, which requires a dialog with the initial authors.

6.17. Proofs of transcendence

Participants: Sophie Bernard, Yves Bertot, Laurence Rideau.

The work on proofs of transcendence that was started the previous year was completed this year by an effort to integrate generic part of the proofs in the Mathematical Components library. A public package for easy re-use by other researchers was also developed.

6.18. Abel's theorem

Participants: Sophie Bernard, Yves Bertot, Cyril Cohen, Laurence Rideau, Assia Mahboubi [Inria Gallinette], Russell O'Connor [McMaster University].

A natural extension of the work on group theory is a proof that polynomials of degree higher than 5 cannot be solved by radicals. This is known as Abel's theorem. We have started an experiment to give a formal proof of this result on top of the Mathematical Components library.

6.19. Formalizing Hermitian Forms

Participants: Cyril Cohen, Laurence Rideau.

We updated the representation and relevant theorems for bilinear, sesquilinear, and hermitian forms in the Mathematical Components library and updated the archived proof of the odd-order theorem (Feit-Thompson) to use the new presentation. This work also includes a proof of the Spectral Theorem.

6.20. Mathematical Components Analysis

Participants: Cyril Cohen, Damien Rouhling, Reynald Affeldt [AIST Japan], Assia Mahboubi [Inria Gallinette], Pierre-Yves Strub [Ecole Polytechnique].

As a synthesis of the lessons learned in the usage of Mathematical Components and Coquelicot, we develop an extension of the Mathematical Components library to cover questions of analysis. This work includes a new tactic called `near` to handle reasoning steps around limits and filters and little-o notation (following Landau's style of asymptotic reasoning). This work is described in [6]. There also contains a new formalization of topoligical structures, Rolle's theorem, the intermediate value theorem, and Heine Borel's theorem. Ongoing work concentrates on a better design of the topological hierarchy and a simplification of the properties expected from real numbers (following a design by A. Mahboubi and P.-Y. Strub).

Some of this work also includes experiments performed with the LEAN theorem prover (developed at Microsoft Research).

6.21. Rigorous Polynomial Approximation

Participants: Florian Steinberg, Laurent Théry.

We have developed a certified library for computing Chebyshev models for formulas composed of polynomials, exponential, logarithm, and trigonometric function. This work is part of the ANR project FastRelax. The code is available at https://github.com/FlorianSteinberg/Cheby

6.22. Formalization of proofs in control theory

Participants: Damien Rouhling, Cyril Cohen.

Damien Rouhling presented his work on formalizing control theory for an inverted pendulum at an international conference in January [19].

The original development was based on Coquelicot. An analysis of the difficulties in formalizing led to the design of Mathematical Components Analysis. The development on control was then ported to this new library. This work was presented at the Coq Workshop in July.

6.23. Formalizing Cylindrical Algebraic Decomposition

Participants: Boris Djalal, Yves Bertot, Cyril Cohen.

Our study of cylindrical algebraic decomposition requires that we find a good representation of semi-algebraic sets. An article on this topic was published [17]. This is also the one of the main topics of Boris Djalal's thesis, which was defended in December.

6.24. A type theory for Algebraic Structures

Participants: Cyril Cohen, Assia Mahboubi, Xavier Montillet.

In collaboration with members of the Inria Gallinette team, we are investigating the properties that a type theory should enjoy to support algebraic structures better than what is currently available.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

Together with IMDEA Madrid (Spain), INESC TEC (Portugal), the Catholic University of Louvain (Belgium), Google, and Ecole Polytechnique, with have a contract with Amazon Web Services. The financial return for Marelle is 67kEuros.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

We are currently members of four projects funded by the French national agency for research funding.

- TECAP "Analyse de protocoles, Unir les outils existants", starting on October 1st, 20117, 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 Marelle. 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.
- FastRelax, "Fast and Reliable Approximations", started on October 1st, 2014, for 60 months, 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.

8.1.2. FUI

The acronym *FUI* stands for “fonds unique interministériel” and is aimed at research and development projects in pre-industrial phase. The Marelle team is part of one such project.

- VERISICC (formal verification for masking techniques for security against side-channel attacks), This contracts 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 Marelle. A sixth company (Ninjalabs) acts as a sub-contractant. The financial grant for Marelle 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.

8.2. International Research Visitors

8.2.1. Visits of International Scientists

8.2.1.1. Internships

Joshua Gansher from Cornell and Sunjay Cauligi from the University of California at San Diego visited for three months, as part of their PhD training.

Vincent Laporte from IMDEA Madrid visited for 9 months.

Benoît Viguier from Radboud University, Nijmegen visited for 1 month.

8.2.2. Visits to International Teams

Yves Bertot visited AIST in February in Tsukuba, Japan, ITU Copenhagen in April in Copenhagen, Denmark, and the DeepSpec Summer School in July at Princeton University.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. Member of the Organizing Committees

Yves Bertot is member of steering committee for the conferences ITP, CPP and UITP.

Yves Bertot organized the Coq Implementor's Workshop in May in Nice, France, where Cyril Cohen, Maxime Dénès, and Enrico Tassi also brought support to newcomers.

Laurence Rideau Organized a meeting of the ANR FastRelax project in June in Sophia Antipolis. There were presentations by Sophie Bernard, Yves Bertot, Cyril Cohen, Damien Rouhling, Laurent Théry during this meeting.

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

Benjamin Grégoire was a Program Committee member for CSF 2018 and JFLA 2019. Enrico Tassi was a Program Committee member for CPP 2019, ITP 2018, UITP 2018, F-IDE 2018. Laurent Théry was a Program Committee member for AISC, CPP 2019, ITP 2018, and UITP 2018. Yves Bertot was a Program Committee member for AISC, CICM, FMM, and UITP.

9.1.3. Journal

9.1.3.1. Reviewer - Reviewing Activities

Laurent Théry was a reviewer for *Annals of Mathematics and Artificial Intelligence*, *Journal of Applied Logic*, and *Science of Computer Programming*. Cyril Cohen was a reviewer for *Journal of Automated Reasoning* and *Mathematical Structures in Computer Science*. Enrico Tassi was a reviewer for *ACM Transactions on Computational Logic* and *Journal of Automated Reasoning*. Yves Bertot was a reviewer for *Journal of Automated Reasoning*.

9.1.4. Invited Talks

Cyril Cohen gave an invited talk on formalizing robotics in January in Nijmegen, the Netherlands.

Cyril Cohen gave an invited talk on asymptotic reasoning in June in Pittsburgh, USA.

Cyril Cohen gave an invited talk at the workshop *Lean User Group* in November in Freiburg, Germany.

Benjamin Grégoire gave an invited talk at the "journées nationales du GDR sécurité" (national days of the CNRS research group on security) in May in Paris, France.

Benjamin Grégoire gave an invited tutorial at the CHES conference (Cryptographic Hardware and Embedded Systems) in September in Amsterdam, the Netherlands.

Enrico Tassi gave a four-hour tutorial at the EUTypes Summer School in August in Ohrid, Macedonia (https://sites.google.com/view/2018eutypesschool/home)

Enrico Tassi gave an invited talk at the ML workshop in September in Saint Louis, Missouri, USA on "ELPI: an extension language with binders and unification variables".

Yves Bertot gave an invited talk at the ICTAC conference in October in Stellenbosch, South Africa on "Formal Verification of a Geometry Algorithm: A Quest for Abstract Views and Symmetry in Coq Proofs". He also gave a half-day tutorial on Coq.

9.1.5. Leadership within the Scientific Community

We organized two one-week courses on the Coq system, both tagged as entry-level, on Coq and Coq and the Mathematical Components library.

9.1.6. Scientific Expertise

Yves Bertot was part of the review committee for the French *Haut Commissariat pour l'Évaluation de la Recherche et de l'Enseignement Supérieur* for the CNRS laboratory SAMOVAR in Evry, France.

9.1.7. Research Administration

- José Grimm is a member of the local committee for hygiene and work safety.
- Yves Bertot was a member of the "Bureau du comité des projets" until June.
- Benjamin Grégoire is a member of the committee on computer tool usage (CUMI) for the Sophia-Antipolis Méditerranée Inria center.
- Laurence Rideau was a member of the hiring committee for researchers in Sophia Antipolis.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Doctorat: Enrico Tassi organized an advanced school on Coq and the Mathematical Components library, where Laurence Rideau, Cyril Cohen, Laurent Théry, and Yves Bertot gave lectures and supervised laboratory sessions. This school took place in December and had about 20 attendants.

Licence: Sophie Bernard gave 54 hours of lectures on probabilities at University of Nice Sophia Antipolis.

Licence: Damien Rouhling taught about 60 hours at University Nice Sophia Antipolis: differential calculus, Fourier analysis, and C programming (First year students).

Master: Yves Bertot organized a school on Coq in January, Boris Djalal and Damien Rouhling supervised the lab sessions.

Master: Laurent Théry taught 3 hours on "introduction to computer verified proof" at Ecole des Mines de Paris,

Licence: Boris Djalal taught 4 hours of computer science for first year students in a "classe préparatoire aux grandes écoles".

Licence: Cécile Baritel-Ruet taught 30 hours of computer science for first year students at Université de Nice, and some lectures on computer science history.

Licence: Cyril Cohen prepares students for oral examination in a "classe préparatoire aux grandes écoles".

9.2.2. Supervision

- Yves Bertot and Cyril Cohen supervised Boris Djalal, whose doctoral thesis was defended on December 3rd.
- Yves Bertot and Cyril Cohen supervise the doctoral thesis of Damien rouhling.
- 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.

9.2.3. Juries

Enrico Tassi was a member of the Thesis jury for Andrea Gabrielli, in October at the University of Florence, Italy.

Yves Bertot was a member of the Thesis jury for Guillaume Davy, in December at the University of Toulouse and the Institut Supérieur d'Aéronautique et de l'Espace, France.

9.3. Popularization

9.3.1. Interventions

Cyril Cohen presented the work of the Marelle team at a presentation for students coming from Mediterranean regions: Meddays.

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Invited Conferences

[10] Y. BERTOT.*Formal Verification of a Geometry Algorithm: A Quest for Abstract Views and Symmetry in Coq Proofs*, in "ICTAC 2018 - International Colloquium on Theoretical of Computing", Stellenbosch, South Africa, October 2018, https://arxiv.org/abs/1809.00559 , https://hal.inria.fr/hal-01866271

International Conferences with Proceedings

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Team MATHNEURO

Mathématiques pour les Neurosciences

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
Computational Neuroscience and Medicine

Table of contents

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
A6.2.2. - Numerical probability
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 de Nice - Sophia Antipolis, Univ Côte d'Azur, Senior Researcher, HDR]
Simona Olmi [Inria, Starting Research Position, from Feb 2018]
Romain Veltz [Inria, Researcher]

External Collaborator

Daniele Avitabile [University of Nottingham (UK)]

PhD Students

Axel Dolcemascolo [CNRS]
Louisiane Lemaire [Inria, from Oct 2018]
Yuri Rodrigues [Univ Côte d'Azur, from Mar 2018]
Halgurd Taher [Inria, from Nov 2018]

Post-Doctoral Fellows

Benjamin Aymard [Inria]
Emre Baspinar [Inria, from Dec 2018]
Elif Köksal Ersöz [Inria]
Émilie Soret [Inria]

Administrative Assistant

Marie-Cecile Lafont [Inria]

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

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 [51] [52] occurring in the network and which phenomenological parameters control these bifurcations. Another issue concerns the interplay between neuron dynamics and 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 [39] and the study of interacting diffusions [3].

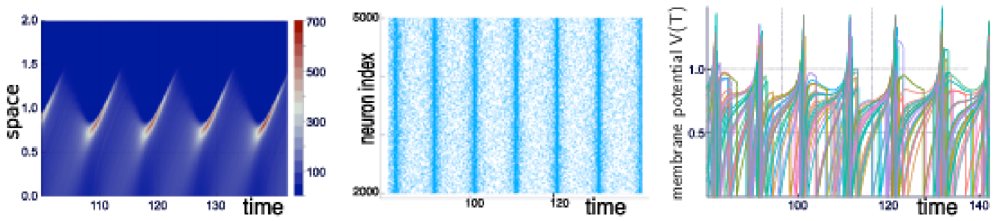

Figure 1. Simulations of the quasi-synchronous state of a stochastic neural network with $N = 5000$ neurons. Left: empirical distribution of membrane potential as a function (t, v). Middle: (raster plot) spiking times as a function of neuron index and time. Right: several membrane potentials $v_i(t)$ as a function of time for $i \in [1, 100]$. Simulated with the Julia Package PDMP.jl from [12]. This figure has been slightly modified from [7].

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 [9], [53], 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 [31], 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 [11], [54]. This theory is based on center manifold and normal forms ideas [10].

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 [44] — and numerical methods such as pseudo-arclength continuation [36]. 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)* [5], [34], [43], which represent an alternation between subthreshold and spiking behaviour, and *bursting oscillations* [35], [41], also corresponding to experimentally observed behaviour [32]; see Figure 2. We are working on extending these results to spatially-extended neural models [2].

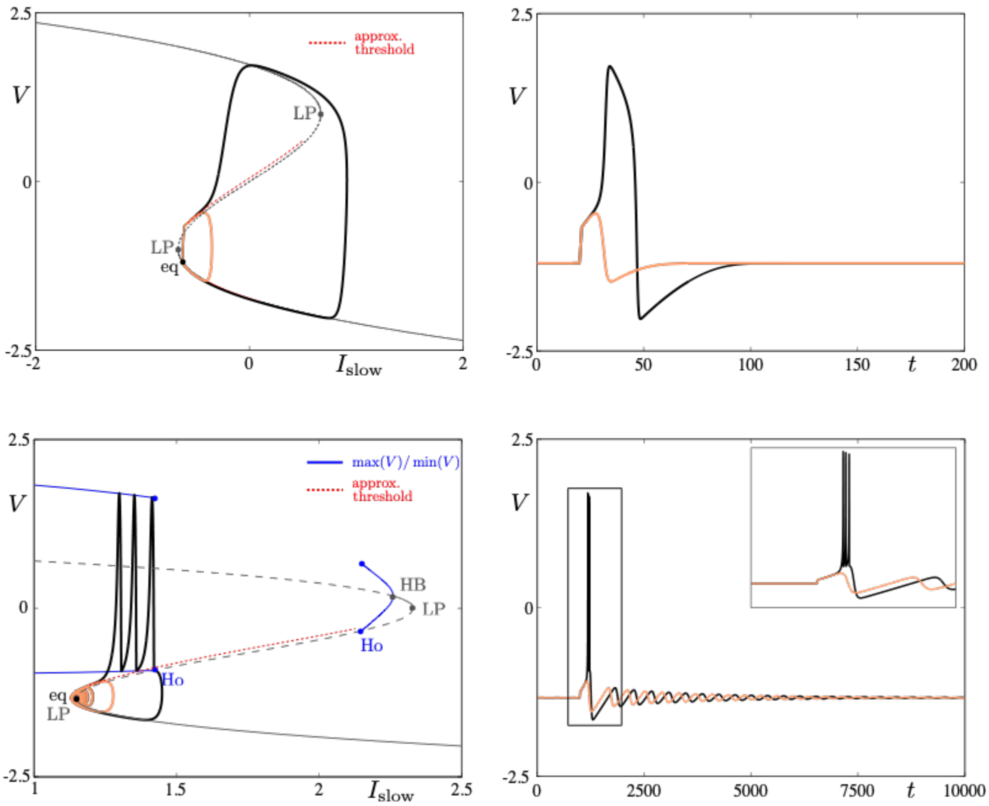

Figure 2. Excitability threshold as slow manifolds in a simple spiking model, namely the FitzHugh-Nagumo model, (top panels) and in a simple bursting model, namely the Hindmarsh-Rose model (bottom panels). This figure is unpublished.

3.5. Modeling neuronal excitability

Excitability refers to the all-or-none property of neurons [38], [42]. 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) [34]. 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, epilepsy or even Alzheimer's Disease. 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 [30]. 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 [4], [8], Hebbian-like or STDP, have strong effects on neuron dynamics complexity, such as synaptic and propagation delays [11], dynamics complexity reduction, and spike statistics.

4. New Results

4.1. Neural Networks as dynamical systems

4.1.1. Latching dynamics in neural networks with synaptic depression

Participants: Elif Köksal Ersöz, Carlos Aguilar [Université de Nice - BCL], Pascal Chossat [Université de Nice - LJAD, Inria MathNeuro], Martin Krupa [Université de Nice - LJAD, UCA, Inria MathNeuro], Frédéric Lavigne [Université de Nice - BCL].

Prediction is the ability of the brain to quickly activate a target concept in response to a related stimulus (prime). Experiments point to the existence of an overlap between the populations of the neurons coding for different stimuli, and other experiments show that prime-target relations arise in the process of long term memory formation. The classical modelling paradigm is that long term memories correspond to stable steady states of a Hopfield network with Hebbian connectivity. Experiments show that short term synaptic depression plays an important role in the processing of memories. This leads naturally to a computational model of priming, called latching dynamics; a stable state (prime) can become unstable and the system may converge to another transiently stable steady state (target). Hopfield network models of latching dynamics have been studied by means of numerical simulation, however the conditions for the existence of this dynamics have not been elucidated. In this work we use a combination of analytic and numerical approaches to confirm that latching dynamics can exist in the context of a symmetric Hebbian learning rule, however lacks robustness and imposes a number of biologically unrealistic restrictions on the model. In particular our work shows that the symmetry of the Hebbian rule is not an obstruction to the existence of latching dynamics, however fine tuning of the parameters of the model is needed.

A natural follow-up of the work which has lead to the article [1] has been initiated through the postdoc project of Elif Köksal Ersöz. The objective is to extend the previous results in several ways. First, to gain more robustness in the heteroclinic chains sustained by the network model. Second, to be able to simulate much larger networks and exhibit heteroclinic dynamics in them. Third, to link with experimental data. The postdoc of Elif Köksal Ersöz, which finished at the end of December 2018, has been funded by the "tail" of the ERC Advanced Grant NerVi held by Olivier Faugeras.

4.1.2. Pseudo-simple heteroclinic cycles in $\mathbb{R}^4$

Participants: Pascal Chossat [Université de Nice - LJAD, Inria MathNeuro], Alexander Lohse [Universität Hamburg, Germany], Olga Podvigina [Institute of Earthquake Prediction Theory and Mathematical Geophysics, Russia].

We study pseudo-simple heteroclinic cycles for a Γ-equivariant system in $\mathbb{R}^4$ with finite $\Gamma \subset O(4)$, and their nearby dynamics. In particular, in a first step towards a full classification – analogous to that which exists already for the class of simple cycles – we identify all finite subgroups of $O(4)$ admitting pseudo-simple cycles. To this end we introduce a constructive method to build equivariant dynamical systems possessing a robust heteroclinic cycle. Extending a previous study we also investigate the existence of periodic orbits close to a pseudo-simple cycle, which depends on the symmetry groups of equilibria in the cycle. Moreover, we identify subgroups $\Gamma \subset O(4)$, $\Gamma\neg \subset SO(4)$, admitting fragmentarily asymptotically stable pseudo-simple heteroclinic cycles (It has been previously shown that for $\Gamma \subset SO(4)$ pseudo-simple cycles generically are completely unstable). Finally, we study a generalized heteroclinic cycle, which involves a pseudo-simple cycle as a subset.

This work has been published in Physica D and is available as [13].

4.1.3. Qualitative stability and synchronicity analysis of power network models in port-Hamiltonian form

Participants: Volker Mehrmann [Technical University of Berlin, Germany], Riccardo Morandin [Technical University of Berlin, Germany], Simona Olmi, Eckehard Schöll [Technical University of Berlin, Germany].

In view of highly decentralized and diversified power generation concepts, in particular with renewable energies, the analysis and control of the stability and the synchronization of power networks is an important topic that requires different levels of modeling detail for different tasks. A frequently used qualitative approach relies on simplified nonlinear network models like the Kuramoto model with inertia. The usual formulation in the form of a system of coupled ordinary differential equations is not always adequate. We present a new energy-based formulation of the Kuramoto model with inertia as a polynomial port-Hamiltonian system of differential-algebraic equations, with a quadratic Hamiltonian function including a generalized order parameter. This leads to a robust representation of the system with respect to disturbances: it encodes the underlying physics, such as the dissipation inequality or the deviation from synchronicity, directly in the structure of the equations, and it explicitly displays all possible constraints and allows for robust simulation methods. The model is immersed into a system of model hierarchies that will be helpful for applying adaptive simulations in future works. We illustrate the advantages of the modified modeling approach with analytics and numerical results.

This work has been published in Chaos and is available as [18].

4.1.4. Collective behavior of oscillating electric dipoles

Participants: Simona Olmi, Matteo Gori [Centre de Physique Théorique, Marseille], Irene Donato [Centre de Physique Théorique, Marseille], Marco Pettini [Centre de Physique Théorique, Marseille].

We investigate the dynamics of a population of identical biomolecules mimicked as electric dipoles with random orientations and positions in space and oscillating with their intrinsic frequencies. The biomolecules, beyond being coupled among themselves via the dipolar interaction, are also driven by a common external energy supply. A collective mode emerges by decreasing the average distance among the molecules as testified by the emergence of a clear peak in the power spectrum of the total dipole moment. This is due to a coherent vibration of the most part of the molecules at a frequency definitely larger than their own frequencies corresponding to a partial cluster synchronization of the biomolecules. These results can be verified experimentally via spectroscopic investigations of the strength of the intermolecular electrodynamic interactions, thus being able to test the possible biological relevance of the observed macroscopic mode.

This work has been published in Scientific Reports and is available as [19].

4.1.5. Controlling seizure propagation in large-scale brain networks

Participants: Simona Olmi, Spase Petkoski [Institut de Neurosciences des Systèmes, Marseille], Maxime Guye [Centre d'Exploration Métabolique par Résonance Magnétique, Marseille], Fabrice Bartolomei [Epilepsies, Lésions Cérébrales et Systèmes Neuraux de la Cognition, 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 submitted for publication and is available as [28].

4.1.6. Effect of disorder and noise in shaping the dynamics of power grids

Participants: Liudmila Tumash [Technical University of Berlin, Germany], Simona Olmi, Eckehard Schöll [Technical University of Berlin, Germany].

The aim of this paper is to investigate complex dynamic networks which can model high-voltage power grids with renewable, fluctuating energy sources. For this purpose we use the Kuramoto model with inertia to model the network of power plants and consumers. In particular, we analyse the synchronization transition of networks of N phase oscillators with inertia (rotators) whose natural frequencies are bimodally distributed, corresponding to the distribution of generator and consumer power. First, we start from globally coupled networks whose links are successively diluted, resulting in a random Erdös-Renyi network. We focus on the changes in the hysteretic loop while varying inertial mass and dilution. Second, we implement Gaussian white noise describing the randomly fluctuating input power, and investigate its role in shaping the dynamics. Finally, we briefly discuss power grid networks under the impact of both topological disorder and external noise sources.

This work has been published in Europhysics Letters and is available as [20].

4.2. Mean field theory and stochastic processes

4.2.1. Emergence of collective phenomena in a population of neurons

Participants: Benjamin Aymard, Fabien Campillo, Romain Veltz.

In this work, we propose a new model of biological neural network, combining a two-dimensional integrate-and-fire neuron model with a deterministic model of electrical synapse, and a stochastic model of chemical synapse. We describe the dynamics of a population of neurons in interaction as a piecewise deterministic Markov process. We prove the weak convergence of the associated empirical process, as the population size tends to infinity, towards a McKean-Vlasov type process and we describe the associated PDE. We are also interested in the simulation of these dynamics, in particular by comparing "detailed" simulations of a finite population of neurons with a simulation of the system with infinite population. Benjamin Aymard has the adapted toolkit to attack these questions numerically. The mean field equations studied by Benjamin are of transport type for which numerical methods are technical. However, they are the domain of expertise of Benjamin. His postdoc is funded by the Flagship Human Brain Project.
Latest results are as follows. A first manuscript concerning the numerical simulation of the mean field model is in preparation. We managed to find a new numerical scheme which is positive, semi-implicit and adaptive in time (of order 2). A second manuscript concerning the existence of stationary distribution for the mean field limit is also in preparation.

4.2.2. 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 dynamic 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 submitted for publication and is available as [24].

4.2.3. Exponential stability of the stationary distribution of a mean field of spiking neural network

Participants: Audric Drogoul [Thales, France], Romain Veltz.

In this work, we study the exponential stability of the stationary distribution of a McKean-Vlasov equation, of nonlinear hyperbolic type which was recently derived in [33], [40]. We complement the convergence result proved in [40] using tools from dynamical systems theory. Our proof relies on two principal arguments in addition to a Picard-like iteration method. First, the linearized semigroup is positive which allows to precisely pinpoint the spectrum of the infinitesimal generator. Second, we use a time rescaling argument to transform the original quasilinear equation into another one for which the nonlinear flow is differentiable. Interestingly, this convergence result can be interpreted as the existence of a locally exponentially attracting center manifold for a hyperbolic equation.

This work has been submitted for publication and is available as [23].

4.2.4. On a toy network of neurons interacting through their dendrites

Participants: Nicolas Fournier Cormier [LPSM, Sorbonne Université, Paris], 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 $w_n \simeq N1/2$. We make use of some recent versions of the results of Deuschel and Zeitouni [37] 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 submitted for publication and is available as [26].

4.2.5. *Mathematical statistical physics applied to neural populations*

Participants: Émilie Soret, Olivier Faugeras, Étienne Tanré [Inria, project-team TOSCA, Sophia-Antipolis].

This project focuses on Mean-Field descriptions or thermodynamics limits of large populations of neurons. They study a system of Stochastic Differential Equations (SDEs) which describes the evolution of membrane potential of each neuron over the time when the synaptic weights are random variables (not assumed to be independent). This setup is well suited to Émilie, who has worked during her PhD and first postdoc on mathematical statistical physics and stochastic processes. Her postdoc is funded by the Flagship Human Brain Project. A manuscript is in preparation.

4.3. Neural fields theory

4.3.1. *A neural field model for color perception unifying assimilation and contrast*

Participants: Anna Song [ENS Paris, France], Olivier Faugeras, Romain Veltz.

We propose a neural field model of color perception in context, for the visual area V1 in the cortex. This model reconciles into a common framework two opposing perceptual phenomena, simultaneous contrast and chromatic assimilation. Previous works showed that they act simultaneously, and can produce larger shifts in color matching when acting in synergy with a spatial pattern. At some point in an image,the color perceptually seems more similar to that of the adjacent locations, while being more dissimilar from that of remote neighbors. The influence of neighbors hence reverses its nature above some characteristic scale. Our model fully exploits the balance between attraction and repulsion in color space, combined at small or large scales in physical space. For that purpose we rely on the opponent color theory introduced by Hering, and suppose a hypercolumnar structure coding for colors. At some neural mass, the pointwise influence of neighbors is spatially integrated to obtain the final effect that we call a color sensation. Alongside this neural field model, we describe the search for a color match in asymmetric matching experiments as a mathematical projector. We validate it by fitting the parameters of the model to data from [45] and [46] and our own data. All the results show that we are able to explain the nonlinear behavior of the observed shifts along one or two dimensions in color space, which cannot be done using a simple linear model.

This work has been submitted for publication and is available as [29].

4.4. Slow-fast dynamics in Neuroscience

4.4.1. *Spike-adding in a canonical three time scale model: superslow explosion & folded-saddle canards*

Participants: Mathieu Desroches, Vivien Kirk [University of Auckland, New-Zealand].

We examine the origin of complex bursting oscillations in a phenomenological ordinary differential equation model with three time scales. We show that bursting solutions in this model arise from a Hopf bifurcation followed by a sequence of spike-adding transitions, in a manner reminiscent of spike-adding transitions previously observed in systems with two time scales. However, the details of the process can be much more complex in this three-time-scale context than in two-time-scale systems. In particular, we find that spike-adding can involve canard explosions occurring on two different time scales and is associated with passage near a folded-saddle singularity. We show that the character of the bursting and the form of spike-adding transitions that occur depend on the geometry of certain singular limit systems, specifically the relative positions of the critical and superslow manifolds. We also show that, unlike the case of spike-adding in two-time-scale systems, the onset of a new spike in our model is not typically associated with a local maximum in the period of the bursting oscillation.

This work has been published in SIAM Journal on Applied Dynamical Systems and is available as [14].

4.4.2. Parabolic bursting, spike-adding, dips and slices in a minimal model

Participants: Mathieu Desroches, Jean-Pierre Françoise [LJLL, Sorbonne Université, Paris], Martin Krupa [Université de Nice - 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 1-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 submitted for publication and is available as [25].

4.4.3. Piecewise-linear (PWL) canard dynamics : Simplifying singular perturbation theory in the canard regime using piecewise-linear systems

Participants: Mathieu Desroches, Soledad Fernández-García [University of Sevilla, Spain], Martin Krupa [Université de Nice - LJAD, UCA, Inria MathNeuro], Rafel Prohens [University of the Balearic Islands, Spain], Antonio E. Teruel [University of the Balearic Islands, Spain].

In this work we have gathered recent results on piecewise-linear (PWL) slow-fast dynamical systems in the canard regime. By focusing on minimal systems in $\mathbb{R}^2$ (one slow and one fast variables) and $\mathbb{R}^3$ (two slow and one fast variables), we prove the existence of (maximal) canard solutions and show that the main salient features from smooth systems is preserved. We also highlight how the PWL setup carries a level of simplification of singular perturbation theory in the canard regime, which makes it more amenable to present it to various audiences at an introductory level. Finally, we present a PWL version of Fenichel theorems about slow manifolds, which are valid in the normally hyperbolic regime and in any dimension, which also offers a simplified framework for such persistence results.

This work has been published as a chapter in the book "Nonlinear Systems, Vol. 1: Mathematical Theory and Computational Methods" published by Springer as part of the Understanding Complex Systems book series, and it is available as [22].

4.4.4. Anticipation via canards in excitable systems

Participants: Elif Köksal Ersöz, 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 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-receiver follow the evolution of a multi-scale excitable system. We present a novel theoretical view point 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-dimentional 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 to a wider class of excitable systems with appropriate theoretical extensions. Anticipation appears as a counter-intuitive observation in a wide range of dynamical systems ranging from biology to engineering applications. It can occur in unidirectionally coupled systems when the receiver is subject to a self-delayed feedback in addition to a signal coming from the sender. This particular interaction permits the receiver to predict the future trajectory of the sender. Anticipation can occur transiently, thus straightforwardly denoted anticipation, or in long-term dynamics, in which case it is referred to as anticipated synchronization. In this study, we focus on both aspects of anticipatory dynamics in the context of excitable systems and explain it via a counter-intuitive phenomenon, namely canards. Canard trajectories structure the excitability and synchronization properties of multiple timescale systems exhibiting excitable dynamics. By developing a theoretical framework enhanced by numerical continuation, we show that the underlying canard structure in excitable systems is responsible for delaying sub-threshold solutions, but anticipating the spiking ones. We also propose an experimental set up that would enable experimentalists to observe anticipated behavior in neural systems, in particular in type-II neurons.

This work has been accepted for publication in Chaos and is available as [17].

4.4.5. *Canard-induced complex oscillations in an excitatory network*

Participants: Elif Köksal Ersöz, Mathieu Desroches, Antoni Guillamon [Polytechnic University of Catalunya, Spain], 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 [50]. The dynamics is that of a classical square-wave burster, with alternation of silent and active phases. Tabak et al. [50] 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 [47], [48], [49] 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 [50] 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 [6]. Finally, we relateed 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 [49].

This work is in progress and is available as [27].

4.4.6. *High-frequency forced oscillations in neuronlike elements*

Participants: Denis Zakharov [Institute of Applied Physics RAS, Russia], Martin Krupa [Université de Nice - LJAD, UCA, Inria MathNeuro], Boris Gutkin [Group for Neural Theory, ENS Paris, France], Alexey Kuznetsov [Indiana University - Purdue University Indianapolis, USA].

We analyzed a generic relaxation oscillator under moderately strong forcing at a frequency much greater that the natural intrinsic frequency of the oscillator. Additionally, the forcing is of the same sign and, thus, has a nonzero average, matching neuroscience applications. We found that, first, the transition to high-frequency synchronous oscillations occurs mostly through periodic solutions with virtually no chaotic regimes present. Second, the amplitude of the high-frequency oscillations is large, suggesting an important role for these oscillations in applications. Third, the 1:1 synchronized solution may lose stability, and, contrary to other cases, this occurs at smaller, but not at higher frequency differences between intrinsic and forcing oscillations. We analytically built a map that gives an explanation of these properties. Thus, we found a way to substantially "overclock" the oscillator with only a moderately strong external force. Interestingly, in application to neuroscience, both excitatory and inhibitory inputs can force the high-frequency oscillations.

This work has been published in Physical Review E and is available as [21].

5. Partnerships and Cooperations

5.1. European Initiatives

5.1.1. FP7 Projects

5.1.1.1. 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.

5.2. International Research Visitors

5.2.1. Visits of International Scientists

Invitation of Andrey Shilnikov, Georgia State University (USA), January 2018

Invitation of Jean-Pierre Françoise, Sorbonne Université (Paris), April 2018

Invitation of Vivien Kirk, University of Auckland (New Zealand), May 2018

Invitation of Peter De Maesschalck, University of Hasselt (Belgium), June 2018

5.2.2. Visits to International Teams

Visit of Mathieu Desroches to Jean-Pierre Françoise (LJLL, Sorbonne Université, Paris) in October 2018

5.2.2.1. 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 2018

6. Dissemination

6.1. Promoting Scientific Activities

6.1.1. Scientific Events Organisation

6.1.1.1. Member of the Organizing Committees

Olivier Faugeras and Romain Veltz were on the Advisory Board of the 4th International Conference on Mathematical Neuroscience, held in Antibes Juan les Pins (France), June 11 - 13, 2018.

6.1.2. Scientific Events Selection

6.1.2.1. Member of the Conference Program Committees

Mathieu Desroches was on the Program Committee of the 4th International Conference on Mathematical Neuroscience, held in Antibes Juan les Pins (France), June 11 - 13, 2018.

Mathieu Desroches was on the Scientific Committe of the 2nd International workshop in Neurodynamics (Ndy'18), held in Castro-Urdiales (Spain), September 26-29, 2018.

6.1.3. Journal

6.1.3.1. Member of the Editorial Boards

Olivier Faugeras is the co-editor in chief of the open access Journal of Mathematical Neuroscience. This journal has obtained in 2018 an Impact Factor of 2.4.

6.1.3.2. 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, 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.

6.1.4. Invited Talks

Pascal Chossat, "Stability of Simple and Pseudo Simple Heteroclinic Cycles in $\mathbb{R}^4$", Perspectives in Nonlinear Science Workshop, Cargese (France), March 2018.

Pascal Chossat, "Computational aspects of equivariant bifurcation theory", Colloque *Symmetry and Computation*, CIRM (France), April 2018.

Pascal Chossat, "Geometry in neurosciences: the example of the visual cortex" (plenary talk), *Systèmes dynamiques et systèmes complexes - Une conférence pour célébrer les 60 ans de Jean-Marc Gambaudo*, Nice (France), Juin 2018.

Pascal Chossat, "Perception of images by the visual cortex: geometry in neuroscience" (plenary talk), *VI Iberoamerican meeting Geometry, Mechanics and Control*, Guanajuato (Mexico), August 2018.

Pascal Chossat, “Transitions de phase dans le plan hyperbolique, application à la détection des textures par le cortex visuel primaire”, Colloque *Géométrie et représentation de la couleur*, UPMC, November 2018.

Mathieu Desroches, “Canards and spike-adding in neural bursters”, MURPHYS-HSFS-2018 meeting, CRM, Barcelona (Spain), May 2018.

Mathieu Desroches, “Three-Timescale Dynamics: Canards and Spike Adding”, New Trends in Mathematical Biology, CRM, Barcelona (Spain), June 2018.

Olivier Faugeras, “Predicting neuronal correlations in large size networks based on meanfield analysis”, Workshop *Mean-field Approaches to the Dynamics of Neuronal Networks*, EITN, Paris (France), January 2018.

Olivier Faugeras, “Neural networks do not become asynchronous in the large size limit when synaptic weights are correlated: there is no propagation of chaos”, Worshop *InSpire – New Insights on Complex Neural Dynamics*, , Cergy (France), June 2018.

Olivier Faugeras, “Neural networks do not become asynchronous in the large size limit: there is no propagation of chaos”, ICMNS 2018, Antibes (France), June 2018.

Elif Köksal Ersöz, “Anticipation via canards”, MURPHYS-HSFS-2018 meeting, CRM, Barcelona (Spain), May 2018.

Elif Köksal Ersöz, “Anticipation via canards in excitable systems”, XXIII National Conference on Statistical Physics and Complex Systems, Parma (Italy), June 2018.

Elif Köksal Ersöz, “Canard mediated mixed-mode bursting oscillations in a rate model”, European Conference on Mathematical and Theoretical Biology (ECMTB 2018), Lisbonne (Portugal), July 2018.

Elif Köksal Ersöz, “Canard mediated mixed-mode bursting oscillations in a rate model”, 2nd International workshop in Neurodynamics (Ndy’18), Castro-Urdiales (Spain), September 2018.

Martin Krupa, “Heteroclinic chains in a model of associative memory”, Systèmes dynamiques et systèmes complexes - Une conférence pour célébrer les 60 ans de Jean-Marc Gambaudo, Nice (France), June 2018.

Romain Veltz, “On a toy network of neurons interacting through nonlinear dendritic compartments”, ICMNS 2018, invited talk, June 2018.

Romain Veltz, “On a toy network of neurons interacting through nonlinear dendritic compartments”, Mean-field approaches to the dynamics of neuronal networks, EITN, 2018.

Romain Veltz, “On a toy network of neurons interacting through nonlinear dendritic compartments”, Systèmes dynamiques et systèmes complexes - Une conférence pour célébrer les 60 ans de Jean-Marc Gambaudo, Nice (France), June 2018.

Romain Veltz, “Models of neurons interacting through nonlinear dendritic compartments”, Séminaire de Probabilités et Statistique, LJAD, Université de Nice Sophia Antipolis, October 2018.

6.1.5. Scientific Expertise

Fabien Campillo was member of the local committee in charge of the scientific selection of visiting scientists (Comité NICE)

Fabien Campillo was member of the HCERES visiting committee for the evaluation of the INRA Research Unit MAIAGE.

Fabien Campillo was member of the visiting committee of the LIRIMA International Laboratory.

Mathieu Desroches was on the Advisory Board of the Complex Systems Academy of the UCA$^{\mathrm{JEDI}}$ Idex.

Olivier Faugeras made a presentation in front of the CCNE (Comité Consultatif National d’Ethique) reporting on the work made by the group “éthique et IA” that he was the president of at the *Académie des Sciences de Paris* in preparation of their revision of the law on bioethics.

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 2018, Jean Ponce, Stéphane Mallat and Francis Bach. This study group has also produced a report for the 2019 G7 meeting.

6.2. Teaching - Supervision - Juries

6.2.1. Teaching

Chalk-learning

Master 2 MVA/UPMC: Romain Veltz, Mathematical Methods for Neurosciences, 20 hours, Paris, France.

Master 1 BIM/UPMC: Mathieu Desroches, Modèles Mathématiques et Computationnels en Neuroscience (Lectures and example classes), 20 hours, Paris, France.

Master 1 BIM/UPMC: Elif Köksal Ersöz, Modèles Mathématiques et Computationnels en Neuroscience (Labs), 10 hours, Paris, France.

Mini-course (Master’s level), Basque Center for Applied Mathematics: Mathieu Desroches (together with Serafim Rodrigues), Introduction to mathematical neuroscience: neuronal models and their bifurcations, 10 hours, Bilbao, Spain.

6.2.2. Supervision

PhD in progress: Axel Dolcemascolo, “All optical neuromimetic devices”, started in January 2016, co-supervised by Romain Veltz and Stéphane Barland (INLN). Successfully defended on 14 December 2018.

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: 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: Quentin Cormier, “Biological spiking neural networks", started in September 2017, 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).

6.2.3. Juries

Mathieu Desroches was president of the Jury of the PhD of Dora Karvouniari (Inria Biovision Team) entitled “Mathematical modeling of retinal waves”, Inria Sophia Antipolis, 15 March 2018.

Pascal Chossat was jury member for the HDR of Philippe Beltrame, Université d’Avignon, 30 November 2018.

Romain Veltz was Examiner for A. Dolcemascolo’s PhD thesis defence entitled "Semiconductor lasers to model and control cells and excitable networks", which took place on 14 December 2018.

6.3. Popularization

6.3.1. Interventions

National events: Romain Veltz participated at the conference "Fête de la Science".

6.3.2. Internal action

Romain Veltz gave a talk at "Café des sciences" about "Vers un modèle de synapse excitatrice"

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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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Project-Team MCTAO

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B5.2.3. - Aviation
B5.2.4. - Aerospace
B5.6. - Robotic systems

1. Team, Visitors, External Collaborators

Research Scientists

Jean-Baptiste Pomet [Team leader, Inria, Senior Researcher, HDR]
Lamberto Dell'Elce [Inria, Researcher, since Nov 2018]
Laetitia Giraldi [Inria, Researcher]

Faculty Members

Bernard Bonnard [Université de Bourgogne, Professor, HDR]
Jean-Baptiste Caillau [Université Côte d'Azur, Professor, HDR]
Pierre Lissy [Université Paris-Dauphine, Associate Professor, on leave at Inria until Jun 2018]
Ludovic Rifford [Université de Nice - Sophia Antipolis, Professor, HDR]
Gilles Lebeau [Université Côte d'Azur, Professor, on leave at Inria since Sep 2018, HDR]

External Collaborators

Thierry Dargent [Thales Alenia Space, Engineer]
Joseph Gergaud [ENSEEIHT Toulouse, Professor]
Jérémy Rouot [EPF Troyes, Associate Professor]

PhD Students

Luca Berti [Université de Strasbourg, since Oct 2018]

Yacine El Alaoui-Faris [Inria]
Sébastien Fueyo [Inria]
Clément Moreau [Ecole Normale Supérieure Cachan]
Michael Orieux [Université Paris-Dauphine]
Agustin Yabo [Université Côte d'Azur, since Oct 2018]

Post-Doctoral Fellows
Lamberto Dell'Elce [Inria, until Aug 2018]
Walid Djema [Inria]

Visiting Scientist
Zeinab Badreddine [Université de Bourgogne, until Jul 2018]

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. 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 [70], [47], [37], 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 [61], [72].

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 [69] of dynamic feedback and the so-called "flatness" property [64].

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 [74], [38], [39] 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]).

Recently, computation of conjugate points was conducted in [6], [5] to determine the optimality status in swimming at low Reynolds number; because of symmetries, and of the periodicity constraint, a tailor-made notion of conjugate point had to be used, see more in [65]. 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 [36]. 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, see section 10.1.1.

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 [63], [62]. 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 [68] 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 [4], 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 [40], [73].

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 ([40], [73]) 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 [78], [65] 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 [78], [65].

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 [77]).

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.

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 [67], 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 [12] 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

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)

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 Hampath 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

Following the historical reference for low Reynolds number locomotion [71], 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 [5], [76], 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, play an important role in locomotion.

4.4. Stability of high frequency amplifiers

Nonlinear hyper-frequency amplifiers are ubiquitous in cell phone relays and many other devices. They must be as compact as possible, yielding 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).

Some techniques do exist (see a state of the art in [75]). They are pioneering but mildly reliable and not clearly mathematically grounded. Potential transfer is important.

This is the topic of an ongoing collaboration between McTAO and the project-team APICS. See results in section 7.15.

5. Highlights of the Year

5.1. Highlights of the Year

Let us mention two events

- Lamberto Dell'Elce was hired as a permanent researcher in 2018. This is not a scientific achievement in itself, but it is an important point in the life of a research team.
- Alessio Figalli recieved a Fields Medal at ICM 2018 in Rio. He is a close collaborator of Ludovic Rifford, member of the team.

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. Well posedness in Optimal Transport

Participants: Zeinab Badreddine, Ludovic Rifford, Robert Mccann [Univ of Toronto, Canada], Abbas Moameni [Carleton Univ, Ottawa, Canada].

Concerning the Kantorovitch problem, in continuation of the work by McCann and Rifford [67], Moameni and Rifford have studied (see [12]) some conditions on the cost which are sufficient for the uniqueness of optimal plans (provided that the measures are absolutely continuous with respect to the Lebesgue measure). As a by-product of their results, the authors show that the costs which are uniquely minimizing for the Kantorovitch problem are dense in the C^0-topology. Many others applications and examples are investigated.

Concerning the Monge problem in the sub-Riemannian setting, Zeinab Badreddine [2] obtained the first result of well-posedness in cases where singular minimizing curves may be present. This study is related to the so-called measure contraction property. In collaboration with Rifford [22], Badreddine obtained new classes of sub-Riemannian structures satisfying measure contraction properties.

7.2. Strong Sard conjecture for sub-Riemannian structures

Participants: Ludovic Rifford, André Belotto Da Silva [Université Aix-Marseille, France], Alessio Figalli [ETH, Swizerland], Adam Parusinski [Université Côte d'Azur, France].

In [25], we address the strong Sard conjecture for sub-Riemannian structures on 3-dimensional analytic manifolds. More precisely, given a totally non-holonomic analytic distribution of rank 2 on a 3-dimensional analytic manifold, we investigate the size of the set of points that can be reached by singular horizontal paths starting from a given point and prove that it has Hausdorff dimension at most 1. In fact, this set is a semi-analytic curve, provided that the lengths of the singular curves under consideration are bounded with respect to a given complete Riemannian metric. As a consequence, combining these techniques with recent developments on the regularity of sub-Riemannian minimizing geodesics, we prove that minimizing sub-Riemannian geodesics in 3-dimensional analytic manifolds are always of class C1, and actually are analytic outside of a finite set of points. This paper can be seen as a major step toward a proof of the Sard conjecture in any dimension.

This is a drastic improvement of the results published in [4] (appeared this year), that proved a slightly weaker property for a less general class of systems.

7.3. Optimal approximation of internal controls for a wave-type problem with fractional Laplacian using finite-difference method

Participants: Pierre Lissy, Ionel Roventa [University of Craiova, Romania].

In paper [30], a finite-difference semi-discrete scheme for the approximation of internal controls of a one-dimensional evolution problem of hyperbolic type involving the spectral fractional Laplacian is considered. The continuous problem is controllable in arbitrary small time. However, the high frequency numerical spurious oscillations lead to a loss of the uniform (with respect to the mesh size) controllability property of the semi-discrete model in the natural setting. For all initial data in the natural energy space, if we filter the high frequencies of these initial data in an optimal way, the uniform controllability property in arbitrary small time is restored. The proof is mainly based on a (non-classic) moment method.

7.4. Singularities in minimum time control

Participants: Jean-Baptiste Caillau, Michaël Orieux, Jacques Féjoz [Univ. Paris Dauphine], Robert Roussarie [Univ. Bourgogne-Franche Comté].

We analyze singularities arising in minimum time systems. Consider a control affine system in dimension four with control on the disc such that the controlled fields together with their first order Lie brackets with the drift have full rank. There is a natural stratification of the codimension two singular set in the cotangent bundle leading to a local classification of extremals in terms of singular and bang arcs. This analysis was done in [56] using the nilpotent model, and extended in [35] by interpreting the singularities of the extremal flow as equilibrium points of a regularized dynamics to prove the continuity of the flow. After a suitable blow-up, one can actually treat these singularities as connections of pairs of normally hyperbolic invariant manifolds in order to find a suitable stratification of the flow and prove finer regularity properties. Another issue is to be able to give global bounds on the number of these heteroclinic connections. This can be done by means of *à la Sturm* estimations. This work is part of the PhD thesis of Michaël Orieux [1] and is described in the preprint [28]. In an ongoing work, we also investigate second order sufficient conditions for extremals with such singularities.

7.5. Software advances

Participants: Jean-Baptiste Caillau, Olivier Cots [Univ. Toulouse], Lamberto Dell'Elce, Thibaud Kloczko, Pierre Martinon [COMMANDS team], Jean-Baptiste Pomet.

McTAO and COMMANDS have been awarded an AMDT (Action Mutualisée de DéveloppemenT) funding of two years to develop a common interface for *Hampath* and BOCOP. This AMDT, coined `ct` for "Control tools" is to start in January 2019. Our midterm goal is to set the standard for the numerical resolution of optimal control problems. On the basis of the two well established codes BOCOP and *Hampath* from the optimal control community, thanks to this ADT we want to design a high-level modular architecture in order to:

- interoperate BOCOP and *Hampath*,
- offer a high-level common user interface for the two codes.

Another expected outcome of the ADT is to integrate state of the art processes into the development of the two solvers (collaborative dev tools, reliable repositories, continuous integration...)

7.6. Averaging optimal control problems with two frequencies

Participants: Jean-Baptiste Caillau, Lamberto Dell'Elce, Jean-Baptiste Pomet.

Averaging is a valuable technique to gain understanding in the long-term evolution of fast-oscillating dynamical systems. Recent contributions (pioneered by McTAO members in the framework of a long-standing project funded by CNES and Thales Alenia Space) proved that averaging can be applied to the extremal flow of optimal control problems. This study extends the aforementioned results by tackling averaging of time optimal systems with two fast variables with particular emphasis on the treatment of adjoint variables and on the understanding of resonance effects on their dynamics. The chapter [18] details part of this work, and a dedicated paper is in preparation [29].

7.7. Integrability properties of the controlled Kepler problem

Participants: Jean-Baptiste Caillau, Michaël Orieux, Jacques Féjoz [Univ. Paris Dauphine], Robert Roussarie [Univ. Bourgogne-Franche Comté].

We prove, using Moralès–Ramis theorem, that the minimum-time controlled Kepler problem is not meromorphically integrable in the Liouville sense on the Riemann surface of its Hamiltonian. The Kepler problem is a classical reduction of the two-body problem. We think of the Cartesian coordinate as being the position of a spacecraft, and of the attraction as the action of the Earth. We are interested in controlling the transfer of the spacecraft from one Keplerian orbit towards another one, in the plane. By virtue of Pontrjagin maximum principle, the minimum time dynamics is a Hamiltonian system. The controlled Kepler problem can be embedded in the two parameter family obtained when considering the control of the circular restricted three-body problem. In the uncontrolled model, it is well known that the Kepler case is integrable and geodesic (there exists a Riemannian metric such that Keplerian curves are geodesics of this metric), while there are obstructions to integrability for positive ratio of masses. In the controlled case, the Kepler problem for the energy cost has been shown to be integrable (and geodesic) when suitably averaged. The aim of this work is to study the integrability properties of the Kepler problem for time minimization. The pioneering work of Ziglin in the 80s, followed by the modern formulation of differential Galois theory in the late 90s by Moralès, Ramis and Simó, have led to a very diverse literature on the integrability of Hamiltonian systems. According to Pontrjagin Maximum principle, one can turn general optimization problems with dynamical constraints into Hamiltonian systems, which are generally not everywhere differentiable. Optimal control theory thus provides an abundant class of dynamical systems for which integrability is a central question. Yet, differential Galois theory has not so often been applied in this context, in part because of the difficulty brought by the singularities. Notwithstanding theses singularities, we show how to apply these ideas to the Kepler system, and prove that it is not meromorphically integrable in the Liouville sense on the Riemann surface of its Hamiltonian. This work is also part of the PhD thesis of Michaël Orieux [1] and is described in the paper [11].

7.8. Quasi-satellite orbits in the proximity of Martian moons

Participants: Lamberto Dell'Elce, Nicola Baresi [JAXA, Japan], Josué Cardoso Dos Santos [Sao Paolo State University, Brasil], 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 investigates the navigability of mid- and high-altitude QSOs in terms of relative orbit elements. After developing an analytical model for the long-term evolution of QSOs and a numerical map between mean and osculating (instantaneous) orbital elements, we use a Lyapunov control law for orbit maintenance purposes based on mean relative orbit element differences. These results were presented in [16] and they pave the way for a perspective collaboration between JAXA and McTAO.

7.9. The Copepod and Purcel swimmer

Participants: Bernard Bonnard, Jérémy Rouot, Piernicola Bettiol, Monique Chyba [U. Hawaii].

In the continuation to J. Rouot Phd thesis (2016), our results are presented in a series of papers [7], [5], [6]. The most efficient strokes are computed using geometric studies and numerical simulations, in relation with sub-Riemannian geometry and periodic optimal control algorithms. In the copepod case the model is validated by simulations and a copepod robot was constructed at Hawaii to mimic the copepod. The experiment was reproduced at EPF Troyes under the supervision of J. Rouot. The reference [21] gathers the results of MRI and swimmers in a unified setting combining geometric and numeric techniques developed in McTAO.

7.10. Multi-link vs flexible filament swimmers

Participants: Laetitia Giraldi, Clément Moreau, Jean-Baptiste Pomet, Hermes Gadhêla [Univ. of York, United Kingdom].

The inertialess fluid-structure interactions of active or passive inextensible filaments and slender-rods are ubiquitous in nature, from the dynamics of semi-flexible polymers and cytoskeletal filaments to cellular mechanics and flagella, or in artificial micro-swimmers (see Section 7.12).

For a microscopic inextensible elastic filament immersed into a fluid, even approximating the fluid-structure interaction by the Resistive Force Theory formulation, the system of PDEs resulting from elastohydrodynamical laws is structurally convoluted and demanding numerically. The N-link swimmer model, where the continuous filament is replaced by N segments with elasticity concentrated at the joints, can be seen as a coarse-graining formulation of the latter. In [10] (see also [31]), the N-link swimmer model is presented in this perspetive and it is demonstrated numerically how this system can be used as an alternative. It can be solved numerically with any ODE solver and overcomes well-known numerical instabilities when solving numerically the full PDE for the filament. Computations can be as much as a hundred times faster. Generalisations for more complex interactions are demonstrated on four examples commonly found in biological systems, a Matlab code is provided as a basis for further generalisations.

More theoretical study of this approximation property are under investigation, also in the framework of Clément Moreau's PhD.

7.11. Energy-optimal strokes for multi-link micro-swimmers

Participants: Laetitia Giraldi, François Alouges [École Polytechnique], Antonio Desimone [SISSA Trieste, Italy], Yshar Or [Technion, Haifa, Israel], Oren Wiezel [Technion, Haifa, Israel].

In a common work that is presented in [33], submitted to *New Journal of Physics*, we consider a slender planar multi-link micro-swimmer (N links, see Section 7.10), where the time derivatives of the angles defining the shape are taken as controls, and we are mostly interested in small-amplitude undulations about its straight configuration.

Based only on the leading order dynamics in that vicinity, the optimal stroke to achieve a given prescribed displacement in a given time period is then obtained as the largest eigenvalue solution of a constrained optimal control problem. Remarkably, the optimal stroke is an ellipse lying within a two-dimensional plane in the (N-1)-dimensional space of joint angles, where N can be arbitrarily large. For large N, the optimal stroke is a traveling wave of bending, modulo edge effects.

We also solved, numerically, the fully non-linear optimal control problem for the cases $N = 3$ (Purcell's three-link swimmer) 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. For $N = 3$ we recover the non-convex planar loops already known from previous studies. For $N = 5$ we obtain non-planar loops, raising the question of characterizing the geometry of complex high-dimensional loops.

7.12. Swimming magnetic micro-robots

Participants: Luca Berti, Yacine El Alaoui-Faris, Laetitia Giraldi, Jean-Baptiste Pomet, Christophe Prud'Homme [Université de Strasbourg], Stéphane Régnier [UPMC - Sorbonne Universités].

We are in a collaboration with the Parisian robotics laboratory ISIR (Institut des Systèmes Intelligents et de Robotique) to enhance the control of artificial micro-swimmers that are actually built and implemented there. This involves building models and using them for control design. These robots are "magnetic micro-swimmers": part of them is magnetized and the control is an ambient magnetic field.

Yacine El Alaoui-Faris's PhD, co-advised with Stéphane Régnier, started October, 2017. It is centered on finite-dimensional models. The robots under consideration are made of a magnetic head and a flexible tail; the model is a 3-D counterpart of the planar "multi-link micro-swimmers" discussed in Section 7.10.

The validation of this nonlinear ODE model, with or without magnetic actuation, has been achieved this year, both against continuous models present in the literature and against experimental data at ISIR. This model has a definite interest by itself, and in the case of magnetic actuation, it allowed the numerical computation of periodic controls (magnetic field) that optimize the longitudinal velocity with prescribed maximum amplitude of the magnetic field oscillations. This process is described in a manuscript under preparation, to be submitted to *Physical Review Letters*.

These controls have very recently been tested in lab and a very significant efficiency gain over classical sinusoidal oscillations has been evidenced. This is a very encouraging experimental result.

Luca Berti's PhD, co-advised with Christophe Prud'homme, started this fall. It is focused on PDE models that are closer to the real physics but more intricate. His master's thesis was mostly a numerical project in the framework of Cemracs 2018 (http://smai.emath.fr/cemracs/cemracs18/), where we modeled the displacement of a deformable swimmer using a coupling between Stokes equations and hyper-elasticity equations. The PDEs was solved using the Feel++ finite elements library. We validated the fluid model using an exact solution for a rotating rigid body. The motion of a one-hinged swimmer (which obeys to the scallop theorem) was successfully simulated. The physical robots from ISIR are now considered in his PhD.

7.13. Necessary conditions for local controllability, motivated by the Two-link Magneto-elastic Micro-swimmer

Participants: Laetitia Giraldi, Pierre Lissy [Univ. Paris Dauphine], Clément Moreau, Jean-Baptiste Pomet.

After proving in [66] a local controllability for the 2-link magneto-elastic swimmer around its straight configuration and noting that this property is weaker than Small-Time Locally Controllable (STLC), we investigated "full" STLC for this system, and were able to show that, except for very specific values of the lengths and magnetizations, this system is *not* STLC. This is published in [9]. This lead us to necessary condition for STLC for more general classes of systems. This is part of Clément Moreau's doctoral research and a publication is under preparation, for classes of control-affine systems with two controls that are not micro-swimmer models, but stem from the observations in [9] and [66].

7.14. Numerical and Symbolic computations in MRI

Participants: Bernard Bonnard, Jérémy Rouot, Thibaut Verron, Olivier Cots [ENSEEIHT Toulouse].

Academic year 2016-17 with the two Postdoctoral position at Toulouse (J. Rouot at LAAS and T. Verron, Enseeith) was the opportunity to complete our investigations about the contrast and multi-saturation problem in MRI. This concerns numeric and symbolic computations using Hampath, Bocop, Gloptipoly and Maple software. The reference [27], to be published in MCRF, contains all the results and techniques about this project and is the final paper of this longstanding work in quantum theory.

7.15. Stability of nonlinear high frequency amplifiers

Participants: Laurent Baratchart [FACTAS project-team], Sébastien Fueyo, Jean-Baptiste Pomet, Gilles Lebeau.

Sébastien Fueyo's PhD is co-advised on this topic. The problem is presented in Section 4.4.

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.

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. This was presented at a local conference, Université Côte d'Azur Complex Days in January, and a more complete publication is under preparation.

On more general structures, new results are available too, publications are in progress.

7.16. Optimal sampled-control with applications to Muscular Control

Participants: Bernard Bonnard, Toufik Bakir [L2I, Univ. de Bourgogne Franche Conté], Jérémy Rouot.

The study was initialized two years ago under the impulse of Toufik Bakir (LE2I-UBFC). Based on preliminary experimental studies, the chosen model to muscular control integrates the fatigue variables and is known as *Ding et al force-fatigue model* in the literature. It is a refinement of the historical Hill model (Medecine Nobel Prize 1922). Preliminary results lead to construct a nonlinear observer and the optimized pulses trains are computed using MPC methods [15]. More recently in collaboration with L. Bourdin (Limoges), optimal control techniques were introduced in the framework of sampled-control problems. Pontryagin type necessary conditions were obtained with preliminary numerical simulations. On these topics, paper [23] has been submitted to *JOTA*, October 2018; [3] is accepted for publication in *Networks and Heterogeneous Media*, 2018.

7.17. An Optimal Control Strategy Separating Two Species of Microalgae in Photobioreactors

Participants: Olivier Bernard [BIOCORE project-team], Walid Djema, Laetitia Giraldi.

We investigate a minimum time control problem in a chemostat continuous photobioreactor model that describes the dynamics of two distinct microalgae populations. Our objective is to optimize the time of selection – or separation – between two species of microalgae. In [17], we focus on Droop's model which takes into account the internal quota storage of each microalgae species. Using the Pontryagin's principle, we find a dilution-based control strategy that steers the model trajectories to a suitable target in minimal time. Our study reveals that singular arcs play a key role in the optimal synthesis. Using numerical simulations, we show that the optimal control strategy is mainly of type bang-singular. A numerical optimal synthesis is performed throughout the paper, thereby confirming the optimality of the provided feedback-control law.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contract with Industry

A bilateral research contract between the company CGG and the team took place in 2018. Duration: 6 months.

8.2. Bilateral Grant with Industry

A grant "PEPS AMIES", title: "Conception d'un électrostimulateur intelligent", has been obtained, co-financed by AMIES and SEGULA. PI: Bernard Bonnard. Start: December 2018. Duration: two years.
A grant PEPS UCA MSI (Maison de la Simulation de l'Innovation) on "Effet des résonances sur la moyennisation en contrôle optimal appliqué à la mécanique spatiale" with Inria and Thales Alenia Space (Cannes). PI: J.-B. Caillau Start: January 2018. Duration: six months

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: 1 years. This project involves colleagues from Paris Sorbonne Université (around S. Régnier's team) and from University of Strasbourg (around C. Prud'Homme's team).

PGMO grant (2016-2018) on "Metric approximation of minimizing trajectories and applications" (PI J.-B. Caillau). This project involved colleagues from Université Paris Dauphine and has funding for two year (originally one, extended), including one intership (M2 level).

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.

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.

P. Lissy was the PI of a PEPS project JCJC (young researchers).

9.2. European Initiatives

9.2.1. Bilateral program with Portugal

Program: FCT (Fundação para a Ciência e a Tecnologia)

Grant no. : PTDC/MAT-CAL/4334/2014

Project title: "Extremal spectral quantities and related problems"

Duration: 05/2016-05/2019

Coordinator: P. Freitas (Univ. Lisbon)

Team member involved: J.-B. Caillau

Other partners: Univ. Lisbon, Univ. Luxembourg, Czech Nuclear Physics Institute, Univ. Bern

Link: https://team.inria.fr/mctao/fct-project-extremal-spectral-quantities-and-related-problems-2016-2019

9.2.2. Bilateral ANR-DFG program with Germany

Program: Projets de recherche collaborative-internationale ANR-DFG (Germany)

Grant no. : ANR-14-CE35-0013-01; DFG-Gl 203/9-1

Project title: "**Exploring the physical limits of spin systems (Explosys).**"

Duration: 11/2014-10/2018

Coordinator: D. Sugny (Univ. de Bourgogne) for France, Glaser (TU München) for Germany.

Team member involved: Bernard Bonnard.

Other partners: TU München, Univ. de Bourgogne (IMB and UCB).

This project involves specialists in physics and control theory in order to make important progresses in the use of spin dynamics, in particular for Magnetic Resonance Medical Imaging.

Link: http://www.agence-nationale-recherche.fr/fileadmin/aap/2014/selection/pa-2014-selection-franco-allemand-dfg.pdf

9.3. International Research Visitors

9.3.1. Visits of International Scientists

Zhen Chen, Technion. Two day visit in July, 2018. Gave a talk "Shortest Dubins Paths through Three Points" at McTAO seminar.

9.3.2. Visits to International Teams

Lamberto Dell'Elce visited Department of Aerospace Engineering at Technion (Haifa, Israel) for a week in July, 2018.

Pierre Lissy was invited one month at Fudan University (China) in March and June, 2018.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

Members of the team have been involved in creating a series of conferences on "The cut locus: A bridge over differential geometry, optimal control, and transport", together with Japanese colleagues, see motivations in Section 3.2. The first one took place in Bangkok, Thailand, in 2016 and the second one was organized this year, September 3-6 in Sapporo, Japan. There are plans to organise the third conference in Nice in 2020.

J.-B. Caillau and L. Rifford were members of the scientific and organising committee for this second edition.

J.-B. Caillau was member of the Scientific committee of the PGMO days 2018, hosted by EDF labs in Saclay, and supported by the Fondation Mathématique Jacques Hadamard (FMJH). The conference gathered about 280 scientists working in optimization and data science. Together with H. Zidani (ENSTA Paristech), J.-B. Caillau organized two sessions of invited talks on "Optimal control and applications" during the conference.

J.-B. Caillau is chair (together with D. Auroux, UCA) of the 19th French-German-Swiss conference on Optimization that will take place in Nice in September 2019. This conference is the main European biennial event in optimization in the broad sense.

10.1.2. Journal

B. Bonnard is a member of the editorial board of the *Pacific Journal of Mathematics for Industry*.

10.1.3. Invited Talks

B. Bonnard, J.-B. Pomet and J. Rouot gave three invited talks at the conference Dynamics, Control, and Geometry, Banach center, Warsaw (Poland): “Sub-Riemannian geometry and the Copepod Micro–swimmer”, “Geometric and numerical methods in optimal control for the time minimal saturation of a pair of spins”, “Dynamic equivalence and flatness of control systems: some results and open questions”.

Olivier Cots gave an invited talk at PGMO Days. Olivier Cots, Bernard Bonnard, Jérémy Rouot and Thibaut Verron, “Geometric and numerical methods for the saturation problem in Magnetic Resonance Imaging”.

J.-B. Pomet gave an invited talk at the 2$^{\text{nd}}$ conference on “The cut locus: A bridge over differential geometry, optimal control, and transport”, September 3-6, Sapporo, Japan.

P. Lissy gave two seminars at Fudan University, Shanghai, China (February).

P. Lissy gave two plenary talks at *PICOF conference*, Beyrouth, Libanon (June) and at *Workshop on Microlocal analysis, numerical analysis and kinetic equations*, Madrid, Spain (February).

J.-B. Caillau gave the following invited talks:

- “Optimal control of slow-fast mechanical systems” (in January), *UCA Complex days*, Nice
- “Smooth and broken Hamiltonian curves in optimal control” (in February), *Recent advances in Hamiltonian dynamics and symplectic topology*, Padova

L. Dell’Elce gave the following seminars:

22/2/2018 *Robust trajectory design using invariant manifolds. Application to the asteroid (65803) Didymos* at Astrogeo, Sophia Antipolis, France.

7/5/2018 *Two-phase averaging of optimal control systems with application to the Eath-Moon transfer* at JAXA, Sagamihara, Japan.

9/7/2018 *Two-phase averaging of optimal control systems* at Technion, Haifa, Israel.

10.1.4. Leadership within the Scientific Community

J.-B. Caillau is member of the following committees:

- Conseil scientifique du GdR Calcul
- Conseil scientifique de l’Institut de Mécanique Céleste et de Calcul des Éphémérides (Observatoire de Paris)
- Conseil scientifique PGMO, Fondation Mathématique Jacques Hadamard
- Jury du prix de thèse PGMO

J.-B. Caillau, L. Dell’Elce and J.-B. Pomet are members of the Centre Spatial Universitaire UCA (projet CubeSat).

10.1.5. Scientific Expertise

J.-B. Caillau and L. Giraldi were hired for a one day expertise for Smart'n Go (startup working in marine routing).

10.1.6. Research Administration

J.-B. Caillau is

- co-organizer of the Séminaire de géométrie hamiltonienne of Sorbonne Université
- member of the Conseil Scientifique 3IA (project on AI supported by Nice-Sophia Antipolis)

Laetitia Giraldi is

- a member of CSD (*Comité du Suivi Doctoral*) at Inria Sophia-Antipolis,
- a redactor of the meeting reports of the *Comité des Équipes-Projets* at Inria Sophia-Antipolis.

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).

Ludovic Rifford is the Executive Director of the CIMPA (Centre International de Mathématiques Pures et Appliquées).

Pierre Lissy is elected member of the "CCR" of the CEREMADE (committee in charge of the recruitment at Dauphine, notably for ATER, months of invited and composition of hiring committees).

Pierre Lissy is member of the team of the website "Opération Postes".

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

B. Bonnard taught 220 hours at undergraduate level (ESIREM engineering school)

J.-B. Caillau taught 200 hours at L3, M1 and M2 level (Polytech Nice Sophia, Universié Nice Sophia).

L. Giraldi taught 10 hours in the Master 2 recherche, Cell Physics (Université de Strasbourg). She also teaches in Classe préparatoire aux grandes écoles d'ingénieurs (Centre International de Valbonne) as a interrogatrice in MP* and MPSI (4 hours per week).

P. Lissy gave a six hour lecture on "Spectral Geometry" at the CIMPA spring school "PDEs and geometry" (May 2018, Jijel, Algeria).

J.-B. Caillau is director of the Applied Math. & Modelling department of Polytech Nice Sophia.

J.-B. Caillau and L. Giraldi are members of the jury of Agrégation externe de mathématiques.

P. Lissy was coordinator of a work group on the recast of the Teaching in Analysis for the initial education in Maths at Université Paris-Dauphine.

10.2.2. Supervision

PhD : Michaël Orieux, "Quelques propriétés et applications du contrôle en temps minimum" [1], Université Paris Dauphine, November 27, 2018, co-supervised by J.-B. Caillau and J. Féjoz (Univ. Paris-Dauphine).

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 magneto-elastic micro-robot from theory to experiment”, started October, 2017, co-supervised by L. Giraldi, J.-B. Pomet and Stephane Régnier (Sorbonne Université).

PhD in progress : Clément Moreau, “Contrôlabilité de systèmes en dimension finie ou infinie issus du vivant”, started September, 2017, co-supervised by L. Giraldi, P. Lissy (Univ. Paris-Dauphine) and J.-B. Pomet.

PhD in progress : Agustin Yabo, “Control of biological processes”, started September, 2018, co-supervised by J.-B. Pomet and J.-L. Gouzé (Biocore team).

PhD in progress : Luca Berti, “Modeling magneto-elastic micro-robot using PDE”, started October, 2018, co-supervised by L. Giraldi and C. Prud’Homme (Université de Strasbourg).

10.2.3. Juries

B. Bonnard was a reviewer of Sofya Maslovskaya’s PhD (ENSTA ParisTech), and he sat in the jury for Toufik Bakir’s Habilitation defense (Univ. de Bourgogne Franche Comté).

J.-B. Caillau was a reviewer of Ivan Beschastnyi PhD thesis (SISSA, September 2018), Francesca Chittaro Habilitation (Univ. Toulon, December 2018), Antoine Olivier PhD thesis (Sorbonne Université, October 2018), Cédric Rommel PhD thesis (École Polytechnique, October 2018), and he sat in the jurys of Clément Gazzino PhD thesis (Univ. Toulouse, January 2018), Ricardo Bonalli PhD thesis (Sorbonne Université, July 2018).

J.-B. Pomet was a reviewer of Riccardo Bonalli’s PhD (Univ. Paris Sorbonne), and he sat in the jury for Sofya Maslovskaya’s PhD (ENSTA ParisTech) and for Toufik Bakir’s Habilitation defense (Univ. de Bourgogne Franche Conté).

L. Rifford was a reviewer of Vincenzo Basco’s PhD (Sorbonne Université) and sat in the jury for Nicolas Juillet’s Habilitation à Diriger des Recherches (Université de Strasbourg).

Pierre Lissy has been a member of hiring committees for “Maître de Conférences” positions at Université Paris-Dauphine (2 positions) and Université Sorbonne Université (1 position).

10.3. Popularization

10.3.1. Internal or external Inria responsibilities

Clément Moreau is a member of the team « équipe actualités » of Images des Mathématiques since October, 2018.

J.-B. Caillau is member of the MASTIC initiative at Inria Sophia (Médiation et animation scientifiques Inria) and delivers regular talks in high school or college.

10.3.2. Articles and contents

Clément Moreau participated in the radio show « La méthode scientifique » on March 7, 2018.

Clément Moreau participated in the national competition « Ma thèse en 180 secondes ».

10.3.3. Education

Lamberto Dell’Elce is involved in the PoBot challenge promoted by MEDITES. Specifically he supervises a class in the College Emile Roux in Cannes.

10.3.4. Interventions

Clément Moreau participated in the « journées portes ouvertes » at Inria Sophia Antipolis in the framework of the 2018 « Fête de la Science », October 7, 2018, and in a scientific discovery workshop for secondary school students at the concrete Art Museum, Mouans-Sartoux, October 11, 2018.

Lamberto Dell’Elce gave the talk "CubeSats: Concevoir et Realiser un Satellite à l’Université" at the *Cafe In* meeting held at Inria Sophia on June 6, 2018, and for high scholl students during the stage MathC2+ in June, 2018.

11. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] M. ORIEUX.*Some properties and applications of minimum time control*, Université Paris Dauphine PSL, November 2018, https://hal.inria.fr/tel-01956833

Articles in International Peer-Reviewed Journal

[2] Z. BADREDDINE.*Mass transportation on sub-Riemannian structures of rank two in dimension four*, in "Annales de l'Institut Henri Poincaré (C) Non Linear Analysis", 2018, https://hal.archives-ouvertes.fr/hal-01952439

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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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A3.4.4. - Optimization and learning
A3.4.6. - Neural networks
A3.4.7. - Kernel methods
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Other Research Topics and Application Domains:

B1.1. - Biology
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B2.6. - Biological and medical imaging

1. Team, Visitors, External Collaborators

Research Scientists

Xavier Descombes [Team leader, Inria, Senior Researcher, HDR]
Laure Blanc-Féraud [CNRS, Senior Researcher, HDR]
Eric Debreuve [CNRS, Researcher, HDR]
Grégoire Malandain [Inria, Senior Researcher, HDR]
Caroline Medioni [CNRS, Researcher]
Florence Besse [CNRS, Senior Researcher, HDR]

Faculty Member

Fabienne de Graeve [Univ de Nice - Sophia Antipolis, Associate Professor, from Sep 2018]

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Fabienne de Graeve [Univ de Nice - Sophia Antipolis, Associate Professor, from May 2018 until Aug 2018]
Sébastien Schaub [CNRS, from Oct 2018]

Technical Staff

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Sarah Laroui [Inria, from Apr 2018 until Jul 2018]
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Arne Henrik Bechensteen [Univ de Nice - Sophia Antipolis]
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Emmanuelle Poulain [GEMS (cifre)]
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Somia Rahmoun [Inria, from Apr 2018]
José Henrique de Morais Goulart [Université Côte d'Azur, from Nov 2018]

Visiting Scientist

Simone Rebegoldi [Universita di Modena e Reggio Emilia, Modena, Italy, until Mar 2018]

Administrative Assistants

Laurence Briffa [Inria, until Jan 2018]
Isabelle Strobant [Inria]

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

4.1.1. Awards

Emmanuel Soubies won the Phd Prize of the GdR MIA (Mathématiques de l’Imagerie et de ses Applications)

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 such as compressed sensing, source separation, and super-resolution imaging.

Based on the results of [20], 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 a minimization algorithm.

We apply the algorithm to the problem of Single-Molecule Localization Microscopy and compare the results with the well-known IHT algorithm [13]. Both visually and numerically the biconvex reformulations perform better. This work has been presented at the iTWIST 2018 workshop [5].

Furthermore, the algorithm has been compared to the IRL1-CEL0 [14] and Deep-STORM [15] (see figure 1). The IRL1-CEL0 minimizes an exact relaxation [19] 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 accepted to the ISBI 2019 conference.

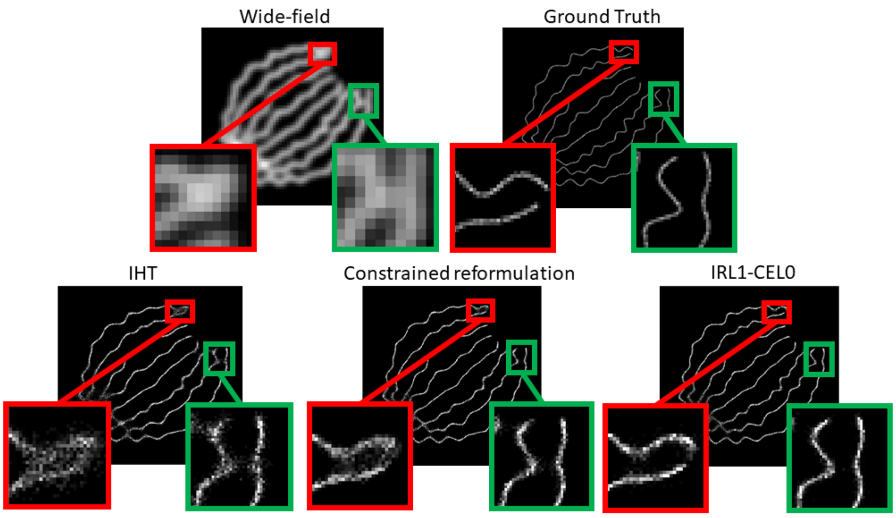


Figure 1. Reconstruction by the different algorithms. Data set from ISBI 2013 challenge [18].

6.2. Reconstruction of mosaic of microscopic images

Participants: Kevin Giulietti, Eric Debreuve, Grégoire Malandain.

This work takes place within the ANR PhaseQuant.

In microscopy imaging, a trade-off has to be made between a high resolution, that enables to see details, and the width of the field of view, that enables to see many objects. Such a trade-off is avoided by mosaicing, which consists in the acquisition of several images, say $N \times N$, with a small overlap between images. This way, an image with a N larger field of view can be reconstructed with the same resolution than a single microscopic image.

Such an imaging protocol is available on many microscopy software. Basically, displacements of the table on which lies the material to be imaged are programmed, and used to reconstruct the mosaic. However, it appears (at the overlapping areas) that a residual offset is still present. Analysis of acquisitions of both real and controlled experiments demonstrate that the table motions are not exactly reproducible (see figure 2), and that the cause of the offset is twofold: first a mis-alignement of the micrometer table axis with respect to the microscope axis, and second errors in the displacement computed by the micrometer table. Thanks to an image-based calculation of the axis mis-alignement, it has been shown that the first type error can easily be corrected.

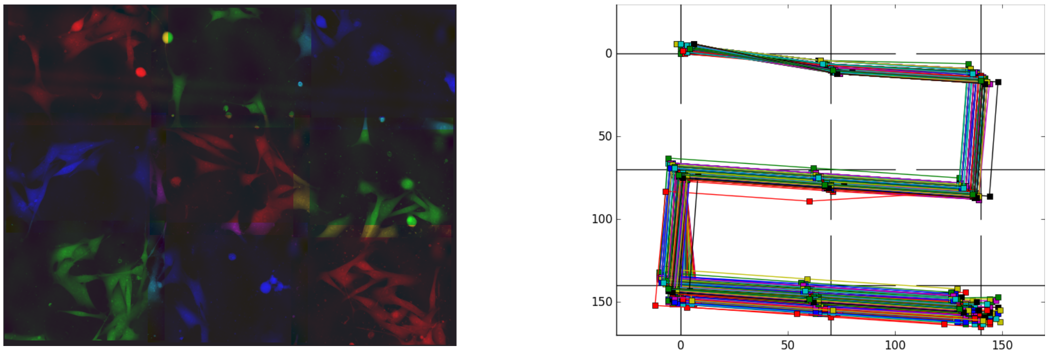


Figure 2. Example of a mosaic reconstructed for one acquisition timepoint. Estimation of the relative image position through time for the whole sequence (displacements with respect to the expected position have been magnified for visualization purpose).

6.3. Cytoplasm segmentation from cells confocal microscopy images

Participants: Somia Rahmoun, Fabienne de Graeve, Eric Debreuve, Xavier Descombes.

This work takes place within the ANR RNAGRIMP.

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 ...).

A specific CellProfiler pipeline has been developed for this, and CellProfiler Analyst has been used to learn a decision tree for automatic nuclei (hence, cell) classification.

The next step is to segment 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 clusters 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. We have evaluated and compared different strategies (based on iterative clustering, minimum spanning tree, persistent edge selection ...) to achieve such a segmentation. Finally, we have selected an automatic algorithm based on the watershed transform. We are currently developing an algorithm to merge superpixels into the final segmentation.

Meanwhile, we have developed a supervised software to manually merge the superpixels (see Fig. 3). This tool can also be used by biologist to correct any segmentation error.

6.4. Cytoneme detection and characterization

Participants: Eric Debreuve, Xavier Descombes.

This work is made in collaboration with Caterina Novelli, Tamas Matusek, Pascal Thérond (iBV).

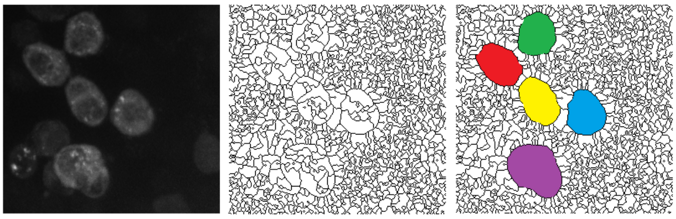


Figure 3. Superpixels merging: each color corresponds to a cell that is obtained by merging several superpixels.

This work is supported by the ANR project HMOVE. Cellular communication is one of the most important processes for controlling the morphogenesis of organs (i.e. the set of laws that determine the structure of tissues and organs during embryonic development). Understanding the communication both ways is an important issue in the field of developmental biology and it has recently been shown that the exchange of information between cells is controlled by long cellular extensions called "cytonemes”. Last year, we had developed a pipeline for automatic cell membrane detection and cytoneme extraction from in vivo images obtained by confocal microscopy. When testing the proposed method on new images with varying acquisition conditions, we found it to be less reliable than expected. While retaining the same general philosophy (use of Frangi enhancement filter, skeletonization, and Dijkstra shortest path algorithm), we largely rethought the approach to make it more robust to acquisition conditions, more reliable in general, and faster (see Fig. 4). Some topological and geometrical features are then computed on the graph-based representation of the cytonemes in order to characterize in which respect wild-type and mutant conditions are different or similar. A journal paper is in preparation based on the analysis and interpretation of these results by our biologist colleagues.

6.5. Classification and Modeling of the Fibronectin Network in Extracellular Matrices

Participants: Anca-Ioana Grapa, Laure Blanc-Féraud, Xavier Descombes, Sébastien Schaub.

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) network, a major extracellular matrix (ECM) molecule expressed in pathological states (fibrosis, cancer, etc). Our goal is to develop numerical quantitative biomarkers that describe the organization of the different FN networks from 2D confocal miscroscopy images (Figure 5).

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 [7].

The second step of our work consists 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). More specifically, Gabor filters are used to enhance the fibrillar structures, followed by a morphological skeletonization of the maximum response of the Gabor filter set. We then derive the corresponding graph networks that generate relevant fiber geometry statistics (e.g fiber length, node degree, node density, etc).

Starting from the graph networks, we manage to reconnect the missing fibers in the skeleton, that are due to previous morphological operations. To do so, we use the Gabor maximum response as a guideline for reconnection, and connect the fibers within a predefined cone sector around the local fiber orientation. The

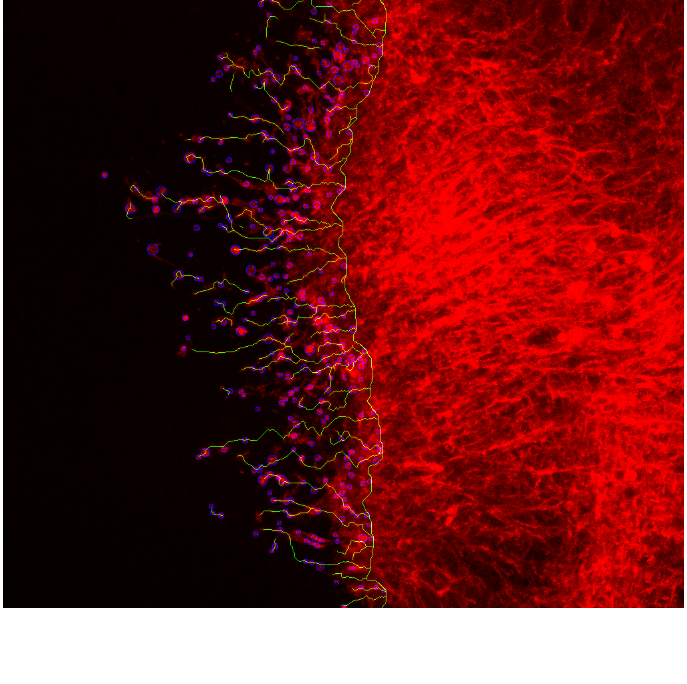


Figure 4. A result of membrane detection and cytoneme extraction.

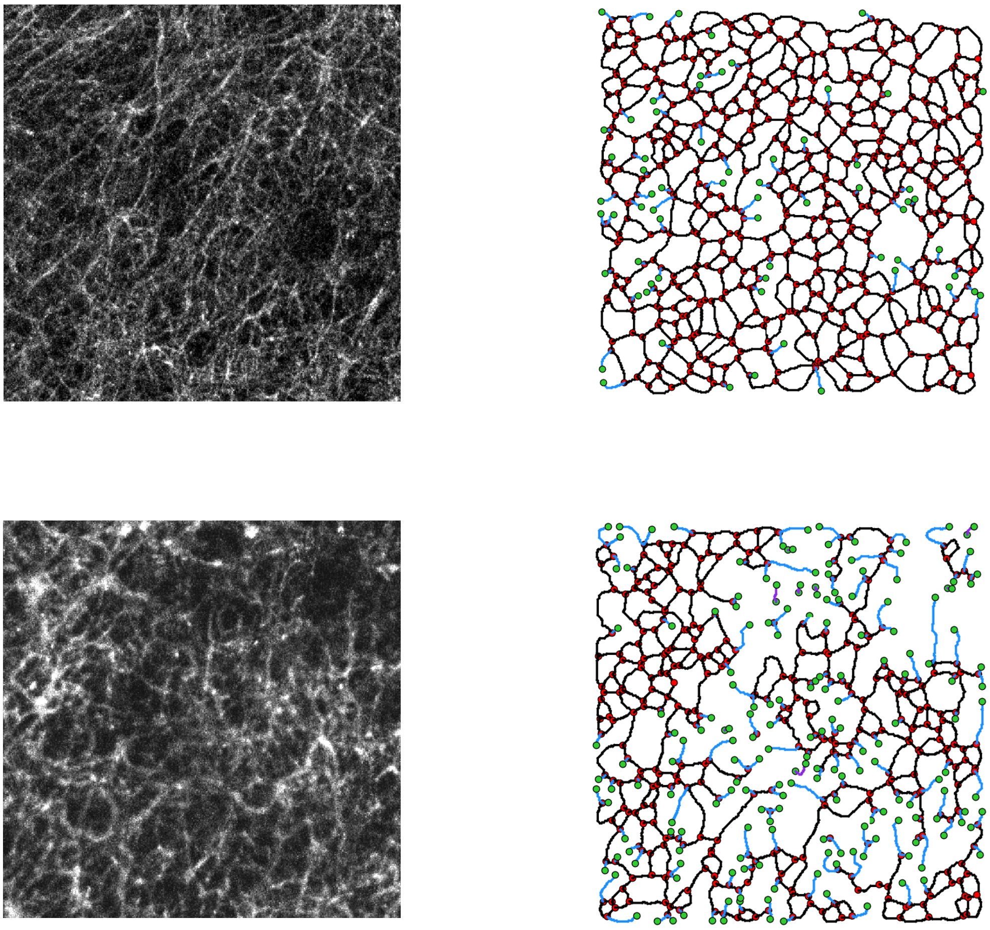


Figure 5. Different variants of FN and their associated graph networks. Top row: A+ fibronectin; bottom row: A-B- fibronectin. Left: confocal images; right: associated graphs.

graph parameters corresponding to the improved skeletonizations of the four FN variants, are then classified by a DAG-SVM. It is thus shown that graph features can discriminate among the FN variants.

The next step concerns the development of a metric between graph networks that takes into account their topology, to provide a meaningful distance between them. We currently investigate methods based on optimal transport, that are able to compare discrete probability distributions and respect the local geometry. The techniques that rely on graph structures to compute a geodesic distance (e.g. Gromov-Wasserstein) and/or barycenter of structured data (e.g. mesh structures) [16], serve as inspiration for our work. The distance is obtained following a minimization of the cost of transport of the mass from one distribution to the other. Despite the fact that they consider the intrinsic distance within each space (i.e graphs) in the cost formulation, these methods don't explicitly take into account the graph structure defined by the adjacency matrices. To counteract some of the shortcomings, we consider parallel graph-matching methods and redefine our problem in a many-to-many graph matching context, where the distance between the graphs is given by the optimal alignment of their structure determined by the mapping between the vertices [21].

Finally, we analyze the advantages and drawbacks of the two techniques both for small-size graphs as well as for FN graphs to derive an appropriate formulation of the distance among them, which will be useful to compare the FN fiber networks.

6.6. Detection of Brain Strokes Using Microwave Tomography

Participant: Laure Blanc-Féraud.

This work is done in collaboration with Vanna Lisa Coli and Juliette Leblond (EPI Factas, Inria Sophia), Pierre-Henri Tournier (Université Sorbonne, CNRS, LJLL, Inria, Paris) , Victorita Dolean (Université Côte d'Azur, CNRS, LJAD, Nice), Ibtissam El Kanfoud, Christian Pichot, Claire Migliaccio (Université Côte d'Azur, CNRS, LEAT, Sophia Antipolis).

Brain strokes are one of the leading causes of disability and mortality in adults in developed countries. The ischemic stroke (85% of total cases) and hemorrhagic stroke (15%) must be treated with opposite therapies, so that the determination of the stroke nature must be made quickly to apply the appropriate treatment. Recent works in biomedical imaging showed that strokes produce variations on brain tissues complex electric permittivity that can be detected by means of microwave tomography.

We present here some synthetic results obtained with an experimental microwave tomography-based portable system for the early detection and monitoring of brain strokes (Figure 6). The determination of electric permittivity requires the solution of a coupled direct-inverse problem, where massive parallel computation from domain decomposition method and regularization techniques for optimization methods are employed. Synthetic data are obtained with electromagnetic simulations and a noise model developed for the specific problem, which has been derived from measurements errors with the experimental imaging system.

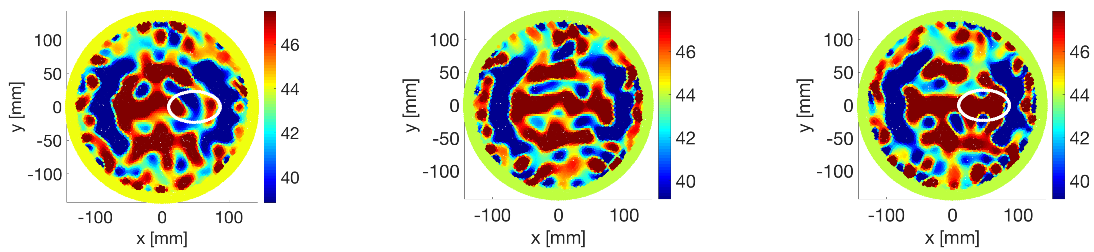


Figure 6. From left to right: brain with ischemic stroke, healthy brain and brain with hemorrhagic stroke (real part of permittivity ϵ_r).

6.7. Organoid growth tracking

Participants: Cédric Girard Riboulleau, Xavier Descombes.

This work is a collaboration with F.-R. Roustan, S. Torrino, S. Clavel and F. Bost from C3M. It was partially supported by the UCA Jedi Idex.

Organoid culture is a major challenge toward personalized medicine. It is now possible to partially reconstruct the structure of organs from a single biopsy. This new technology named organoid for sane cells or tumoroid for cancer cells allows the test of different molecules on cells withdrawn on a patient to retrieve the most efficient one for this patient. In this context, the main goal of this work is to develop a numerical scheme to automatically assess the effect of a given treatment on the organoid growth. We consider a time sequence of 2D confocal microscopy images of a population of organoids. We have considered different approaches to detect the organoids in the images. These approaches include edge detection using Canny filter, thresholding combined with mathematical morphology tools, texture analysis through Markov Random Fields, marked point processes. We have also modified several times the imaging protocol in order to simplify the object detection. To evaluate the growth of each organoid we have to match the objects detected in two consecutive frames. We have developed a matching algorithm based on a majority voting. We compute the vector between every pair of detected objects on both frames. Assuming that there is only a translation between the two frames we estimate it as the most represented vector. With this framework we have shown that the studied treatment has stopped the organoid growth (see figure 7).

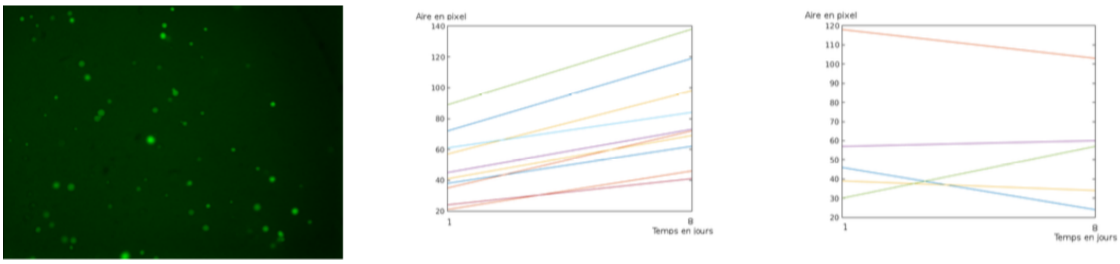


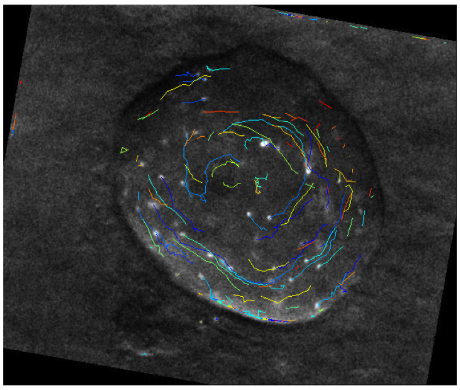
Figure 7. Image of organoids (left), Temporal evolution of some organoid size without treatment (middle) and with treatment (right).

6.8. Vesicles tracking

Participants: Raphael Pages, Xavier Descombes.

This work is a collaboration with P. Juan, M. Furthauer from iBV. It was partially supported by the UCA Jedi Idex.

We take advantage of the optical transparency of the zebrafish to study the formation, transport and function of extracellular vesicles in vivo. In the zebrafish Left/Right Organizer (LRO) a cilia-driven fluid flow promotes the directional transport of extracellular vesicles in the organ lumen. We have developed a software to analyze the vesicles trajectory. Assuming that the speed is slow enough, the detection is performed by considering the 2D+t time sequence of data as a 3D volume in which the vesicle trajectories are represented by tubular shapes. We first remove the background in each slice by subtracting a temporal mean computed on a sliding window. The trajectories are than enhanced by a Frangi filter followed by a top hat operator. Finally, the trajectories are obtained by a threshold and filtered to remove those corresponding to cilia movement. To compare different populations we then compute a mean shape of the LRO using an elastic shape metric. The trajectories detected on the different samples of a given population are then projected onto this common space. To have a dense representation of the vesicles speed inside the LRO we then extrapolate the detected trajectories on the whole population using a Markov random field regularization (see figure 8).



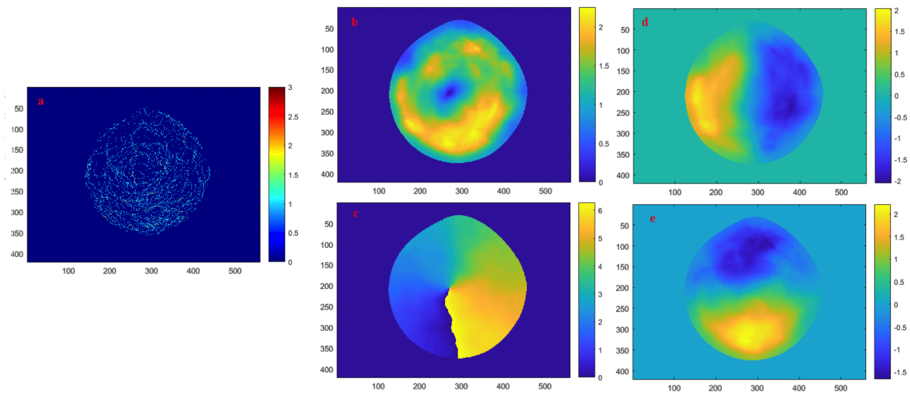


Figure 8. Trajectories detected on one LRO (top). Bottom: trajectories detected the whole population (right a), horizonal (b), vertical (c) radial (d) and angular (e) speeds.

6.9. Comparison of tracking strategies

Participants: Sarah Laroui, Grégoire Malandain, Gaël Michelin.

This work takes place within the ANR PhaseQuant.

In video-microscopy, subject-based studies require the tracking of every individual to both quantify its dynamics (speed, etc) and detect special events (mitosis). In high throughput experiments, manual annotation or correction of sequences is not feasible, and computed-based strategies are definitevely prefered. In such a context, where cells have already been segmented in video-microscopy images (by a third party method), this work aims to assess different tracking strategies in presence of unavoidable segmentation errors (missing cells, over- or under-segmentations).

Two main strategies have been under examination. In the first one, all pairing hypothesis (based on a proximity criteria) have been generated. Further stages of both selection of plausible pairings or rejection of non-plausible ones have been tested to end up with tracking results. In the second one, pairings are built progressively based on their plausibility (one cell can be paired forward to 0, 1 or 2 cells; one cell can be paired backward to 0 or 1 cell). In both strategies, jumps are allowed to take into account possible segmentation errors.

It appears that the first strategie is more likely to end up with undecidable unplausible situations, that can not occur, by construction, with the second one.

6.10. 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 [17]. Although, we faced a segmentation problem when we wanted to move from the tracking of one vessel to the entire set. For this reason, we have worked this year on the vessel centerline extraction in x-ray projection images.

2D Angiographic images are often first enhanced, before centerline extraction, by dedicated filters, e.g. Hessian based filters. Such filters exhibit critical defects, one of them being the non-uniform response for vessels of different sizes. This fact largely compromised the next step of centerline extraction. This last step requires a threshold step which is usually not clearly explained in other established methods. We worked on a model-based study of two widely used Hessian-based filter. It demonstrates that the non-uniform response for vessels of different sizes is due to the projective effect, and further enables to propose an X-ray projection dedicated method for centerline extraction which overpass this behavior. It is complemented by a component-based hysteresis thresholding. Last, the huge variability of coronary image aspect, due to imaging parameters, makes the threshold choice quite complex. We have shown that the thresholds can be determined automatically taking into account the kilovoltage peak (kVp), one key technical parameter of the X-ray acquisition. These thresholds are determined without any a priori on the image content. This technique not only allows to obtain an almost optimal segmentation, but also performs well for non-injected frames. Results of our proposed method and methods from state of the art are presented in Fig. 9.

6.11. Mitochondrial network detection and classification

Participants: Guillaume Lavisse, Xavier Descombes.

This work is a collaboration with C. Badot and M. Chami from IPMC and A. Charezac, S. Clavel and F. Bost from C3M. It was partially supported by the UCA Jedi Idex.

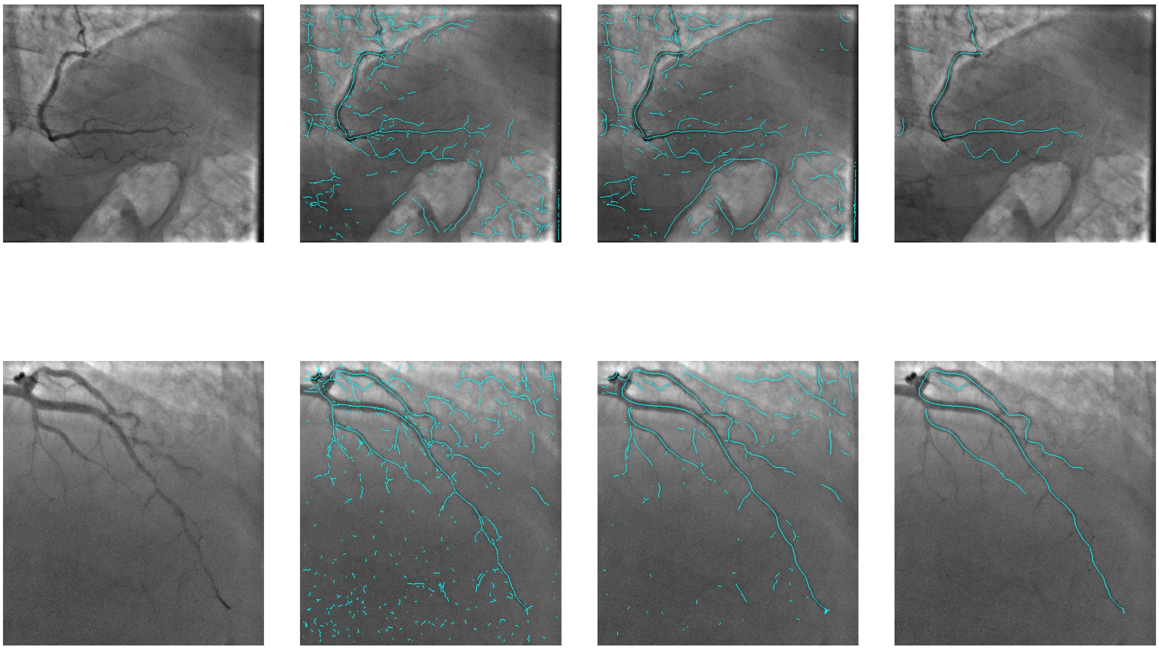


Figure 9. The obtained results of the different methods on a right coronary sample (first line), and left coronary sample (second line). From left to right: the original image, the result of Frangi (OPHT), the result of Krissian (OPHT), and the result of the proposed method (CCHT). The two first methods were tuned to obtain the same sensitivity than the third one.

Last year we had developed a framework to classify mitochondrial networks. In this framework, mitchondrial networks are first binarized using our algorithm ATOLS. Some geometrical features are then computed for each connected component providing a clustering at the object level in the feature space. A signature of a given image is then defined by the ratio of objects in the different classes. A second classification, performed by an SVM on this signature, provides a global class for the image. The different classes are defined as fragmented, tubular and filamentous. This year, we have validated this framework on two other databases, one consisting of cultured cells, the other being constituted of Alzheimer neuronal cells. The results were not satisfactory compared to those obtained on the first database last year. This is mainly due to the signal heterogeneity within an image. To compensate this heterogeneity we have applied a local normalization (see figure 10). We then have recovered classification performances comparable to those obtained by an expert. The next step consists in following in time the mitochondria of Alzheimer neuron. To this aim, we have developed a matching algorithm between two sets of mitochondria based on geometrical features and location of detected objects at two different instants.

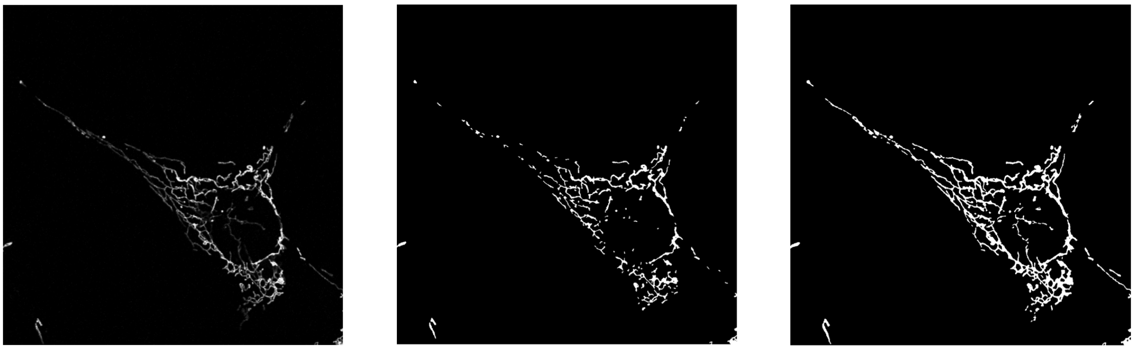


Figure 10. Image of Mitochondria (left), Binarization obtained without local normalization (middle) and with local normalization (right).

6.12. 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 a collaboration with Aurelia Vernay (Bayer, Lyon, France).

Botrytis cinerea is a reference model of filamentous phytopathogen fungi. Some chemical treatments can lead to characteristic morphological changes, or phenotypic signatures, observable with transmitted light microscopy. These phenotypes could be associated with the treatment Mode of Action (figure 11). The goal of this work is the recognition of already known phenotypes but also the detection of new phenotypes. Because of the different dose-response effects, each given molecule is tested at ten concentrations.

In this context, we are developing a robust image analysis and classification framework relying on morphometric and topological characteristics to automatically recognize such phenotypes. Specifically, these characteristics are used in a supervised machine-learning framework to learn a Random Forest classifier.

After object detection, we calculate the skeleton of each object and we converted them into graphs, a more convenient data structure. Two types of parameters were extracted: those calculated globally on all the objects of an image like for example the number of objects and the skeleton length variance, and those computed on each object of an image like the number of nodes, the mean branch length and the object area.

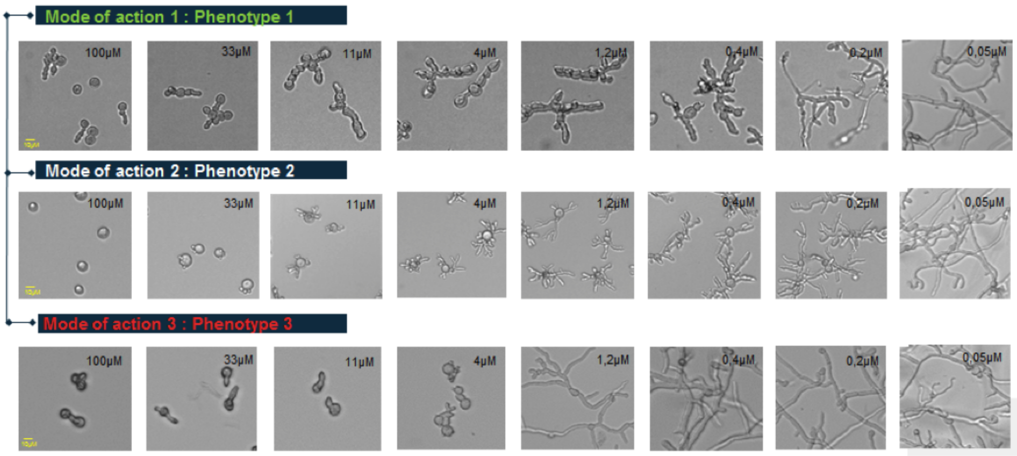


Figure 11. Each row depicts the observed phenotypic signatures associated with a given molecules. Columns correspond to different molecule concentrations.

6.13. Automatic zooplankton classification using hierarchical approaches

Participants: Eric Debreuve, Baptiste Pouthier.

This work is made in collaboration with Frédéric Precioso (I3S) and Jean-Olivier Irisson (Laboratoire d'Océanographie de Villefranche-sur-mer).

In marine ecology routine, zooplankton organisms are imaged using a single camera system. With the purpose of building an automatic classifier of plankton images, databases of annotated images are built. For each species, such databases contain a set of images of similar organisms, but seen under different point of views, i.e., having potentially very different appearances. Hence, learning an automatic classifier for zooplankton from such databases is difficult. In consequence, feeding the learning process with as much information as possible is essential. One piece of information we have access to is a taxonomic structure (hence hierarchical structure) of zooplankton species established by environmental biologists (see Fig. 12). Therefore, we have explored (and we continue to explore) different strategies to use such a hierarchy in the learning process, from the straightforward one consisting of learning a coarse-to-fine tree of independent convolutional neural networks (CNNs) to using neural network architectures explicitly accounting for hierarchical constraints.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

General Electric Healthcare: a 36 months (from feb. 2016 to jan. 2019) companion contract for the Cifre 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.

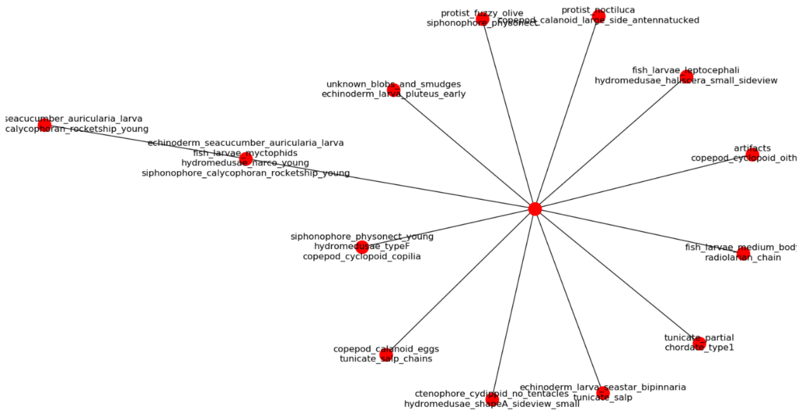


Figure 12. An Illustration of the zooplankton taxonomy.

Florence Besse and Xavier Descombes are members of the Scientific Committee.

8.1.2. Idex UCA Jedi

Florence Besse is a member of the scientific council of the IDEX JEDI Academy 2.

Laure Blanc-Féraud is chair of the scientific council of Academy 1 of Idex UCA JEDI.

A number of projects has been partially funded by the Idex.

- Artificial intelligence application to the identification of functional traits of zooplankton from high-resolution images (ARTIFACTZ) collaboration with Laval University, Québec / UCA Coll. with : F. Maps (ULaval), D. Laurandeau (ULaval),L. Guidi (LOV), S. Ayata (LOV), J.-O. Irisson (LOV) Participants : E. Debreuve
- Biological Image Super-resolution Enhanced with Tensor (Biset) supported by Académie 1 RISE Coll. with G. Favier (I3S), G. Sandoz (iBV) Participants : E. Debreuve, L. Blanc-Féraud, S. Schaub
- Quantitative analysis of exovesicle transport dynamics in the zebrafish Left/Right organizer. supported by Academy 2 "Complex Systems" Coll. with M. Furthauer (PI, iBV), T. Juan (iBV) Participants: R. Pages, X. Descombes
- Study of a complex biological system pf prostate organoid: applications in biomedical research. supported by Academy 2 "Complex Systems" Coll. with F. Bost (PI, C3M), S. Clavel (C3M), R.F. Roustan (C3M), S. Torrino (C3M). Participants: C. Girard-Ribouleau, X. Descombes
- Imaging analysis for mitochondrial network tracking and recgnition. supported by Academy 1 "Living Sciences" Coll. with M. Chami (IPMC), C. Badot (IPMC), F. Bost (C3M), S. Clavel (C3M), A. Charezac (C3M) Participants: G. Lavisse, X. Descombes.

8.1.3. 3AI Côte d'Azur

Laure Blanc-Féraud is a member of the scientific committee of the 3IA proposal of Nice.

8.2. National Initiatives

8.2.1. ANR RNAGRIMP

Participants: Florence Besse [PI], Fabienne de Graeve, Xavier Descombes, Eric Debreuve.

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.

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 DIG-EM

Participants: Grégoire Malandain, Xavier Descombes, Gaël Michelin.

Morphogenesis controls the proper spatial organization of the various cell types. While the comparatively simple process of patterning and cell differentiation has received considerable attention, the genetic and evolutionary drivers of morphogenesis are much less understood. In particular, we very poorly understand why some morphogenetic processes evolve very rapidly, while others show remarkable evolutionary stability.

This research program aims at developing a high-throughput computational framework to analyze and formalize high-throughput 4D imaging data, in order to quantify and formally represent with cellular resolution the average development of an organism and its variations within and between species. In addition to its biological interest, a major output of the project will thus be the development of robust general computational methods for the analysis, visualization and representation of massive high-throughput light-sheet data sets.

This 4-years project started october the 1st, 2014 and is leaded by P. Lemaire (CRBM, Montpellier). Participants are the CRBM, and two Inria project-team, Morpheme and Virtual Plants.

8.2.4. ANR PhaseQuant

Participants: Grégoire Malandain, Eric Debreuve, Kevin Giulietti, Sarah Laroui.

The PhaseQuantHD project aims at developing a high-content imaging system using quadriwave lateral shearing interferometry as a quantitative phase imaging modality. Automated analysis methods will be developed and optimized for this modality. Finally an open biological study question will be treated with the system.

This 3-years project started october the 1st, 2014 and is leaded by B. Wattelier (Phasics, Palaiseau). Participants are Phasics, and three academic teams TIRO (UNS/CEA/CAL), Nice, Mediacoding (I3S, Sophia-Antipolis), and Morpheme.

8.2.5. 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.).

8.2.6. Octopus Project

Participant: Eric Debreuve.

The Octopus project deals with automatic classification of images of zooplankton. It is conducted in collaboration with the Laboratoire d'Océanographie de Villefranche-sur-mer (LOV) et l'ENSTA Paris. The kickoff meeting took place in May 2015 and a 3-day *brainstorming* meeting on Deep Learning took place in December 2015. Participants are I3S (Frédéric Precioso and Mélanie Ducoffe), LOV (Marc Picheral and Jean-Olivier Irisson), and ENSTA Paris (Antoine Manzanera).

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Selection

9.1.1.1. Member of the Conference Program Committees

Eric Debreuve was a member of the Program Committee of ACIVS 2018 (Advanced Concepts for Intelligent Vision Systems) and Reconnaissance des Formes, Image, Apprentissage (RFIAP).

9.1.1.2. Reviewer

Laure Blanc-Féraud was a reviewer for the conferences IEEE ICIP and ICASSP.

Eric Debreuve was a reviewer for the conferences IEEE International Symposium on Biomedical Imaging (ISBI) and IEEE International Conference on Image Processing (ICIP).

Xavier Descombes was a reviewer for ISBI18, ICASSP18 and ICIP18.

Grégoire Malandain was a reviewer for the conferences EMBS, ISBI and MICCAI.

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.

Xavier Descombes is Associated Editor for the journal Digital Signal Processing.

9.1.2.2. Reviewer - Reviewing Activities

Laure Blanc-Féraud was a reviewer for the Journal of Optimization Theory and Applications.

Eric Debreuve was a reviewer for the journals Digital Signal Processing (Elsevier) and Pattern Recognition (Elsevier).

Xavier Descombes was reviewer for the journals IEEE TMI and Digital Signal Processing.

Grégoire Malandain was reviewer for the journal IEEE TMI.

9.1.3. Invited Talks

Florence Besse gave a talk ”Modeling Cell fate” at the Jacques Monod Conférence, November 2018.

Laure Blanc-Féraud was invited to the Workshop on Computational Methods for Inverse Problems in Imaging, Como Italy, 16-18 July 2018, and to the OSA Imaging and Applied Optics Congress, Orlando, USA, 25-28 June 2018.

Xavier Descombes was invited to give a talk at Tlemcen Univeristy during the Biomedical Doctoral School day. He was invited to give a talk at the SIAM conference on Imaging Science in Bologna. He was also a speaker during the C@UCA days in Fréjus and during Modelife days in Nice, workshops organized within the UCA Jedi Idex.

9.1.4. Leadership within the Scientific Community

Laure Blanc-Féraud is the directrice of the GdR 720 ISIS of CNRS (see website gdrisis.fr).

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 was president of the HCERES expert committee visit of the LTCI Lab (4-6 Dec.). She is a member of the ANR scientific evaluation committee ASTRID. She was part of the selection committee of section 61 of CNU for a professor position in Paris-Est University. She was expert for the CPER Numeric of Poitiers. She was member of the Commission d’admission CRCN of CNRS INS2I. Laure Blanc-Féraud was expert for the Italian Ministery of Research (MUIR) and for the FNRS (Belgium).

Xavier Descombes is an expert for the DRRT (Paca, Ile de France, Bretagne). He is member of the committee “Mathématiques et Sciences du Numérique pour la santé et la biologie” of ANR. He was in the HCERES committee to evaluate MAP5 laboratory.

9.1.6. Research Administration

Xavier Descombes is member of the "comité des projets" of Inria CRISAM. He is a member of the Comité Permanent des Ressources Humaines (CPRH), UNS, section 61.

Eric Debreuve is a member of the Comité Permanent des Ressources Humaines (CPRH), UNS, section 61.

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, 12h, L1, Polytech Nice Sophia, France

Master: Arne Bechensteen, Traitement Numérique des Images, 10h, M2, Polytech Nice Sophia, France

Master: Florence Besse, genetic tools for the study of neuronal networks, 4h, Université Côte d'Azur, France.

Master: Florence Besse, RNA localization and neuronal morphology, 4h, Université Côte d'Azur, France.

Master: Laure Blanc-Féraud, management of the module Traitements numériques des images (24h), teaching 5h CM.

Master : Eric Debreuve, scientific image processing, 9h EqTD, master SVS, Université Côte d'Azur, France

Master/Engineer : Debreuve, data mining, 27h EqTD, M2/Engineer 5, 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 VIM, 12h 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, 6h Eq. TD Niveau M2, Université Côte d'Azur.

Master : Anca Grapa, Traitement d'images, master GBM, 12h Eq. TD, Niveau M1, Université Côte d'Azur, France.

Master : Anca Grapa, Compression, Analysis and Visualization of Multimedia Content, master SSTIM (GMD), Niveau M2, 14h Eq. TD, PolyTech Nice Sophia, France.

9.2.2. Supervision

PhD in progress: Arne Bechensteen, TIRF-MA and super-resolution by sparse estimation method, 2 October 2017, Laure Blanc-Féraud, Gilles Aubert, Sébastien Schaub.

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: Emmanuelle Poulain, Fluoroscopy/CTA dynamic registration, 1st february 2016, Grégoire Malandain.

9.2.3. Internships

Baptiste Pouthier, Hierarchical deep learning for zooplankton image classification, Polytech Nice-Sophia Antipolis, UNS/UCA - MAM4, Eric Debreuve (sup.).

Simon Bahadoran, Deep learning for PALM superresolution in fluorescence microscopy. Supervisors: Laure Blanc-Féraud, Eric Debreuve.

Cédric Girard Riboulleau, Morphological tracking of organoids for the prostate cancer, Master BIM, Université Côte D'Azur, Xavier Descombes (sup.).

Guillaume Lavisse, Detection, classification and characterization of mitochondrial networks: application to Alzheimer desease and cancer, Master BIM, Université Côte D'Azur, Xavier Descombes (sup.).

Raphael Pages, Quantitative analyse of vesicles transport within the Left/Right organizer in the zebrafish, Master MAPI3, Université Paul Sabatier Toulouse, Xavier Descombes (sup.).

9.2.4. Juries

Laure Blanc-Féraud participated to the PhD thesis committees of Clara Barbanson (Télécom ParisTech & ONERA) as member, Quentin Denoyelle (Ceremade, Dauphine University) as president, William Meiniel (Pasteur Institute) as president, and to the HDR jury of Nabil El Korso (Paris Nanterre university) as member.

Xavier Descombes participated to the PhD committes of Agustina Razetti (Morpheme) as supervisor, Tran Thi Nhu Hoa (IPAL, Singapore and Sorbonne University), Amine Benomar (Tlemcen University, Algeria) and Jessica Sodjo (Bordeaux University) as a reviewer and Jean-Dominique Favreau (Titane, Inria) as an examinator. He was reviewer in the HDR juries of Sylvain Faisan (Strasbourg University) and Adel Hafiane (Orléans University).

Grégoire Malandain participated as reviewer to the PhD thesis committee of Ketan Bacchuwar (Paris Est univ.), Marc Filippi (Grenoble Alpes univ.), Julie Robic (Paris Est univ.), as member to the PhD thesis committee of Bertha Mayela Toledo Acosta (Rennes I univ.), and as reviewer to the HDR thesis committee of Antoine Vacavant (Clermont Auvergne univ.).

9.3. Popularization

9.3.1. Interventions

The Morpheme team took part in "La fête de la Science” both at Inria and during the "Village de la Science” in Juan-Les-Pins. Sarah Laroui, Somia Rahnmoun and Arne Bechensteen were holding a stand in these events.

10. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] A. RAZETTI.*Modelling and characterizing axon growth from in vivo data*, Université Côte d'Azur, April 2018, https://tel.archives-ouvertes.fr/tel-01868324

Articles in International Peer-Reviewed Journal

[2] I. DAVID, P. L. KOHNKE, J. FEHRENBACH, A. R. LOPES SIMOES, E. DEBREUVE, X. DESCOMBES, F. PLOURABOUÉ, P. DEGOND, X. DRUART.*New objective measurements of semen wave motion are associated with fertility in sheep*, in "Reproduction, Fertility and Development", 2018, vol. 30, n^{o} 6, p. 889-896 [*DOI :* 10.1071/RD17472], https://hal.archives-ouvertes.fr/hal-01808988

[3] K. MCDOLE, L. GUIGNARD, F. AMAT, A. BERGER, G. MALANDAIN, L. ROYER, S. TURAGA, K. BRANSON, P. KELLER.*In Toto Imaging and Reconstruction of Post-Implantation Mouse Development at the Single-Cell Level*, in "Cell", October 2018, vol. 175, n^{o} 3, p. 859 - 876.e33 [*DOI :* 10.1016/J.CELL.2018.09.031], https://hal.inria.fr/hal-01900416

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Conferences without Proceedings

[9] N. CEDILNIK, E. DEBREUVE, F. DE GRAEVE, F. BESSE, X. DESCOMBES.*SPADE: A Small Particle Detection Method Using A Dictionary Of Shapes Within The Marked Point Process Framework*, in "IEEE International Symposium on Biomedical Imaging (ISBI) 2018", Washington, DC, United States, April 2018, https://hal.inria.fr/hal-01867805

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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, from Oct 2018]
Loula Fezoui [Inria, Senior Researcher]
Marie-Hélène Lallemand Tenkes [Inria, Researcher]

Faculty Members

Stéphane Descombes [Université Côte d'Azur, Professor, HDR]
Claire Scheid [Université Côte d'Azur, Associate Professor]

External Collaborator

Yves d'Angelo [Université Côte d'Azur, Professor, from Jun 2018]

Technical Staff

Jonathan Viquerat [Inria, until Nov 2018]

PhD Students

Alexis Gobé [Inria]
Georges Nehmetallah [Inria]
Nikolai Schmitt [Université Côte d'Azur, until Sep 2018]

Post-Doctoral Fellows

Mahmoud Elsawy [Inria, from Oct 2018]
Mostafa Javadzadeh Moghtader [Inria]

Visiting Scientists

Weslley Da Silva Pereira [LNCC, Petropolis, Brazil, Visiting PhD student, until Aug 2018]
Kun Li [UESTC, Chengdu, China, Visiting PhD student, from Mar 2018]
Liang Li [UESTC, Chengdu, China, Visiting scientist, from Jul to Aug 2018]
Frédéric Valentin [LNCC, Petropolis, Brazil, Visiting scientist, from Dec 2017 until Jan 2018]

Administrative Assistant

Montserrat Argente [Inria]

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 [42] 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 [48] 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 [37] 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 [46] 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 [34]- [35]- [36]- [41]:

- 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]-[13]-[12]. 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.*[39] 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[11].
- **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]-[13]-[12] 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 [10]. 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 [15]. In the context of seismic wave propagation, we are interested by the intrinsic attenuation of the medium [14]. 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 [48]. 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

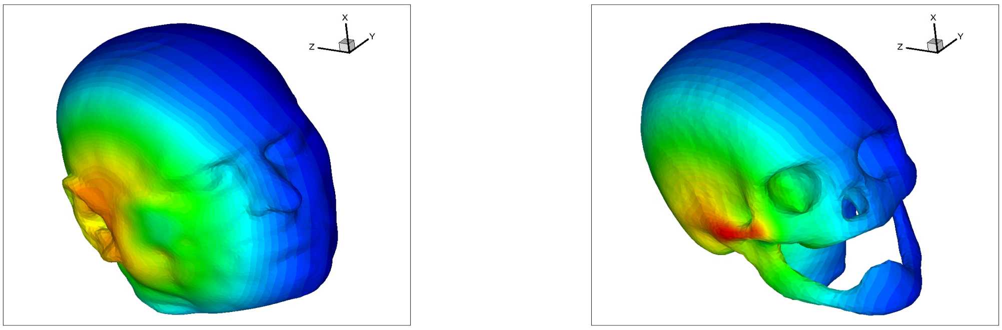

Figure 1. Exposure of head tissues to an electromagnetic wave emitted by a localized source. Top figures: surface triangulations of the skin and the skull. Bottom figures: contour lines of the amplitude of the electric field.

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 [40]- [49].

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 [45]. 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 [43]- [44]- [38]. 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.

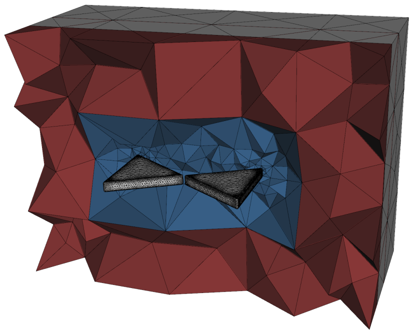

Figure 2. Simulation of the field enhancement at the tip of a gold bowtie nanoantenna (PhD thesis of Jonathan Viquerat).

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 [46] and based on the first order velocity-stress hyperbolic system of elastic waves equations, which is an extension of the scheme derived by Yee [48] 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.

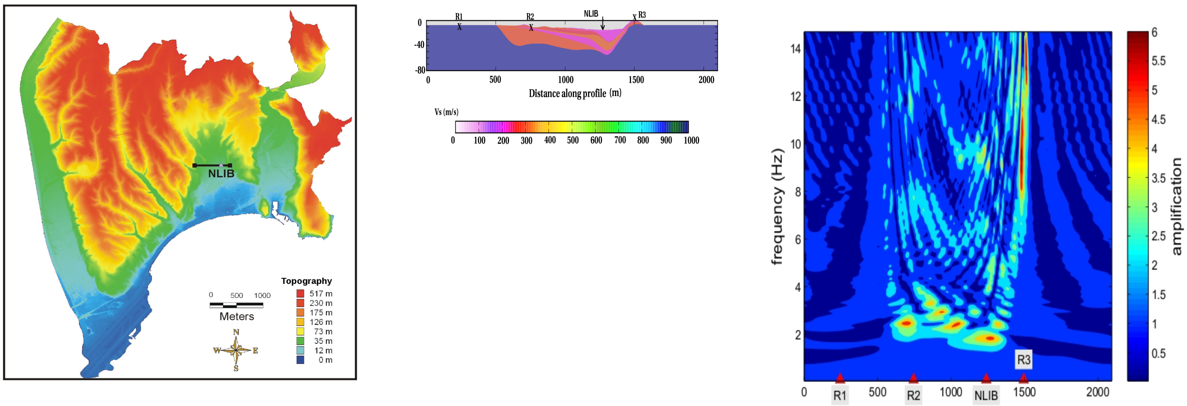

Figure 3. Propagation of a plane wave in a heterogeneous model of Nice area (provided by CETE Méditerranée). Left figure: topography of Nice and location of the cross-section used for numerical simulations (black line). Middle figure: S-wave velocity distribution along the cross-section in the Nice basin. 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 Gobe and Jonathan Viquerat
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- 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.

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- 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.

- 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. Numerical treatment of non-local dispersion for nanoplasmonics

Participants: Herbert de Gersem [TEMF, Technische Universität Darmstadt, Germany], Stéphane Lanteri, Antoine Moreau [Université Clermont Auvergne], Claire Scheid, Dimitrios Loukrezis [TEMF, Technische Universität Darmstadt, Germany], Serge Nicaise [Université de Valenciennes et du Hainaut-Cambresis], Armel Pitelet [Université Clermont Auvergne], Nikolai Schmitt, Jonathan Viquerat.

When metallic nanostructures have sub-wavelength sizes and the illuminating frequencies are in the regime of metal's plasma frequency, electron interaction with the exciting fields have to be taken into account. Due to these interactions, plasmonic surface waves (called plasmons) can be excited and cause extreme local field enhancements. Exploiting such field enhancements in applications of interest requires a detailed knowledge about the occurring fields which can generally not be obtained analytically. For the numerical modeling of light-matter interaction on the nanoscale, the choice of an appropriate model is a crucial point. Approaches that are adopted in a first instance are based on local (no interaction between electrons) dispersion models e.g. Drude or Drude-Lorentz. From the mathematical point of view, these models lead to an additional ordinary differential equation in time that is coupled to Maxwell's equations. When it comes to very small structures in a regime of 2 nm to 25 nm, non-local response due to electron collisions have to be taken into account. This leads to additional, in general non-linear, partial differential equations and is significantly more difficult to treat, though. The classical model is based on a hydrodynamical approach that takes non-local response of the electrons into account. We in particular focus our attention on the linearized version of this model called Linearized Hydrodynamical Drude model. We conducted numerical studies in 2D (published in 2016) and 3D on a linearized hydrodynamic model (published in 2018). However differences between local and nonlocal response are still small. Especially for today's fabrication precision, it remains a challenging task to find reliable structures where non-locality is dominant over e.g. geometrical errors. Motivated by trying to find experimental setups where non-locality is clearly distinguishable from other effects, we studied two promising structures, in close collaboration with physicists. First, in collaboration with A. Pitelet and A. Moreau from Université Clermont Auvergne, and D. Loukrezis and H. De Gersem from Technische Universität Darmstadt, we studied the impact of non-locality on gratings and showed that non-locality can affect surface plasmons propagating at the interface between a metal and a dielectric with a sufficiently high permittivity. We then design a grating coupler that should allow to experimentally observe this influence. Finally, we carefully set up a procedure to measure the signature of spatial dispersion precisely, paving the way for future experiments. Indeed, to ensure that the impact of non-locality exceeds geometric fabrication uncertainties, we proposed a post-fabrication characterization of the grating coupler. Based on the solution of inverse problems leading to the actually fabricated geometry and an uncertainty quantification (UQ) analysis, we conclude that non-locality should clearly be measurable in the grating coupler setting. This work has been submitted in a physics journal. Secondly in collaboration with A. Moreau we considered a nanocube setup that consists of an infinite gold ground layer plus a dielectric spacer of a given height above which a silver nanocube is chemically deposited. Due to this particular setting, the illumination of such a device is creating inside the gap between the nanocube and the ground layer (i.e. inside the dielectric layer) a gap plasmon that is very sensitive to non-locality. We proposed a surrogate-model based telemetry strategy in order to obtain the fabricated cube dimension (inverse problem). Based on this geometric characterization, we decreased the gap-size between the gold substrate and the silver cube and have compared local and non-local numerical simulations. We showed that the influence of non-locality exceeds the experimental error-bars for gap-sizes below 3.1 nm. Additionally, our nonlocal simulations are able to explain the discrepancy between the experiment and local simulations for very small gap-sizes. This project is still ongoing, since we are waiting for another set of experimental results.

On a theoretical side, we pursue the collaboration with S. Nicaise (Université de Valenciennes et du Hainaut-Cambresis) and proved well-posedness of the linearized non-local Drude model for various boundary conditions. We furthermore focused on establishing polynomial stability with optimal energy decay rate. We conducted a thorough study of energy stability for various numerical schemes and DG formulation using a general framework and finally numerically investigate the discrete polynomial stability. This work is almost finalized.

6.1.3. Study of 3D periodic structures at oblique incidences

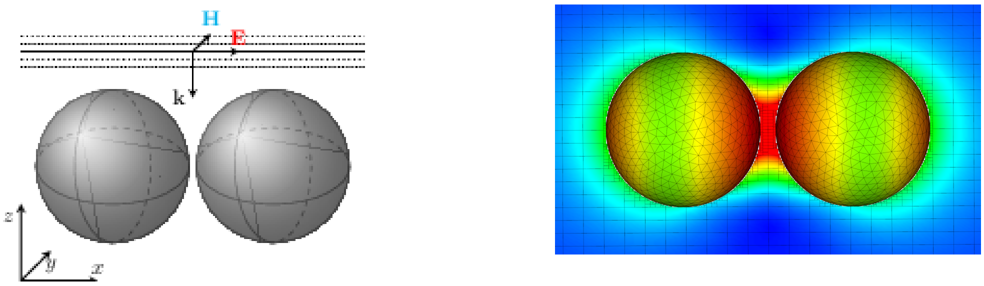


Figure 4. Nanosphere dimer system. Left figure sketches the dimer setup with an $\mathbf{e}_x$ polarized incident plane wave. Right figure shows the 3D field distribution of the electric field on the dimer surface and on a cutting plane and along the dimer axis (PhD thesis of Nikolai Schmitt).

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 is under review.

6.1.4. Toward thermoplasmonics

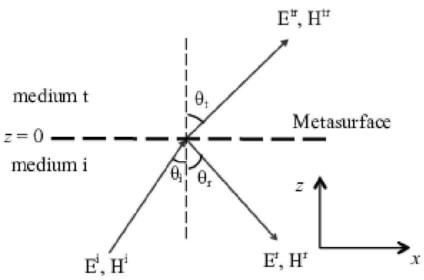
Participants: Yves d'Angelo, Guillaume Baffou [Fresnel Institute, Marseille], Stéphane Lanteri, Claire Scheid.

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.

6.1.4.1. Numerical modeling of metasurfaces

Participants: Loula Fezoui, Patrice Genevet [CRHEA laboratory, Sophia Antipolis], Stéphane Lanteri, Liang Li [UESTC, Chengdu, China], Ronan Perrussel [Laplace laboratory, Toulouse].

Metamaterials are composed of periodic subwavelength metal/dielectric structures that resonantly couple to the electric and/or magnetic components of the incident electromagnetic fields, exhibiting properties that are not found in nature. Planar metamaterials with subwavelength thickness, or metasurfaces, consisting of a layer of dielectric or plasmonic nanostructures, can be readily fabricated using lithography and nanoprinting methods, and the ultrathin thickness in the wave propagation direction can greatly suppress the undesirable losses. Metasurfaces enable a spatially varying optical response, mold optical wavefronts into shapes that can be designed at will, and facilitate the integration of functional materials to accomplish active control and greatly enhanced nonlinear response. Designing metasurfaces is generally a challenging inverse problem. A recently introduced synthesis techniques is based on so-called General Sheet Transition Conditions (GSTC) that can be leveraged to define the components of general bianisotropic surface susceptibility tensors characterizing the metasurface. A GSTC-based design technique has several advantages: 1) it is exact; 2) it is general, transforming arbitrary incident waves into arbitrary reflected and transmitted waves, 3) it often admits closed-form solutions, 4) it provides deep insight into the physics of the transformations, 5) it allows multiple (at least up to 4) simultaneous and independent transformations. We study the numerical treatment of GSTC in the time-domain and frequency-domain regimes in the DG and HDG settings respectively.



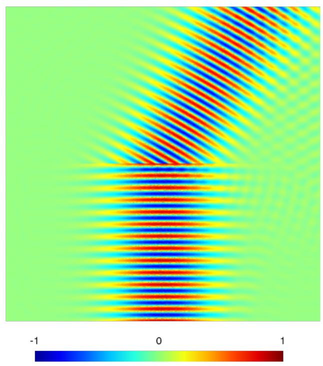


Figure 5. Simulation of a generalized refracting metasurface: problem formulation (left) and real part of H_y, refraction at $\theta = \pi/6$ (right).

6.1.4.2. Corner effects in nanoplasmonics

Participants: Camille Carvalho [Applied Mathematics Department, University of California Merced, USA], Patrick Ciarlet [ENSTA, POEMS project-team], Claire Scheid.

In this work, we study nanoplasmonic structures with corners (typically a diedral/triangular structure). This is the central subject considered in the PhD thesis of Camille Carvalho. In the latter, the focus is made on a lossles Drude dispersion model with a frequency-domain approach. Several well posedness problems arise due to the presence of corners and are addressed in the PhD thesis. A time-domain approach in this context is also relevant and we propose to use the techniques developed in the team in this prospect. Even if both approaches (time-domain and frequency-domain) represent similar physical phenomena, problems that arise are different. These two approaches appear as complementary; it is thus worth bridging the gap between the two frameworks. We are currently performing a thorough comparison in the case of theses 2D structures with corners and we especially focus on the amplitude principle limit that raises a lot of questions.

6.1.4.3. 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.

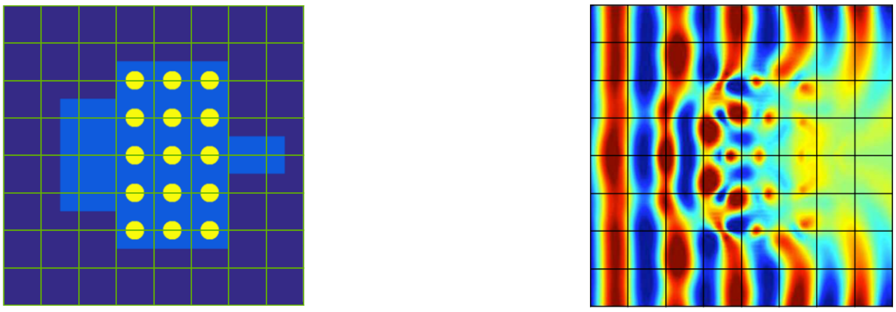


Figure 6. Light propagation in a photonic crystal structure using a MHM-DGTD method for solving the 2D Maxwell's equations. Left: quadrangular mesh. Right: contour lines of the amplitude of the electric field.

6.1.4.4. MHM methods for the frequency-domain Maxwell equations

Participants: Théophile Chaumont-Frelet, Zakaria Kassali, Stéphane Lanteri, Frédéric Valentin [LNCC, Petropolis, Brazil].

We have initiated this year a study of MHM methods for the system of frequency-domain Maxwell equations based on very promising results recently obtained by T. Chaumont-Frelet and F. Valentin for the Helmholtz equation. The design principles are very similar to those underlying MHM methods for the system of time-domain Maxwell equations however we expect to achieve more convincing results for highly multiscale problems since we do not have to deal with the time dimension in the present case. Part of this study is conducted in the context of the PHOTOM (PHOTOvoltaic solar devices in Multiscale computational simulations) Math-Amsud project.

6.1.4.5. HDG methods for the time-domain Maxwell equations

Participants: Stéphane Descombes, Stéphane Lanteri, Georges Nehmetallah.

This study is concerned with the development of accurate and efficient solution strategies for the system of 3D time-domain Maxwell equations coupled to local dispersion models (e.g. Debye, Drude or Drude-Lorentz models) in the presence of locally refined meshes. Such meshes impose a constraint on the allowable time step for explicit time integration schemes that can be very restrictive for the simulation of 3D problems. We consider here the possibility of using an unconditionally stable implicit time or a locally implicit time integration scheme combined to a HDG discretization method. As a preliminary step, we have investigated a fully explicit HDG method generalizing the classical upwind flux-based DG method for the system of time-domain Maxwell equations. We have studied the stability of this new HDG method and in particular, the influence of the stabilization parameter on the CFL condition. We are now progressing toward the design of a new family of high order in time hybrid explicit-implicit HDG methods to deal efficiently with CFL restriction due to grid-induced stiffness.

6.1.4.6. HDG methods for frequency-domain plasmonics

Participants: Stéphane Lanteri, Mostafa Javadzadeh Moghtader, Liang Li [UESTC, Chengdu, China].

HDG method is a new class of DG family with significantly less globally coupled unknowns, and can leverage a post-processing step to gain super-convergence. Its features make HDG a possible candidate for computational electromagnetics applications, especially in the frequency-domain. The HDG method introduces an hybrid variable, which represents an additional unknown on each face of the mesh, and leads to a sparse linear system in terms of the degrees of freedom of the hybrid variable only. Our HDG method had been first introduced for the system of 3D time-harmonic Maxwell's, combined to an iterative Schwarz domain decomposition (DD) algorithm to allow for an efficient parallel hybrid iterative-direct solver. The resulting DD-HDG solver has been applied to classical applications of electromagnetics in the microwave regime. In the present study we further focus on this particular physical context and propose a arbitrary high order HDG method for solving the system of 3D frequency-domain Maxwell equations coupled to a generalized model of physical dispersion in metallic nanostructures at optical frequencies. Such a generalized dispersion model unifies most common dispersion models, like Drude and Drude-Lorentz models, and it permits to fit large range of experimental data. The resulting DD-HDG solver is capable of using different element types and orders of approximation, hence enabling the possibilities of p-adaptivity and non-conforming meshing, and proves to have interesting potentials for modeling of complex nanophotonic and nanoplasmonic problems.

6.2. Elastodynamic wave propagation

6.2.1. Multiscale DG methods for the time-domain elastodynamic equations

Participants: Marie-Hélène Lallemand, Claire Scheid, Weslley Da Silva Pereira [LNCC, Petropolis, Brazil], Frédéric Valentin [LNCC, Petropolis, Brazil].

In the context of the visit of Frédéric Valentin in the team, we have initiated a study aiming at the design of novel multiscale methods for the solution of the time-domain elastodynamic equations, in the spirit of MHM (Multiscale Hybrid-Mixed) methods previously proposed for fluid flow problems. Motivation in that direction naturally came when dealing with non homogeneous anisotropic elastic media as those encountered in geodynamics related applications, since multiple scales are naturally present when high contrast elasticity parameters define the propagation medium. Instead of solving the usual system expressed in terms of displacement or displacement velocity, and stress tensor variables, a hybrid mixed-form is derived in which an additional variable, the Lagrange multiplier, is sought as representing the (opposite) of the surface tension defined at each face of the elements of a given discretization mesh. We consider the velocity/stress formulation of the elastodynamic equations, and study a MHM method defined for a heterogeneous medium where each elastic material is considered as isotropic to begin with. If the source term (the applied given force on the medium) is time independent, and if we are given an arbitrarily coarse conforming mesh (triangulation in 2D, tetrahedrization in 3D), the proposed MHM method consists in first solving a series of fully decoupled (therefore parallelizable) local (element-wise) problems defining parts of the full solution variables which are directly related to the source term, followed by the solution of a global (coarse) problem, which yields the degrees of freedom of both the Lagrange multiplier dependent part of the full solution variables and the Lagrange multiplier itself. Finally, the updating of the full solution variables is obtained by adding each splitted solution variables, before going on the next time step of a leap-frog time integration scheme. Theoretical analysis and implementation of this MHM method where the local problems are discretized with a DG method, are underway.

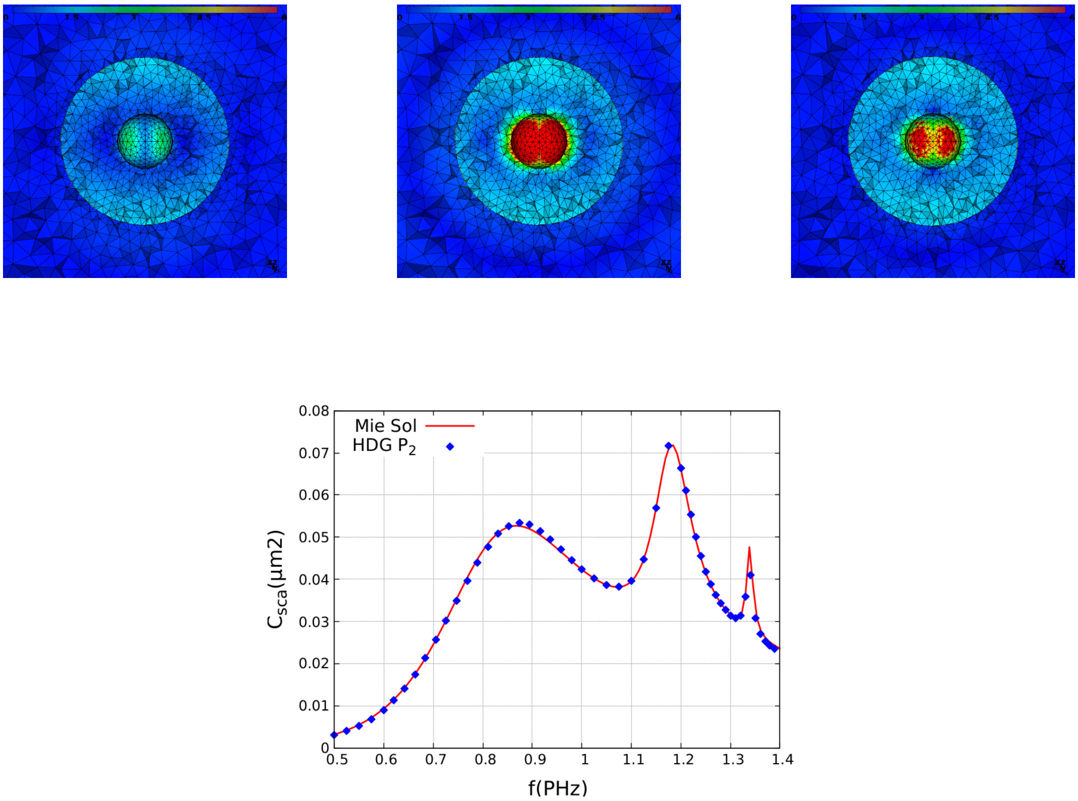


Figure 7. Top figures: scattering of a plane wave by a 50 nm gold nanosphere: magnitude of $\mathbf{E}$ *field at frequencies 1070 THz (left), 1185 THz (middle) and 1300 THz (right). Simulations based on a HDG-*$\mathbb{P}_2$ *method. Bottom figure: Scattering cross section.*

6.3. High performance numerical computing

6.3.1. High order HDG schemes and domain decomposition solvers for frequency-domain electromagnetics

Participants: Emmanuel Agullo [HIEPACS project-team, Inria Bordeaux - Sud-Ouest], Cristobal Samaniego Alvarado [HIEPACS project-team, Inria Bordeaux - Sud-Ouest], Mathieu Faverge [HIEPACS project-team, Inria Bordeaux - Sud-Ouest], Luc Giraud [HIEPACS project-team, Inria Bordeaux - Sud-Ouest], Matthieu Kuhn [HIEPACS project-team, Inria Bordeaux - Sud-Ouest], Stéphane Lanteri, Grégoire Pichon [HIEPACS project-team, Inria Bordeaux - Sud-Ouest], Pierre Ramet [HIEPACS project-team, Inria Bordeaux - Sud-Ouest].

This work is undertaken in the context of PRACE 5IP (http://www.prace-ri.eu/prace-5ip/) project and aims at the development of scalable frequency-domain electromagnetic wave propagation solvers, in the framework of the HORSE simulation software. HORSE 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 heterogeneous 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 and, on the other hand, the leveraging of low rank compression techniques for reducing the memory footprint of the factorization of subdomain problems using the PaStiX (Parallel Sparse matriX package - http://pastix.gforge.inria.fr/) package.

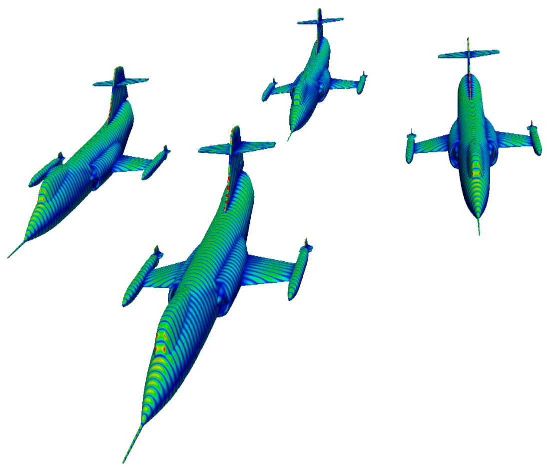


Figure 8. Scattering of a plane wave by a squadron Lockheed F-104 Starfighter. Contour lines of the amplitude of **E** *field. Simulations are performed with a HDG scheme based on a cubic interpolation of the electric and magnetic field unknowns, combined with a PDE-based domain decomposition solver.*

6.3.2. High order HDG schemes and domain decomposition solvers for frequency-domain electromagnetics

Participants: Stéphane Lanteri, Laércio Lima Pilla [CORSE project-team, Inria Grenoble - Rhône Alpes], Jean-François Méhaut [CORSE project-team, Inria Grenoble - Rhône Alpes].

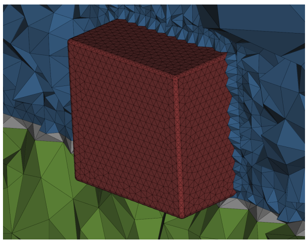
This work is undertaken in the context of PRACE 5IP (http://www.prace-ri.eu/prace-5ip/) project and aims at the development of a hybrid MPI/OpenMP parallellization of the DGTD solver of the DIOGENeS software suite. In practice, we concentrated our efforts on identifying and evaluating the best approaches for implementing fine grain parallism of the main DG numerical kernels, based on OpenMP features for loop-based parallelism on one hand, and task-based parallelism on the other hand.

6.4. Applications

6.4.1. Gap-plasmon confinement with gold nanocubes

Participants: Stéphane Lanteri, Antoine Moreau [Institut Pascal, Université Blaise Pascal], Armel Pitelet [Institut Pascal, Université Blaise Pascal], Claire Scheid, Nikolai Schmitt, Jonathan Viquerat.

The propagation of light in a slit between metals is known to give rise to guided modes. When the slit is of nanometric size, plasmonic effects must be taken into account, since most of the mode propagates inside the metal. Indeed, light experiences an important slowing-down in the slit, the resulting mode being called *gap-plasmon*. Hence, a metallic structure presenting a nanometric slit can act as a light trap, i.e. light will accumulate in a reduced space and lead to very intense, localized fields. Recently, the chemical production of random arrangements of nanocubes on gold films at low cost was proved possible by Antoine Moreau and colleagues at Institut Pascal. Nanocubes are separated from the gold substrate by a dielectric spacer of variable thickness, thus forming a narrow slit under the cube. When excited from above, this configuration is able to support gap-plasmon modes which, once trapped, will keep bouncing back and forth inside the cavity. At visible frequencies, the lossy behavior of metals will cause the progressive absorption of the trapped electromagnetic field, turning the metallic nanocubes into efficient absorbers. The frequencies at which this absorption occurs can be tuned by adjusting the dimensions of the nanocube and the spacer. In collaboration with Antoine Moreau, we propose to study numerically the impact of the geometric parameters of the problem on the behaviour of a single nanocube placed over a metallic slab (see Fig. 9).



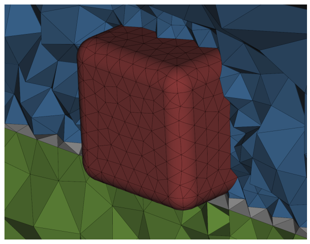


Figure 9. Meshes of rounded nanocubes with rounding radii ranging from 2 to 10 nm. Red cells correspond to the cube. The latter lies on the dielectric spacer (gray cells) and the metallic plate (green). Blue cells represent the air surrounding the device.

6.4.2. Photovoltaics

The ultimate success of photovoltaic (PV) cell technology requires substantial progress in both cost reduction and efficiency improvement. An actively studied approach to simultaneously achieve these two objectives is to leverage *light trapping* schemes. Light trapping allows solar cells to absorb sunlight using an active material layer that is much thinner than the material's intrinsic absorption length. This then reduces the amount of materials used in PV cells, which cuts cell cost in general, and moreover facilitates mass production of PV cells that are based on less abundant materials. In addition, light trapping can improve cell efficiency, since thinner cells provide better collection of photo-generated charge carriers. Enhancing the light absorption in ultrathin film silicon solar cells is thus of paramount importance for improving efficiency and reducing cost. We are involved in several studies in collaboration with physicists that aim at simulating light trapping in complex solar cell structures using high order DG and HDG solvers developed in our core research activities.

6.4.2.1. Light-trapping in texturized thin film solar cells

Participants: Urs Aeberhard [IEK5 - Photovoltaik, Forschungszentrum Juelich GmbH, German], Karsten Bittkau [IEK5 - Photovoltaik, Forschungszentrum Juelich GmbH, German], Alexis Gobé, Stéphane Lanteri.

This work is undertaken in the context of the EoCoE Center of Excellence in collaboration with researchers from IEK5 - Photovoltaik, Forschungszentrum Juelich GmbH, Germany. The objective is to design a scalable high order DGTD solver for the simulation of light trapping in a multi-layer solar cell with surface texture. For that purpose, we rely on the DIOGENeS software suite from which we extract a high order DGTD solver for the problem under consideration, taking into account its specificities (in particular, with regards to material models and boundary conditions). We also need to specify and develop a dedicated preprocessing tool for building topography conforming geometrical models. Simulations are performed on the Occigen PRACE system at CINES.

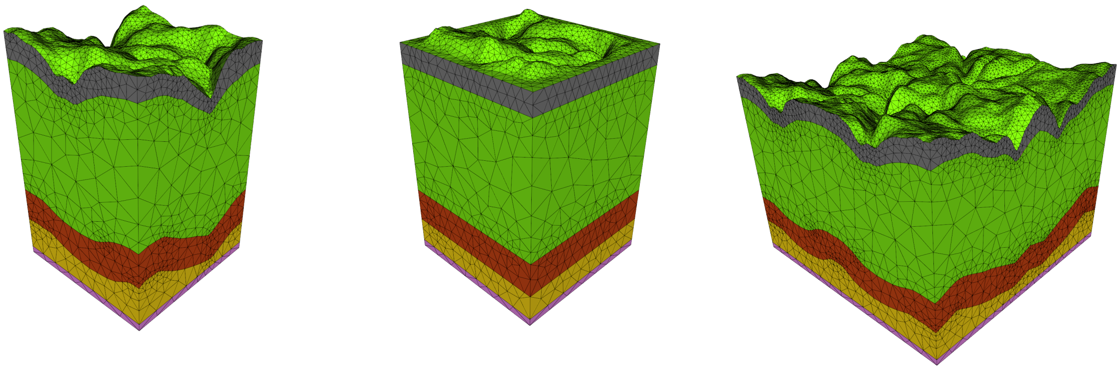


Figure 10. Simulation of light trapping in a multi-layer solar cell with surface texture using a high order DGTD fullwave solver and topography conforming geometrical models.

6.4.2.2. 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 [47]. In the present study, we adopt the nanocone grating considered in [47]. 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.

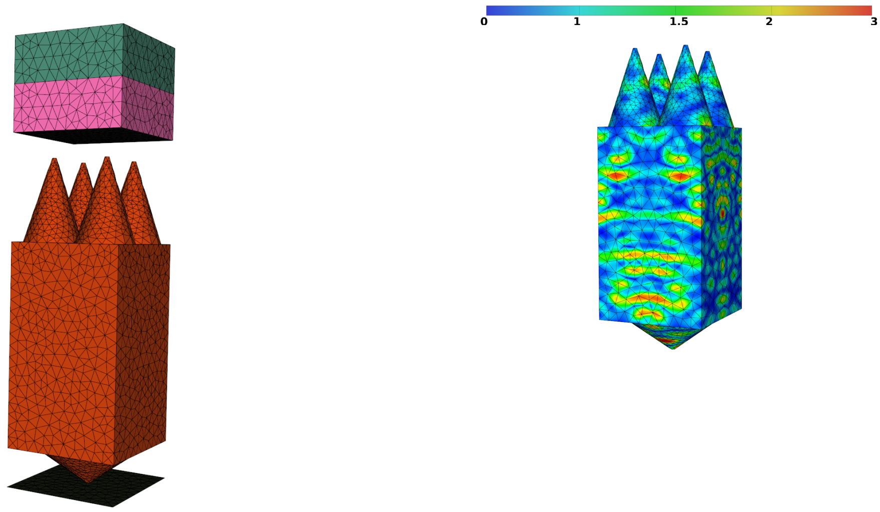


Figure 11. Simulation of light trapping in a solar cell based on nanocone gratings. Geometrical model (left) and contour lines of the module of the DFT of $\mathbf{E}$ *for a wavelength* $\lambda = 857$ *nm (right).*

6.4.3. Inver design of metasurfaces

Participants: Régis Duvigneau [ACUMES project-team, Inria Sophia Antipolis-Méditerranée], Mahmoud Elsawy, Patrice Genevet [CRHEA laboratory, Sophia Antipolis], Stéphane Lanteri.

Metasurfaces are flat surfaces consisting of sub-wavelength nanoresonators, made of plasmonic or high dielectric refractive index materials patterned in a specific way. These flat surfaces provide nearly full control of the light properties in a very short propagation distance with high resolution. By changing the dimensions, shapes, and orientation of these nanoresonators, different functionalities can be obtained. The complexity of the problem and the wide parameter space, make the direct modelling problem insufficient. Recently, several optimization techniques have been applied to the field of nanophotonics (including metasurfaces) by solving an inverse design problem. Generally speaking, there are two classes of optimization techniques that have been used in the metasurface designs; local and global techniques. The local methods depend on the initial guess and most of them require the computation of the gradient, which might be challenging. In addition, they are limited to small parameter space. On the other hand, global optimization techniques are suitable for optimizing several parameters moreover, they do not stuck in a local minima/maxima like the local methods. However, most of the global techniques used in the metasurface designs require costly simulations (for large parameter space), which make them inapplicable for modeling real-life designs that require 3D fullwave solvers. In this study conducted in collaboration with physicists at CRHEA, we use two efficient global optimization techniques based on statistical learning in order to overcome the disadvantageous of usual global optimization methods. The first one is the covariance matrix adaptation evolutionary strategy (CMA-ES). The CMA-ES has been gaining a lot of attention since it requires fewer cost function evaluations compared to the other evolutionary algorithms like genetic algorithms especially for 3D problems that require expensive simulations even with the high-performance computational resources. The second method is the Efficient Global Optimization (EGO) algorithm. The EGO algorithm is based on the surrogate modelling, that is to say, replacing the complex or costly evaluation process by a simpler and cheaper model to reduce dramatically the computational cost (number of calls for the electromagnetic simulations). Both techniques are offered by the Famosa library (http://famosa.gforge.inria.fr), which is developed by R. Duvigneau and colleagues in the ACUMES project-team.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. Numerical study of light absorption in a photovoltaic glass

Participants: Alexis Gobé, Badre Kerzabi [Sunpartner Technologies, Rousset], Stéphane Lanteri.

Sunpartner Technologies is a company in the field of novel technologies for a sustainable environment, which develops innovative photovoltaic solutions dedicated to the connected object, building and transport markets. In particular, the company is designing devices using solar energy to improve the autonomy of connected objects such as smartphones. Supartner Technologies also offers glass modules that can be integrated on the screen of a watch or a smart e-reader, for example. These glass modules are transparent and integrate photovoltaic cells to recover solar energy in order to recharge the batteries. In all these products, nanostructuring of constituent materials is an exploited strategy to maximize the absorption of sunlight. In addition to measurement, the simulation of the interaction between light and nanostructured matter is an important ingredient in the implementation of this strategy. As an extension of the simulation, the optimization of nanostructuring makes it possible to explore many solutions before the design stage. In the context of this partnership that has started this year, we aim at adapting and applying a DGTD solver from the DIOGENeS software suite to characterize and further optimize the nanostructuring of a photovoltaic glass.

8. Partnerships and Cooperations

8.1. European Initiatives

8.1.1. FP7 & H2020 Projects

8.1.1.1. EoCoE

Title: Energy oriented Centre of Excellence for computer applications

Program: H2020

See also: https://www.eocoe.eu

Duration: October 2015 - October 2018

Coordinator: CEA

Partners:

- Barcelona Supercomputing Center (Spain)
- CEA (France)
- CERFACS (France)
- CNR (Italy)
- The Cyprus Institute (Cyprus)
- ENEA (Italy)
- Fraunhofer–Gesellschaft (Germany)
- Instytut Chemii Bioorganicznej Polskiej Akademii Nauk (Poland)
- Forschungszentrum Julich (Germany)
- Max-Planck-Gesellschaft (Germany)

University of Bath (United Kingdom)

Universite Libre de Bruxelles (Belgium)

Universita Degli Studi di Trento (Italy)

Inria contact: Michel Kern

The aim of the present proposal is to establish an Energy Oriented Centre of Excellence for computing applications, (EoCoE). EoCoE (pronounce “Echo”) will use the prodigious potential offered by the ever-growing computing infrastructure to foster and accelerate the European transition to a reliable and low carbon energy supply. To achieve this goal, we believe that the present revolution in hardware technology calls for a similar paradigm change in the way application codes are designed. EoCoE will assist the energy transition via targeted support to four renewable energy pillars: Meteo, Materials, Water and Fusion, each with a heavy reliance on numerical modelling. These four pillars will be anchored within a strong transversal multidisciplinary basis providing high-end expertise in applied mathematics and HPC. EoCoE is structured around a central Franco-German hub coordinating a pan-European network, gathering a total of 8 countries and 23 teams. Its partners are strongly engaged in both the HPC and energy fields; a prerequisite for the long-term sustainability of EoCoE and also ensuring that it is deeply integrated in the overall European strategy for HPC. The primary goal of EoCoE is to create a new, long lasting and sustainable community around computational energy science. At the same time, EoCoE is committed to deliver high-impact results within the first three years. It will resolve current bottlenecks in application codes, leading to new modelling capabilities and scientific advances among the four user communities; it will develop cutting-edge mathematical and numerical methods, and tools to foster the usage of Exascale computing. Dedicated services for laboratories and industries will be established to leverage this expertise and to foster an ecosystem around HPC for energy. EoCoE will give birth to new collaborations and working methods and will encourage widely spread best practices.

8.1.1.2. PRACE 5IP

Title: PRACE Fifth Implementation Phase (PRACE-5IP) project

See also: http://www.prace-ri.eu/prace-5ip

Duration: January 2017 - April 2019

Partners: see http://www.prace-ri.eu/member-systems

Inria contact: Stéphane Lanteri

The mission of PRACE (Partnership for Advanced Computing in Europe) is to enable high-impact scientific discovery and engineering research and development across all disciplines to enhance European competitiveness for the benefit of society. PRACE seeks to realise this mission by offering world class computing and data management resources and services through a peer review process. PRACE also seeks to strengthen the European users of HPC in industry through various initiatives. PRACE has a strong interest in improving energy efficiency of computing systems and reducing their environmental impact. The objectives of PRACE-5IP 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 transition to PRACE2 including ananalysis of TransNational Access; strengthening the internationally recognised PRACE brand; continuing and extend advanced training which so far provided more than 18 800 persontraining days; preparing strategies and best practices towards Exascale computing; coordinating and enhancing the operation of the multi-tier HPC systems and services; supporting users to exploit massively parallel systems and novel architectures.

8.1.1.3. 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.

8.2. International Initiatives

8.2.1. Participation in Other International Programs

8.2.1.1. 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

Instituto de Matemáticas, PUCV (Chile), Diego Paredes

Duration: 2018 - 2019

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.

8.2.2. Inria International Partners

8.2.2.1. Informal International Partners

Prof. Kurt Busch, Humboldt-Universität zu Berlin, Institut für Physik, Theoretical Optics & Photonics

Prof. Martijn Wubs, Technical University of Denmark (DTU), Structured Electromagnetic Materials Theory group

Dr. Urs Aeberhard and Dr. Markus Ermes, Theory and Multiscale Simulation, IEK-5 Photovoltaik, Forschungszentrum Jülich, Germany

8.3. International Research Visitors

8.3.1. Visits of International Scientists

Prof. Liang Li, School of Mathematical Sciences, University of Electronic Science and Technology of China, Chengdu. From July to August 2018.

Stéphane Lanteri and Théophile Chaumont-Frelet at LNCC, Petropolis, Brazil, March 12-16, 2018.

Stéphane Lanteri and Claire Scheid at UAM and CSIC, Spain, May 29-30, 2018.

Stéphane Lanteri and Claire Scheid at Humboldt-Universität zu Berlin, Berlin, Germany, July 12-13, 2018.

Stéphane Lanteri at Barcelona Supercomputing Center, Barcelona, Spain, July 23-24, 2018.

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 CLIPhTON (advanCed numericaL modelIng for multiscale and multiphysics nanoPhoTONics) network that took place at Humboldt-Universität zu Berlin, Berlin, Germany, July 12-13, 2018.

9.1.2. Invited Talks

Claire Scheid, "A Discontinuous Galerkin Time-Domain framework for nanoplasmonics", Topical Workshop "Computational Aspects of Time Dependent Electromagnetic Wave Problems in Complex Materials", ICERM, Brown University, Providence, USA, June 25-29, 2018

Stéphane Lanteri, "Discontinuous Galerkin solvers for the numerical modeling of nanoscale light-matter interactions", MATHIAS 2018 - Computational Science Engineering & Data Science by TOTAL, Paris, October 22-24, 2018

Stéphane Lanteri, "Rigorous modeling of light absorption in nanostructured materials using a parallel high order finite element time-domain technique", Research Center for Advanced Science and Technology, The University of Tokyo, Japan, July, 30 2018

Stéphane Lanteri, "An upscaled DGTD method for time-domain electromagnetics", Special Session "Multiscale and multiphysics computation and applications", Progress In Electromagnetics Research Symposium - PIERS 2018, Toyama, Japan, August 1-4, 2018

9.1.3. Scientific Expertise

Stéphane Lanteri is a member of the Scientific Committee of CERFACS.

9.1.4. Research Administration

Stéphane Lanteri is a member of the Project-team Committee's Bureau of the Inria Sophia Antipolis-Méditerranée research center.

Stéphane Lanteri is a member of the Sciences Fondamentales et Appliquées Doctoral School Committee (until December 2018).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Stéphane Descombes, *Scientific computing*, M1, 36 h, Université Côte d'Azur.

Stéphane Descombes, *Principal components analysis*, M2, 30 h, Université Côte d'Azur.

Stéphane Lanteri, *High performance scientific computing*, MAM5, 24 h, Polytech Nice Sophia.

Claire Scheid, *Analyse Hibertienne et analyse de Fourier, Practical works*, Master 1 MPA, 36h, Université Côte d'Azur.

Claire Scheid, *Option Math 2*, Licence 1, 20h, Université Côte d'Azur.

Claire Scheid, *Méthodes numériques en EDP, Lectures and practical works*, Master 1 MPA and IM, 63h, Université Côte d'Azur.

Claire Scheid, *Option Modélisation, Lectures and practical works*, Master 2 Agrégation, 48h, Université Côte d'Azur.

Claire Scheid, *Analyse, Lecture and practical works*, Master 2 Agrégation, 27h, Université Côte d'Azur.

Claire Scheid, *EDP et Différences Finies, Lectures and practical works*, Master 1 MPA and IM, 72h, Université Côte d'Azur.

9.2.2. Supervision

PhD in progress: Alexis Gobé, *Multiscale hybrid-mixed methods for time-domain nanophotonics*, November 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 defened in September 2018: Nikolai Schmitt, *High-order simulation and calibration strategies for spatially dispersive metals in nanophotonics*, Stéphane Lanteri and Claire Scheid.

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Major publications by the team in recent years

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[15] J. VIQUERAT, M. KLEMM, S. LANTERI, C. SCHEID.*Theoretical and numerical analysis of local dispersion models coupled to a discontinuous Galerkin time-domain method for Maxwell's equations*, Inria, May 2013, n^{o} RR-8298, 79, http://hal.inria.fr/hal-00819758

Publications of the year

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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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A6.1.1. - Continuous Modeling (PDE, ODE)
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B9.5.1. - Computer science
B9.5.2. - Mathematics
B9.6.3. - Economy, Finance
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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]

Technical Staff
Gagan Deep Singh Chhabra [Inria, until Oct 2018]

PhD Students
Zaid Allybokus [Huawei]
Abhishek Bose [Inria, from Jun 2018]
Said Boularouk [Univ. d'Avignon et des pays du Vaucluse]
Mandar Datar [Inria, from May 2018]
Maximilien Dreveton [Inria, from Oct 2018]
Guilherme Iecker Ricardo [Institut Telecom, from Sep 2018]
Marie Masson [Orange]
Dimitra Politaki [Univ. de Nice - Sophia Antipolis]

Post-Doctoral Fellows
Nicolas Allegra [Inria, from Sep 2018]
Swapnil Dhamal [Inria]
Albert Sunny [Inria, until Apr 2018]
Chuan Xu [Inria, from Nov 2018]

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

NEO started a collaboration with QWANT within the joint QWANT-Inria laboratory, with two research projects. One is a direct collaboration, the other one is within the PIA ANSWER project. See Sections 8.1.2 and 9.2.1.

The book "Constrained Markov Decision Processes" by Eitan Altman is cited over 1000 times in Google Scholar.

Giovanni Neglia has been nominated IEEE Infocom 2018 Distinguished TPC member (Jan. 2018).

5.1.1. Awards

BEST PAPERS AWARDS :

[36]
E. HARGREAVES, D. S. MENASCHÉ, G. NEGLIA, C. AGOSTI.*Visibilidade no Facebook: Modelos, Medições e Implicações*, in "Brazilian Workshop on Social Network Analysis and Mining (BraSNAM)", Natal, Brazil, July 2018, https://hal.inria.fr/hal-01956316

[33]
K. VEERARUNA, S. MEMON, M. K. HANAWAL, E. ALTMAN, R. DEVANAND.*User Response Based Recommendations: A Local Angle Approach*, in "COMSNETS 2018 - 10th International Conference on COMmunication Systems & NETworkS", Bangalore, India, January 2018, p. 1-8, https://hal.inria.fr/hal-01702355

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.

- Participants: Alain Jean-Marie, Hlib Mykhailenko, Benjamin Briot, Franck Quessette, Issam Rabhi, Jean-Marc Vincent and Jean-Michel Fourneau
- Partner: UVSQ
- Contact: Alain Jean-Marie
- 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: Eitan Altman, Konstantin Avrachenkov, Mandar Datar, Swapnil Dhamal, Alain Jean-Marie, Albert Sunny.

7.1.1. Markov chains with restart/jumps

In [7], K. Avrachenkov together with A. Piunovskiy and Y. Zhang (Univ. of Liverpool, UK) consider a discrete-time Markov process with restart. At each step the process either with a positive probability restarts from a given distribution, or with the complementary probability continues according to a Markov transition kernel. The main contribution of this work is an explicit expression for the expectation of the hitting time (to a given target set) of the process with restart. The formula is convenient when considering the problem of optimization of the expected hitting time with respect to the restart probability. The results with are illustrated with two examples in uncountable and countable state spaces and with an application to network centrality.

Then, in [19], K. Avrachenkov and I. Bogdanov (HSE, Russia) study the relaxation time in the random walk with jumps. The random walk with jumps combines random walk based sampling with uniform node sampling and improves the performance of network analysis and learning tasks. They derive various conditions under which the relaxation time decreases with the introduction of jumps.

7.1.2. Markov modeling of Lasers

A. Jean-Marie has continued the investigation of Markov models of Lasers at several levels of physical accuracy, in conjunction with F. Philippe, L. Chusseau and A. Vallet (Univ. Montpellier and CNRS). In [17], a Markov model of relatively low complexity, the “Canonical Markov Model” (CMM), is built on the basis of a time-scale decomposition of physical phenomena. This simplified model is validated by comparison with a “microscopic Markov model” previously existing. Thanks to its smaller state space, simulations with the CMM are orders of magnitude faster, and numerical investigation of stationary and transient features become possible. As an example, the focus is put in [17], [39] on the Laser “threshold”, a phenomenon related to sojourn of the CMM in states where no light is emitted. Simulations and numerical solutions reveal the existence of a bi-modal distribution for the particles for a certain range of parameters, thereby predicting a certain instability of the Laser for these values. Investigations continue with a quantification of the intensity of “flashes” through the computation of hitting times in the CMM.

7.1.3. The marmoteCore platform

The development of `marmoteCore` (see Section 6.1) has been pursued by A. Jean-Marie. The software library is now being used in NEO's research projects such as [17] or queuing models supporting the analysis of Green Data Centers. `marmoteCore` provides the classes necessary to represent the state space of Markov models, from the elementary bricks that are interval or rectangular domains, simplices, or binary sequences. From there, the user easily programs the construction of probability transition matrices or infinitesimal generators. Structural analysis methods allow to identify recurrent and transient classes, and to compute the period of the model. Numerous methods allow the Monte Carlo simulation of the chain, the computation of transient and stationary distributions, as well as hitting times. In conjunction with E. Hyon (Univ. Paris-Nanterre), extensions of the core of the software are being programmed for Markov Decision Processes and Stochastic Games.

7.1.4. Blockchain mining

S. Dhamal, T. Chahed (Telecom SudParis), W. Ben-Ameur (Telecom SudParis), E. Altman, A. Sunny, and S. Poojary (UAPV, the Univ. of Avignon) have studied a stochastic game framework for distributed computing settings such as blockchain mining in [42]. A continuous-time Markov chain model, where players arrive and depart according to a stochastic process, is proposed, and their investment strategies are determined based on the state of the system. Two scenarios are analyzed, based on whether the rate of problem getting solved is dependent on or independent of the computational power invested by the players. The equilibrium strategies are shown to follow a threshold policy when this rate is proportional to the total invested power, while the players are shown to invest proportionally to the reward-cost ratio when this rate is independent of the invested power. The effects of arrival and departure rates on the players' utilities are quantified using simulations.

The paper extends the game theoretic modeling and analysis of the static case (fixed number of miners) done in [18] by E. Altman in collaboration with A. Reiffers-Masson (IISc, India), D. Sadoc Menasché (UFRJ), M. Datar and S. Dhamal, and C. Touati (Inria Grenoble Rhône-Alpes).

7.2. Queueing Theory

Participants: Sara Alouf, Konstantin Avrachenkov, Alain Jean-Marie, Dimitra Politaki.

7.2.1. Multiclass processor sharing and random order scheduling policies

In [2], K. Avrachenkov and T. Bodas (LAAS-CNRS) consider a single server system serving a multiclass population. Some popular scheduling policies for such system are the discriminatory processor sharing (DPS), discriminatory random order service (DROS), generalized processor sharing (GPS) and weighted fair queueing (WFQ). In this work, the authors propose two classes of policies, namely MPS (Multi-class Processor Sharing) and MROS (Multi-class Random Order Service), that generalize the four policies mentioned above. For the special case when the multi-class population arrive according to Poisson processes and have independent and exponential service requirement with parameter μ, they show that the tail of the sojourn time distribution for a class i customer in a system with the MPS policy is a constant multiple of the tail of the waiting time distribution of a class i customer in a system with the MROS policy. This result implies that for a class i customer, the tail of the sojourn time distribution in a system with the DPS (GPS) scheduling policy is a constant multiple of the tail of the waiting time distribution in a system with the DROS (respectively WFQ) policy.

7.2.2. The marmoteCore-Q tool

Using the `marmoteCore` platform, a tool called `marmoteCore-Q` has been developed by D. Politaki under the supervision of S. Alouf and A. Jean-Marie for the simulation of a family of queueing models based on the general BMAP/PH/c queue with impatience and resubmissions. There exist many special cases of this queue for which analytical results are known. Examples are: the M/M/1 queue and its finite capacity version, the M/M/c/K queue, the M/PH/1 and M/PH/∞ queues, the M^X/M/1 and M^X/M/∞ queues. Such examples are used to validate the implementation of the `marmoteCore-Q` tool.

7.3. Random Graph and Matrix Models

Participants: Konstantin Avrachenkov, Maximilien Dreveton.

In [5], K. Avrachenkov, together with A. Kadavankandy (CentraleSupélec) and N. Litvak (Univ. of Twente, The Netherlands), analyse a mean-field model of Personalized PageRank on the Erdös-Rényi random graph containing a denser planted Erdös-Rényi subgraph. They investigate the regimes where the values of Personalized PageRank concentrate around the mean-field value. They also study the optimization of the damping factor, the only parameter in Personalized PageRank. Their theoretical results help to understand the applicability of Personalized PageRank and its limitations for local graph clustering.

7.4. Data Analysis and Learning

Participant: Konstantin Avrachenkov.

7.4.1. Unsupervised learning

In [6], K. Avrachenkov, together with A. Kondratev, V. Mazalov (Petrozavodsk State Univ., Russia) and D. Rubanov (Amadeus), applied game-theoretic methods for community detection in networks. The traditional methods for detecting community structure are based on selecting dense subgraphs inside the network. Here the authors propose to use the methods of cooperative game theory that highlight not only the link density but also the mechanisms of cluster formation. Specifically, they suggest two approaches from cooperative game theory: the first approach is based on the Myerson value, whereas the second approach is based on hedonic games. Both approaches allow to detect clusters with various resolutions. However, the tuning of the resolution parameter in the hedonic games approach is particularly intuitive. Furthermore, the modularity-based approach and its generalizations as well as ratio cut and normalized cut methods can be viewed as particular cases of the hedonic games. Finally, for approaches based on potential hedonic games a very efficient computational scheme using Gibbs sampling is suggested.

7.4.2. Semi-supervised learning

Graph Semi-supervised learning (gSSL) aims to classify data exploiting two initial inputs: firstly, the data are structured in a network whose edges convey information on the proximity, in a wide sense, of two data points (e.g. correlation or spatial proximity) and, second, there is a partial information on some nodes, which have previously been labelled. Thus, the classification problem is usually a balance between two terms: one diffusing the information from the labelled points to the unlabelled ones through the network and another one that constrains the solution to be similar, on the labelled nodes, to the given labels. In practice, popular SSL methods as Standard Laplacian (SL), Normalized Laplacian (NL) or PageRank (PR), exploit those operators defined on graphs to spread the labels and, from a random walk perspective, the classification of a given point is given the maximum of the expected number of visits from one class. Anomalous diffusion can alter the way a graph is “explored” and, therefore, it can alter classification performance. In a nushell, Lévy flights/walks are a way to create superdiffusive regimes: the customary rule for their ignition is to allow the walkers to perform non-local jumps, whose length is distributed according to a fat-tailed probability density function with diverging second moment. Mathematically speaking, there have been several attempts to convert the Lévy flight phenomenon on networks and, in the context of gSSL, K. Avrachenkov in conjunction with S. De Nigris, E. Bautista, P. Abry and P. Gonçalves, settled in [38] for the use of fractional operators. In this SSL context, the authors cast those operators in the SSL problem in each different incarnation (SL, PR and NL) and investigated the beneficial effect of such a procedure for classification.

In [13], K. Avrachenkov, together with A. Kadavankandy (CentraleSupélec), L. Cottatellucci (EURECOM) and R. Sundaresan (IISc, India), tackle the problem of hidden community detection. We consider Belief Propagation (BP) applied to the problem of detecting a hidden Erdös-Rényi (ER) graph embedded in a larger and sparser ER graph, in the presence of side-information. We derive two related algorithms based on BP to perform subgraph detection in the presence of two kinds of side-information. The first variant of side-information consists of a set of nodes, called cues, known to be from the subgraph. The second variant of side-information consists of a set of nodes that are cues with a given probability. It was shown in past works that BP without side-information fails to detect the subgraph correctly when a so-called effective signal-to-noise ratio (SNR) parameter falls below a threshold. In contrast, in the presence of non-trivial side-information, we show that the BP algorithm achieves asymptotically zero error for any value of a suitably defined phase-transition parameter. We validate our results on synthetic datasets and a few real world networks.

7.4.3. Supervised learning

Graphlets are defined as k-node connected induced subgraph patterns. For instance, for an undirected graph, 3-node graphlets include closed triangles and open triangles. The number of each graphlet, called graphlet count, is a signature which characterizes the local network structure of a given graph. Graphlet count plays a prominent role in network analysis of many fields, most notably bioinformatics and social science. However, computing exact graphlet count is inherently difficult and computational expensive because the number of graphlets grows exponentially large as the graph size and/or graphlet size grow. To deal with this difficulty, many sampling methods were proposed to estimate graphlet count with bounded error. Nevertheless, these methods require large number of samples to be statistically reliable, which is still computationally demanding. Intuitively, learning from historic graphs can make estimation more accurate and avoid many repetitive counting to reduce computational cost. Based on this idea, in [29] K. Avrachenkov, together with X. Liu, J. Chen and J. Lui (CUHK, Hong Kong), propose a convolutional neural network (CNN) framework and two preprocessing techniques to estimate graphlet count. Extensive experiments on two types of random graphs and real world biochemistry graphs show that their framework can offer substantial speedup on estimating graphlet count of new graphs with high accuracy.

7.5. Game Theory

Participants: Eitan Altman, Swapnil Dhamal.

7.5.1. Resource allocation polytope games

S. Dhamal, W. Ben-Ameur, T. Chahed (both from Telecom SudParis), and E. Altman have studied two-player resource allocation polytope games in [24]. The strategy of a player is considered to be restricted by the strategy of the other player, with common coupled constraints. In the context of such games, novel notions of independent optimal strategy profile and common contiguous set are introduced. Necessary and sufficient conditions are derived for the game to have a unique pure strategy Nash equilibrium. Given an instance of the game, an efficient algorithm is presented to compute the price of anarchy. Under reasonable conditions, the price of stability is shown to be 1. A paradox is shown that higher budgets may lead to worse outcomes.

7.6. Applications in Telecommunications

Participants: Zaid Allybokus, Sara Alouf, Eitan Altman, Konstantin Avrachenkov, Swapnil Dhamal, Alain Jean-Marie, Giovanni Neglia, Dimitra Politaki.

7.6.1. Caching

A fundamental brick of the information-centric architectures proposed for Internet evolution is in-network caching, i.e. the possibility for the routers to store locally the contents and directly serve future requests. This has raised a new interest in the performance of networks of caches. Since 2012, there has been a significant research activity in NEO on this topic. Our work raised the attention of researchers at Akamai Technologies (the world leader in Content Delivery Networks). In real caching systems the hit rate is often limited by the speed at which contents can be retrieved by the Hard-Disk Drive (HDD) (this is the so-called *spurious misses*' problem). Akamai researchers asked us to design an algorithm to solve this problem. In [43] G. Neglia and D. Tsigkari, together with D. Carra (Univ. of Verona, Italy), M. Feng, V. Janardhan (Akamai Technologies, USA), and P. Michiardi (EURECOM) have proposed a simple randomized caching policy that makes optimal use of the RAM to minimize the load on the HDD and then the number of spurious misses. Moreover, experiments in Akamai CDN have shown that our policy reduces the HDD load by an additional 10% in comparison to the (highly optimized) baseline policy currently employed by Akamai. In [15] a subset of the same authors (G. Neglia, D. Carra, P. Michardi) have shown that the same approach can be adapted to minimize any miss cost function as far as the cost is additive over the misses.

More recently, we moved to consider the problem of caches' coordination in a dense cellular network scenario, where caches are deployed at base stations (BSs) and a user can potentially retrieve the content from multiple BSs. In this setting, the optimal content placement problem is NP-hard even when the goal is simply to maximize the hit ratio. Most of the existing literature has proposed heuristics assuming that content popularities are static and known, but in reality their estimation can be very difficult at the scale of the geographical area covered by a BS. In [14] E. Leonardi (Politecnico di Torino, Italy) and G. Neglia have introduced a class of simple and fully distributed caching policies, which require neither direct communication among BSs, nor a priori knowledge of content popularity (strongly deviating from the assumptions of existing literature). They have shown that optimal coordination can be achieved by applying minor changes to existing policies and piggybacking an additional information bit to each content request. How to achieve coordination for more complex performance metrics (e.g. the retrieval time or fairness) is still an open research problem that is now the PhD subject of G. Iecker, co-supervised by G. Neglia and T. Spyropoulos (EURECOM).

7.6.2. Modeling and workload characterization of data center clusters

There are many challenges faced when modeling computing clusters. In such systems, jobs to be executed are submitted by users. These jobs may generate a large number of tasks. Some tasks may be executed more than once while other may abandon before execution. D. Politaki, S. Alouf, F. Hermenier (Nutanix), and A. Jean-Marie have developed a multi-server queueing system with abandonments and resubmissions to model computing clusters. To capture the correlations observed in real workload submissions, a Batch Markov Arrival Process is considered. The service time is assumed to have a phase-type distribution. This model has not been analyzed in the literature. The distributions of the interarrivals and the service times found in the Google Cluster Data have been characterized and compared with fitted distributions. The authors findings support the model assumptions. Ongoing work investigates the approaches that can be adopted to overcome the technical challenges found in the performance evaluation of the computing clusters. In particular, the developed tool `marmoteCore-Q` (see §7.2.2) will be used.

To understand the essential characteristics of a computing cluster for modelling purposes, the same authors have looked into two datasets consisting of job scheduler logs. The first dataset comes from a Google cluster and is publicly available (https://github.com/google/cluster-data). The second dataset has been collected from the internal computing cluster of Inria Sophia-Antipolis Méditerrannée. After a preliminary analysis and sanitizing of each dataset, a numerical analysis is performed to characterize the different stochastic processes taking place in the computing cluster. In particular, the authors characterize the impatience process, the re-submission process, the arrival process (batch sizes and correlations) and the service time, considering the impact of the scheduling class and of the execution type.

7.6.3. Software Defined Networks (SDN)

The performance of computer networks relies on how bandwidth is shared among different flows. Fair resource allocation is a challenging problem particularly when the flows evolve over time. To address this issue, bandwidth sharing techniques that quickly react to the traffic fluctuations are of interest, especially in large scale settings with hundreds of nodes and thousands of flows. In this context, K. Avrachenkov and Z. Allybokus, together with J. Leguay (Huawei Research) and L. Maggi (Nokia Bell Labs), in [1] propose a distributed algorithm based on the Alternating Direction Method of Multipliers (ADMM) that tackles the multi-path fair resource allocation problem in a distributed SDN control architecture. Their ADMM-based algorithm continuously generates a sequence of resource allocation solutions converging to the fair allocation while always remaining feasible, a property that standard primal-dual decomposition methods often lack. Thanks to the distribution of all computer intensive operations, they demonstrate that large instances can be handled at scale.

7.6.4. Impulsive control of G-AIMD dynamics

Motivated by various applications from Internet congestion control to power control in smart grids and electric vehicle charging, in [20] K. Avrachenkov together with A. Piunovskiy and Y. Zhang (Univ. of Liverpool, UK) study Generalized Additive Increase Multiplicative Decrease (G-AIMD) dynamics under impulsive control in continuous time with the time average alpha-fairness criterion. They first show that the control under relaxed constraints can be described by a threshold. Then, they propose a Whittle-type index heuristic for the hard constraint problem. They prove that in the homogeneous case the index policy is asymptotically optimal when the number of users is large.

7.6.5. Application of Machine Learning to optimal resource allocation in cellular networks

In [9], E. Altman in collaboration with A. Chattopadhyay and B. Błaszczyszyn (from Inria DYOGENE team) consider location-dependent opportunistic bandwidth sharing between static and mobile downlink users in a cellular network. 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 Markov decision process (MDP) where the per-step reward is a linear combination of instantaneous data volumes received by static and mobile users. The transition structure of this MDP is not known in general. They thus propose a learning algorithms based on stochastic approximation with one and with two time scales. The results are extended to address the issue of fair bandwidth sharing between the two classes of users.

To optimize routing of flows in datacenters, SDN controllers receive a packet-in message whenever a new flow appears in the network. Unfortunately, flow arrival rates can peak to millions per second, impairing the ability of controllers to treat them on time. Flow scheduling copes with this by segmenting the traffic between elephant and mice flows and by treating elephant flows in priority, as they disrupt short lived TCP flows and create bottlenecks. In [21], E. Altman in collaboration with F. De Pellegrini (UAPV), L. Maggi (Huawei), A. Massaro (FBK Trento), D. Saucez (Inria DIANA team) and J. Leguay (Huawei Research) propose a stochastic approximation based learning algorithm called SOFIA and able to perform optimal online flow segmentation. Extensive numerical experiments characterize the performance of SOFIA.

7.6.6. Forecast Scheduling

With the age of big data and with geo-localisation measurements available, the precision in predicting the mobility of users increases, and hence also that of the prediction of channel conditions. In [35], E. Altman in collaboration with H. Zaaraoui, S. Jema, Z. Altman (Orange Labs) and T. Jimenez (UAPV) propose a convex optimization approach to Forecast Scheduling which makes use of current and future predicted channel conditions to obtain an optimal alpha fair schedule. They further extend the model in [34] to take into account different types of random events such as arrival and departure of users and uncertainties in the mobile trajectories. Simulation results illustrate the significant performance gain achieved by the Forecast Scheduling algorithms in the presence of random events.

7.6.7. Fairness in allocation to users with different time constraints

E. Altman and S. Ramanath (IIT Bombay, India) study in [31] how to allocate resources fairly when different users have different time constraints for using the resources. They formulate this as a Markov Decision Process (MDP) for a two user case and provide a Dynamic Program (DP) solution. Simulation results in an LTE framework are provided to support the theoretical claims.

7.7. Applications in Social Networks

Participants: Eitan Altman, Konstantin Avrachenkov, Swapnil Dhamal, Giovanni Neglia.

7.7.1. Fairness in Online Social Network Timelines

Facebook News Feed personalization algorithm has a significant impact, on a daily basis, on the lifestyle, mood and opinion of millions of Internet users. Nonetheless, the behavior of such algorithm lacks transparency, motivating measurements, modeling and analysis in order to understand and improve its properties. E. Altman and G. Neglia, together with other researchers from THANES team (E. Hargreaves and D. Menasché from UFRJ, A. Reiffers-Masson from IIsc, and E. Altman) and with the journalist C. Agosti (Univ. of Amsterdam), have proposed a reproducible methodology encompassing measurements, an analytical model and a fairness-based News Feed design. The model leverages the versatility and analytical tractability of time-to-live (TTL) counters to capture the visibility and occupancy of publishers over a News Feed. Measurements from 2018 Italian political election are used to parameterize and to validate the expressive power of the proposed model. Then, we have conducted a what-if analysis to assess the visibility and occupancy bias incurred by users against a baseline derived from the model. Our results indicate that a significant bias exists and it is more prominent at the top position of the News Feed. In addition, we have found that the bias is non-negligible even for users that are deliberately set as neutral with respect to their political views, motivating the proposal of a novel and more transparent fairness-based News Feed design. This is a very recent research direction, but it has already led to 4 publications [36], [27], [28], [12] with a *best paper award* for [36].

7.7.2. Sampling online social networks

In the framework of network sampling, random walk (RW) based estimation techniques provide many pragmatic solutions while uncovering the unknown network as little as possible. Despite several theoretical advances in this area, RW based sampling techniques usually make a strong assumption that the samples are in stationary regime, and hence are impelled to leave out the samples collected during the burn-in period. In [4] K. Avrachenkov, together with V.S. Borkar (IIT Bomaby, India), A. Kadavankandy (CentraleSupélec) and J.K. Sreedharan (Purdue Univ., USA), propose two sampling schemes without burn-in time constraint to estimate the average of an arbitrary function defined on the network nodes, for example, the average age of users in a social network. The central idea of the algorithms lies in exploiting regeneration of RWs at revisits to an aggregated super-node or to a set of nodes, and in strategies to enhance the frequency of such regenerations either by contracting the graph or by making the hitting set larger. Our first algorithm, which is based on reinforcement learning (RL), uses stochastic approximation to derive an estimator. This method can be seen as intermediate between purely stochastic Markov chain Monte Carlo iterations and deterministic relative value iterations. The second algorithm, which we call the Ratio with Tours (RT)-estimator, is a modified form of respondent-driven sampling (RDS) that accommodates the idea of regeneration. We study the methods via simulations on real networks. We observe that the trajectories of RL-estimator are much more stable than those of standard random walk based estimation procedures, and its error performance is comparable to that of respondent-driven sampling (RDS) which has a smaller asymptotic variance than many other estimators. Simulation studies also show that the mean squared error of RT-estimator decays much faster than that of RDS with time. The newly developed RW based estimators (RL- and RT-estimators) allow to avoid burn-in period, provide better control of stability along the sample path, and overall reduce the estimation time.

7.7.3. Crawling ephemeral content

In [3], K. Avrachenkov and V.S. Borkar (IIT Bombay, India) consider the task of scheduling a crawler to retrieve from several sites their ephemeral content. This is content, such as news or posts at social network groups, for which a user typically loses interest after some days or hours. Thus development of a timely crawling policy for ephemeral information sources is very important. The authors first formulate this problem as an optimal control problem with average reward. The reward can be measured in terms of the number of clicks or relevant search requests. The problem in its exact formulation suffers from the curse of dimensionality and quickly becomes intractable even with a moderate number of information sources. Fortunately, this problem admits a Whittle index, a celebrated heuristics which leads to problem decomposition and to a very simple and efficient crawling policy. The authors derive the Whittle index for a simple deterministic model and provide its theoretical justification. They also outline an extension to a fully stochastic model.

7.7.4. Posting behavior

In [32], E. Altman in collaboration with A. Reiffers-Masson (IISc, India), Y. Hayel and G. Marrel (UAPV) consider a “generalized” fractional program in order to solve a popularity optimization problem in which a source of contents controls the topics of her contents and the rate with which posts are sent to a time line. The objective of the source is to maximize its overall popularity in an Online Social Network (OSN). The authors propose an efficient algorithm that converges to the optimal solution of the Popularity maximization problem.

7.7.5. Recommendation system for OSNs

When a user interested in a service/item, visits an online web-portal, it provides description of its interest through initial search keywords. The system recommends items based on these keywords. The user is satisfied if it finds the item of its choice and the system benefits, otherwise the user explores an item from the list. In [33], E. Altman in collaboration with K. Veeraruna, S. Memon, M. Hanawal and R. Devanand (IEOR IIT Bombay, India), develop algorithms that efficiently utilize user responses to recommended items and find the item of user's interest quickly. The authors first derive optimal policies in the continuous Euclidean space and adapt the same to the space of discrete items.

7.7.6. Opinion dynamics

S. Dhamal, W. Ben-Ameur, T. Chahed (both from Telecom SudParis), and E. Altman have studied the problem of optimally investing in nodes of a social network, wherein two camps attempt to maximize adoption of their respective opinions by the population. In [11], 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. In [23], the possibility of campaigning in multiple phases is explored, where the final opinion of a node in a phase acts as its initial bias for the next phase. A further intricate setting where a camp's influence on a node also depends on the node's initial bias, is analyzed in [22]. Extensive simulations are conducted on real-world social networks for all the considered settings.

7.7.7. Information diffusion under practical models

S. Dhamal has studied the effectiveness of adaptive seeding in multiple phases under the independent cascade model of information diffusion, in [25]. The effect on the mean and standard deviation of the extent of diffusion is observed, with an explanation of how adaptive seeding reduces uncertainty in diffusion. The other aspects studied are: how the number of phases impacts the effectiveness of diffusion, how the diffusion progresses phase-by-phase, and how to optimally split the total seeding budget across phases. Another study [26] generalizes the linear threshold model to account for multiple product features, and presents an integrated framework 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.

7.8. Applications to Energy

Participant: Giovanni Neglia.

7.8.1. Smart grids

Balancing energy demand and production is becoming a more and more challenging task for energy utilities because of the larger penetration of renewable energies, more difficult to predict and control. While the traditional solution is to dynamically adapt energy production to follow the time-varying demand, a new trend is to drive the demand itself. We have first considered the direct control of inelastic home appliances, whose energy consumption cannot be shaped, but simply deferred. Our solution does not suppose any particular intelligence at the appliances, the actuators are rather smart plugs, simple devices with communication capabilities that can be inserted between appliances' plugs and power sockets and are able to interrupt/reactivate power flow. During previous years we have considered both closed-loop and open-loop control of such devices in order to satisfy a probabilistic bound on the aggregated power consumption. Recently, G. Neglia, together with L. Giarré (Univ. di Modena e Reggio Emilia, Italy), I. Tinnirello and G. Di Bella (Univ. di Palermo, Italy) have considered a mixed approach [16]. They have been able to quantify the trade-off between the amount of controlled power and delays experienced by the users to evaluate to which scale this solution should be deployed.

We have also looked at Demand-Response (DR) programs, whereby users of an electricity network are encouraged by economic incentives to re-arrange their consumption in order to reduce production costs. Several recent works proposed DR mechanisms relying on a macroscopic description of the population that does not model individual choices of users. In [8], G. Neglia, together with A. Benegiamo (EURECOM/Inria) and P. Loiseau (EURECOM) has shown that these macroscopic models hide important assumptions that can jeopardize the mechanisms' implementation (such as the ability to make personalized offers and to perfectly estimate the demand that is moved from a timeslot to another). Then, starting from a microscopic description that explicitly models each user's decision, they have introduced new DR mechanisms with various assumptions on the provider's capabilities. Contrarily to previous studies, they have found that 1) the resulting optimization problems are complex and can be solved numerically only through heuristics, 2) the savings from DR mechanisms are significantly lower than those suggested by previous studies.

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 one ADR "Distributed Learning and Control for Network Analysis" (see §8.1.1).
- Inria-QWANT joint laboratory "Smart search is privacy" (see §8.1.2);
- Inria-Orange Labs joint laboratory (see §8.1.3).

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, Alain Jean-Marie.

- 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. Qwant contract on "Asynchronous on-line computation of centrality measures" (15 December 2017 – 14 May 2020)

Participants: Nicolas Allegra, Konstantin Avrachenkov.

- Contractor: Qwant
- Collaborator: Sylvain Peyronnet

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.

8.1.3. *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://orange.jobs/site/en-innovation-rd/)
- 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 (vRAN).

8.1.4. *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 is 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.

9. Partnerships and Cooperations

9.1. Regional Initiatives

MYDATA (Sept. 2018 - Nov. 2020) 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."

9.2. National Initiatives

9.2.1. *PIA ANSWER*

Participants: Konstantin Avrachenkov, Abhishek Bose.

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.

9.3. 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, Erdös-Rényi 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) - Department of Computer and Systems Engineering (PESC/COPPE) - Daniel Ratton Figueiredo, Edmundo De Souza e Silva

Universidade Federal do Rio de Janeiro (Brazil) - Math institute - Giulio Iacobelli

Purdue Univ. (USA) - Computer Science Department - Bruno Ribeiro

Start year: 2017

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

We plan move beyond the study of a single network and focus on multiplex networks, i.e. multiple interacting networks. Multiplex networks have recently raised as “one of the newest and hottest themes in the statistical physics of complex networks.” They originate from the observation that many complex systems, ranging from living organisms to critical infrastructures, operate through multiple layers of distinct interactions among their constituents. In particular we plan to work on the co-evolution of the different layers of a multiplex network and on how epidemics spread in such setting.

9.4.2. Inria International Partners

9.4.2.1. Informal International Partners

NEO has continued collaborations with researchers from GERAD, Univ. Montreal (Canada), Flinders Univ. (Australia), Univ. of South Australia (Australia), National Univ. of Rosario (Argentina), Technion - Israel Institute of Technology (Israel), Univ. of Arizona (USA), Univ. of Illinois at Urbana-Champaign (USA), Univ. of Liverpool (UK), Univ. of Massachusetts at Amherst (USA), Univ. of Florence (Italy), Univ. of Palermo (Italy), Univ. of Twente (The Netherlands), Saint Petersburg State Univ. (Russia), Petrozavodsk State Univ. (Russia) and Ghent Univ. (Belgium).

9.4.3. Participation in Other International Programs

9.4.3.1. 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

Damiano Carra, Date: 23-27 April, Institution: Univ. of Verona (Italy)

Daniel Figueiredo, Date: 9-13 July, Institution: UFRJ (Brazil)

Giulio Iacobelli, Date: 9-13 July, Institution: UFRJ (Brazil)

Nikhil Karamchandani, Date: 11-15 June, Institution: IIT Bombay (India)

Nelly Litvak, Date: 2-14 July, Institution: Univ. of Twente (Netherlands)

Vladimir Mazalov, Date: 16-17 July, Institution: Petrozavodsk State Univ. (Russia)

Daniel Sadoc Menasché, Date: 31 August - 6 September, Date: 8-12 December, Institution: UFRJ (Brazil)

Bruno Ribeiro, Date: 9-18 July, Institution: Purdue Univ. (USA)

Vikas Vikram Singh, Date: 1-8 June, Institution: IIT Delhi (India)

Rajesh Sundaresan, Date: 15-26 January, Institution: IISc Bangalore (India)

9.5.1.2. Postdoc/PhD Students

Víctor Bucarey López, Date: 18-19 October, Institution: Université Libre de Bruxelles (Belgium)

Yuzhou Chen, Date: 7 June - 6 September, Institution: Southern Methodist Univ. (USA)

Eduardo Hargreaves, Date: 31 August - 6 September, Institution: UFRJ (Brazil)

Mayank Kakodkar, Date: 9-13 July, Institution: Purdue Univ. (USA)

Mikhail Kamalov, Date: 1 September - 30 November, Institution: Univ. St. Petersburg (Russia)

Maria Kleshnina, Date: 2-8 July, Institution: Queensland Univ. (Australia)

Suhail Mohmad Shah, Date: 18 June - 14 August, Institution: IIT Bombay (India)

9.5.2. Internships

Note: UNS is the Univ. Nice Sophia-Antipolis.

Nour Elhouda Ayari, Date: 4 April - 8 October, Institution: Tunis SUP'COM, Supervisors: E. Altman and M. Haddad (UAPV), Subject: Speed Estimation in Mobile Networks

Gianmarco Calbi, Date: 15 March - 31 August, Institution: Master RIF, UNS, Supervisor: G. Neglia, Subject: Asynchronous Approximate Distributed Computation for Machine Learning

Yu-Zhen Chen, Date: 1 June - 31 July, Institution: The Chinese Univ. of Hong Kong, Supervisor: K. Avrachenkov, Subject: Application of deep learning for graphlet statistics estimation

Kostantinos Dermentzis, Date: 20 November 2017 - 19 May 2018, Institution: National Technical Univ. of Athens (Greece), Supervisor: G. Neglia, Subject: Caching Policies with Partial Future Knowledge: the case of Spark

Vladyslav Fedchenko, Date: 1 March - 31 August, Institution: Master IFI Ubinet, UNS, Supervisor: G. Neglia, Subject: Estimating Content Popularity in Cache Networks

Pulkit Goel, Date: 15 May - 31 July, Institution: IIT New Delhi (India), Supervisor: K. Avrachenkov, Subject: Application of Deep Learning for Recovering Graph Motifs

Nisha Mishra, Date: 5 February - 20 July, Institution: ENSIMAG, Supervisor: E. Altman and C. Touati, Subject: Routing Games

Utsav Sen, Date: 15 May - 31 July, Institution: IIT New Delhi (India), Supervisor: K. Avrachenkov, Subject: Asynchronously distributed and randomized methods for computing network centralities

Adeel Siddiqui, Date: 1 October 2018 - 30 September 2019, Institution: Univ. Côte d'Azur, Supervisor: G. Neglia, Subject: Achieve Web Privacy by Obfuscation

Xing Yafei, Date: 1 March - 31 August, Institution: Master IFI Ubinet, UNS, Supervisor: K. Avrachenkov, Subject: Distributed Approaches for Graph-based Unsupervised Learning

Xiawen Zhu, Date: 1 March - 31 August, Institution: Master IFI Ubinet, UNS, Supervisor: K. Avrachenkov, Subject: Distributed Approaches for Graph-based Unsupervised Learning

9.5.3. Visits to International Teams

9.5.3.1. Research Stays Abroad

Eitan Altman

- Date: 1-8 March, Institution: Technion (Israel)
- Date: 12-23 April, Institution: Technion and Univ. Tel-Aviv (Israel)
- Date: 10-21 December, Institution: IIT Bombay (India)

Konstantin Avrachenkov

- Date: 29 January - 2 February, Institution: Univ. Liverpool (United Kingdom)
- Date: 21-22 May, Institution: Saint Petersburg State Univ. (Russia)
- Date: 17-18 September, Institution: Univ. Leiden (The Netherlands)
- Date: 19-23 September, Institution: Univ. Twente (The Netherlands)
- Date: 15-18 October, Institution: IIT Bombay (India)

Abhishek Bose

- Date: 19-23 November, Institution: IIT Bombay (India)

Swapnil Dhamal

- Date: 17-18 September, Institution: IISc Bangalore (India)
- Date: 19 September, Company: IBM Research Labs Bangalore (India)

Alain Jean-Marie

Date: 24 September - 14 October, Institution: Univ. of Montreal (Canada)

Date: 2-27 November, Institution: National Univ. of Rosario (Argentina)

Giovanni Neglia

- Date: 11-16 November, Institution: Purdue Univ. (USA)
- Date: 3-8 November, Institution: IIT Bombay (India)

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 6th Intl. Conf. on Wireless Networks and Mobile Communications (WINCOM'18), Marrakesh, Morocco, 16-19 October 2018;
- Eitan Altman is 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;
- Eitan Altman is a steering committee member of the
  - 4th Intl. Symposium on Ubiquitous Networking (UNET 2018), Hammamet, Tunisia, 2-5 May 2018;
  - 9th EAI Intl. Conf. on Game Theory for Networks (GAMENETS 2019), Paris, France, 25-26 April 2019;
- Dimitra Politaki was the general chair of the workshop “Monde des mathematiques industrielles (MOMI),” Inria Sophia Antipolis Méditerranée, 26-27 February 2018.

10.1.1.2. Member of the Organizing Committees

- G. Neglia is publicity co-chair of the 20th Intl. Symposium on Mobile Ad Hoc Networking and Computing (ACM Mobihoc, Catania, Italy, 2019).

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

- Eitan Altman was TPC co-chair of ITC 30 (Vienna, Austria, Sept. 2018);

10.1.2.2. Member of the Conference Program Committees

- ACM Sigmetrics / IFIP Performance 2019 (Phoenix, Arizona, USA) (S. Alouf, K. Avrachenkov)
- 19th Conf. of the Société Française de Recherche Opérationnelle et d'Aide à la Décision (ROADEF 2018, Lorient, France) (A. Jean-Marie)
- 9th EAI Intl. Conf. on Sensor Systems and Software (S-CUBE 2018, Chengdu, China) (E. Altman)
- 15th European Performance Engineering Workshop (EPEW 2018, Paris, France) (A. Jean-Marie)
- IEEE Intl. Conf. on Computer Communications (INFOCOM 2019, Paris, France) (G. Neglia)
- 26th IEEE Intl. Conf. on Network Protocols (ICNP 2018, Cambridge, UK) (K. Avrachenkov)
- 3rd Intl. Conf. on Pervasive and Embedded Computing (PEC 2018) (K. Avrachenkov)
- 6th Intl. Conf. on Wireless Networks and Mobile Communications (WINCOM'18, Marrakesh, Morocco) (E. Altman)
- European Conf. on Queueing Theory (ECQT 2018, Jerusalem, Israel) (K. Avrachenkov)
- 9th Intl. Conf. on Network Games, Control and Optimization (NETGCOOP 2018, New York, USA) (K. Avrachenkov)
- 18th Intl. Symposium on Dynamic Games and Applications (ISDG 2018, Grenoble, France) (E. Altman)
- 2018 Intl. Workshop on Resource Allocation, Cooperation and Competition in Wireless Networks (RAWNET, Shangai, China, 2018) (K. Avrachenkov, G. Neglia)
- Workshop on AI in Networks (WAIN, Toulouse, France, 2018) (G. Neglia)
- 15th Workshop on Algorithms and Models for the Web Graph (WAW 2018, Moscow, Russia) (K. Avrachenkov)
- 20th Workshop on MAthematical performance Modeling and Analysis (MAMA 2018, Irvine, USA) (A. Jean-Marie)
- 2018 Intl. Workshop on Content Caching and Delivery in Wireless Networks (CCDWN 2018, Shanghai, China) (K. Avrachenkov)
- Workshop Technologies for the Wireless Edge (EdgeTech 2018) (K. Avrachenkov)

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- *Elsevier Computer Communications (COMCOM)* (G. Neglia);
- *Elsevier International Journal of Performance Evaluation* (K. Avrachenkov);
- *ACM Transactions on Modeling and Performance Evaluation of Computing Systems (ACM ToMPECS)* (K. Avrachenkov);
- *Wiley Transactions on Emerging Telecommunications Technologies (ETT)* (S. Alouf);
- *IEEE JSAC* Special issue on Caching for Communication Systems and Networks (S. Alouf, G. Neglia);

10.1.3.2. Reviewer - Reviewing Activities

- *ACM Transactions on Modeling and Performance Evaluation of Computing Systems* (ACM ToMPECS) (G. Neglia)

- *European Journal of Operational Research* (A. Jean-Marie)
- *IEEE Networking Letters* (G. Neglia)
- *EURASIP Journal on Wireless Communications and Networking* (G. Neglia)
- *Journal of Economic Dynamics and Control* (A. Jean-Marie)
- *IEEE Transactions on Parallel and Distributed Systems* (G. Neglia)
- *IEEE Transactions on Signal and Information Processing over Networks* (G. Neglia)
- *IEEE/ACM Transactions on Networking* (G. Neglia)
- *Performance Evaluation* (PEVA) (S. Alouf)
- *Probability in the Engineering and Informational Sciences* (A. Jean-Marie)

10.1.4. Invited Talks

- E. Altman gave a keynote lecture on “Game Theoretic Models for Routing Over Wireless Links ” at the 6th Intl. Conf. on Wireless Networks and Mobile Communications (WINCOM’18), October 16-19, Marrakesh, Morocco.
- K. Avrachenkov gave an invited talk on “Analysis of relaxation time in random walk with jumps” at the Intl. Conf. on Trends and Perspectives in Linear Statistical Inference (LinStat’2018, 19-25 August) in Bedlewo, Poland.
- K. Avrachenkov gave an invited talk on “Singularly perturbed linear programs and their application to MDP” at Univ. of Twente, September 20, Enschede, The Netherlands.
- G. Neglia gave an invited talk on “Implicit Coordination of Caches in Small Cell Networks under Unknown Popularity Profiles” at the workshop Technologies for the Wireless Edge (EdgeTech) EdgeTech of the 24th Annual Intl. Conf. on Mobile Computing and Networking (ACM MobiCom 2018), November 2, New Delhi, India.
- G. Neglia gave an invited talk on “Transient and Slim versus Recurrent and Fat: Random Walks and the Trees they Grow” at the UCA workshop on Social Interactions and Complex Dynamics, November 29-30, Nice, France.

10.1.5. Leadership within the Scientific Community

- E. Altman is a fellow member of IEEE (Class of 2010).
- E. Altman and A. Jean-Marie are (elected) members of IFIP WG 7.3 on “Computer System Modeling”.
- E. Altman is member of WG 6.3 of IFIP on Performance of Communication Systems.

10.1.6. Research Administration

S. Alouf

- is member of the scientific committee of the joint laboratory Inria-Alstom since May 2014;
- 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 committee for Labex UCN@Sophia;

– is a member of scientific and pedagogical committee for the graduate school of UCA DS4H.

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 a member of the Steering Committee of the GDR RO, a national research initiative on Operations Research sponsored by the CNRS;

– 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;

– is member of the scientific animation committee for the IDEX UCA$^{\mathrm{JEDI}}$ research program "Social Interactions and Complex Dynamics" since 2017.

D. Politaki was one of the organizers of the fortnightly PhD Seminars of Inria Sophia Antipolis Méditerranée until September 2018.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence :

G. Neglia, "Probability", 60H, Undergraduate Water Engineering degree (L3), Univ. of Nice Sophia Antipolis (UNS), France.

Master :

A. Jean-Marie, "Performance Evaluation of Networks", 15.75H, M2 IFI Ubinet, UNS, France.

G. Neglia, "Distributed Optimization and Games", 31.5H, M2 IFI Ubinet, UNS, France.

G. Neglia, "Performance Evaluation of Networks", 15.75H, M2 IFI Ubinet, UNS, France.

G. Neglia, responsible for the "Winter School on Complex Networks", 22.5H, M1 Computer Science, UNS, France.

Doctorat:

A. Jean-Marie, "Advanced Markov Modeling", 18H, Univ. of Montpellier, France.

10.2.2. Supervision

PhD defended:

Said Boularouk, "Helping space apprehension by visually impaired people", UAPV, 5 Dec. 2018, advisors: Eitan Altman and Didier Josselin.

PhD in progress :

Zaid Allybokus, "Scalable Online Algorithms for SDN Controllers", 1 July 2016, advisors: Konstantin Avrachenkov and Lorenzo Maggi (Huawei).

Abhishek Bose, “Adaptive crawling with machine learning techniques”, 1 June 2018, advisor: Konstantin Avrachenkov.

Mandar Datar, “Singular perturbation approach for machine learning in multiobjective optimisation”, 1 May 2018, advisor: Eitan Altman.

Maximilien Dreveton, “Statistical Physics Methods for Distributed Machine Learning”, 1 Oct. 2018, advisor: Konstantin Avrachenkov.

Guilherme Iecker Ricardo, “Caching for wireless networks”, 1 Sept. 2018, advisors: Giovanni Neglia and Pietro Elia (EURECOM).

Marie Masson, “Fonctionnalités auto-organisantes dans le réseau d’accès radio 5G virtuels”, 1 Dec. 2017, advisors: Eitan Altman and Zwi Altman (Orange).

Dimitra Politaki, “Greening data center”, 1 February 2016, advisors: Sara Alouf and Fabien Hermenier (UNS).

10.2.3. Juries

NEO members participated in the Ph.D. committees of (in alphabetical order):

- Hafiz Ali, “Random Matrix Theory and Large Dimensional graphs”, CentraleSupelec, 24 September (K. Avrachenkov as reviewer);
- Xinwei Bai, “Performance bounds for random walks in the positive orthant”, Univ. Twente, 20 September (K. Avrachenkov as reviewer);
- Yoann Couble, “Optimisation de la gestion des ressources de la voie retour”, Institut National Polytechnique de Toulouse, 3 September (S. Alouf as reviewer);
- Thibault Debatty, “Design and analysis of distributed k-nearest neighbors graph algorithms”, TELECOM ParisTech, 5 October (G. Neglia as reviewer);
- Philippe Ezran, “Topology Optimization of Wireless Networks”, Univ. Paris-Saclay, 23 January (E. Altman as reviewer);
- Dalia-Georgiana Popescu, “Les hyperfractales pour la modelisation des reseaux sans fil”, LINCS, 21 November (K. Avrachenkov as reviewer);
- Rémi Varloot, “Dynamic Network Formation”, Université de recherche Paris Sciences et Lettres, École normale supérieure, 1 June (G. Neglia as jury president).

10.3. Popularization

10.3.1. Internal or external Inria responsibilities

- D. Politaki is a member of MASTIC, a commission in charge of popularization and regional and internal scientific animation, since July 2016.

10.3.2. Interventions

On October 12th, in the framework of *La Fête de la Science*, M. Dreveton participated in a mediation activity at *Espace de l’Art Concret* in Mouans-Sartoux. It was a mix between art and sciences (maths and physics). The topic was randomness and the targeted public was primary school students, from two different classes (one in the morning and one in the afternoon). Activities involved loaded dices, Galton Board, double pendulum, and some online program (http://weavesilk.com/, pupils really liked this). Each game was presented and students would figure out where the randomness comes from, and play/experiment by themselves (30 min per group).

11. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journal

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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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B2.1. - Well being
B7.1.1. - Pedestrian traffic and crowds
B8.1. - Smart building/home
B8.4. - Security and personal assistance

1. Team, Visitors, External Collaborators

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Administrative Assistant

Laurence Briffa [Inria]

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 cognitive vision 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.

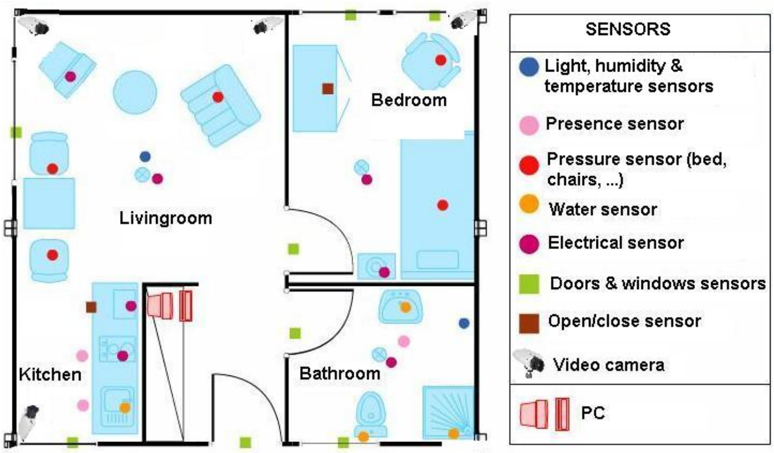


Figure 1. Homecare monitoring: the set of sensors embedded in an apartment

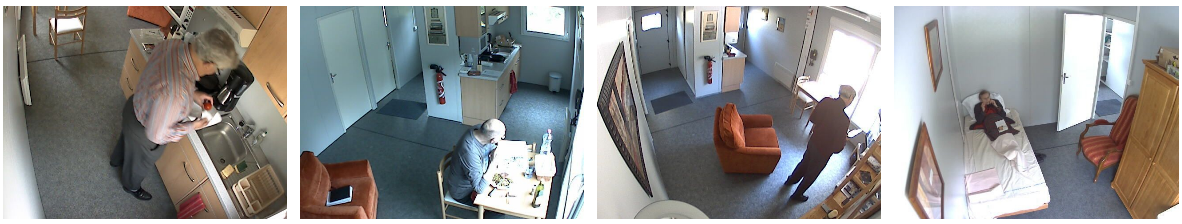


Figure 2. Homecare monitoring: the different views of the apartment captured by 4 video cameras

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. We had or have industrial collaborations in several domains: *transportation* (CCI Airport Toulouse Blagnac, SNCF, Inrets, Alstom, Ratp, 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), *multimedia* (Multitel (Belgium), Thales Communications, Idiap (Switzerland)), *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), 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).

3. Research Program

3.1. Introduction

Stars follows three main research directions: perception for activity recognition, semantic activity recognition, and software engineering for activity recognition. **These three research directions are interleaved**: *the software engineering* research direction provides new methodologies for building safe activity recognition systems and *the perception* and *the semantic activity recognition* directions provide new activity recognition techniques which are designed and validated for concrete video analytic and healthcare applications. Conversely, these concrete systems raise new software issues that enrich the software engineering research direction.

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, 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 videosurveillance 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. Semantic Activity Recognition

Participants: François Brémond, Sabine Moisan, Monique Thonnat.

: Activity Recognition, Scene Understanding, Computer Vision

3.3.1. 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.

3.3.2. 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 ...).

3.3.3. 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.

3.3.4. 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, they will be detailed in section 3.4.

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).

3.4. Software Engineering for Activity Recognition

Participants: Sabine Moisan, Annie Ressouche, Jean-Paul Rigault, François Brémond.

: Software Engineering, Generic Components, Knowledge-based Systems, Software Component Platform, Object-oriented Frameworks, Software Reuse, Model-driven Engineering

The aim of this research axis is to build general solutions and tools to develop systems dedicated to activity recognition. For this, we rely on state-of-the art Software Engineering practices to ensure both sound design and easy use, providing genericity, modularity, adaptability, reusability, extensibility, dependability, and maintainability.

This research requires theoretical studies combined with validation based on concrete experiments conducted in Stars. We work on the following three research axes: *models* (adapted to the activity recognition domain), *platform architecture* (to cope with deployment constraints and run time adaptation), and *system verification* (to generate dependable systems). For all these tasks we follow state of the art Software Engineering practices and, if needed, we attempt to set up new ones.

3.4.1. Platform Architecture for Activity Recognition

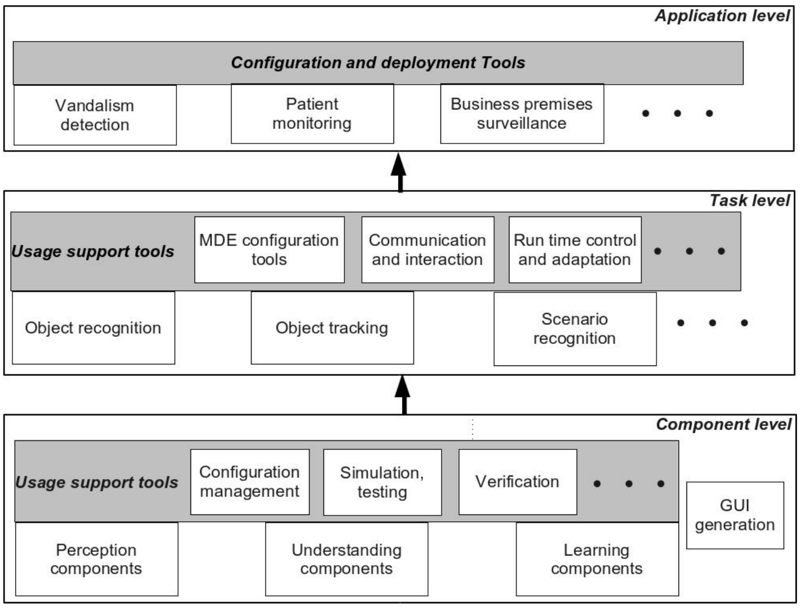


Figure 4. Global Architecture of an Activity Recognition The gray areas contain software engineering support modules whereas the other modules correspond to software components (at Task and Component levels) or to generated systems (at Application level).

In the former project teams Orion and Pulsar, we have developed two platforms, one (VSIP), a library of real-time video understanding modules and another one, LAMA [14], a software platform enabling to design not only knowledge bases, but also inference engines, and additional tools. LAMA offers toolkits to build and to adapt all the software elements that compose a knowledge-based system.

Figure 4 presents our conceptual vision for the architecture of an activity recognition platform. It consists of three levels:

- The **Component Level**, the lowest one, offers software components providing elementary operations and data for perception, understanding, and learning.
  - *Perception components* contain algorithms for sensor management, image and signal analysis, image and video processing (segmentation, tracking...), etc.
  - *Understanding components* provide the building blocks for Knowledge-based Systems: knowledge representation and management, elements for controlling inference engine

strategies, etc.

– *Learning components* implement different learning strategies, such as Support Vector Machines (SVM), Case-based Learning (CBL), clustering, etc.

An Activity Recognition system is likely to pick components from these three packages. Hence, tools must be provided to configure (select, assemble), simulate, verify the resulting component combination. Other support tools may help to generate task or application dedicated languages or graphic interfaces.

- The **Task Level**, the middle one, contains executable realizations of individual tasks that will collaborate in a particular final application. Of course, the code of these tasks is built on top of the components from the previous level. We have already identified several of these important tasks: Object Recognition, Tracking, Scenario Recognition... In the future, other tasks will probably enrich this level.

  For these tasks to nicely collaborate, communication and interaction facilities are needed. We shall also add MDE-enhanced tools for configuration and run-time adaptation.

- The **Application Level** integrates several of these tasks to build a system for a particular type of application, e.g., vandalism detection, patient monitoring, aircraft loading/unloading surveillance, etc.. Each system is parameterized to adapt to its local environment (number, type, location of sensors, scene geometry, visual parameters, number of objects of interest...). Thus configuration and deployment facilities are required.

The philosophy of this architecture is to offer at each level a balance between the widest possible genericity and the maximum effective reusability, in particular at the code level.

To cope with real application requirements, we shall also investigate distributed architecture, real time implementation, and user interfaces.

Concerning implementation issues, we shall use when possible existing open standard tools such as NuSMV for model-checking, Eclipse for graphic interfaces or model engineering support, Alloy for constraint representation and SAT solving for verification, etc. Note that, in Figure 4, some of the boxes can be naturally adapted from SUP existing elements (many perception and understanding components, program supervision, scenario recognition...) whereas others are to be developed, completely or partially (learning components, most support and configuration tools).

3.4.2. Discrete Event Models of Activities

As mentioned in the previous section (3.3) we have started to specify a formal model of scenario dealing with both absolute time and logical time. Our scenario and time models as well as the platform verification tools rely on a formal basis, namely the synchronous paradigm. To recognize scenarios, we consider activity descriptions as synchronous reactive systems and we apply general modeling methods to express scenario behavior.

Activity recognition systems usually exhibit many safeness issues. From the software engineering point of view we only consider software security. Our previous work on verification and validation has to be pursued; in particular, we need to test its scalability and to develop associated tools. Model-checking is an appealing technique since it can be automatized and helps to produce a code that has been formally proved. Our verification method follows a compositional approach, a well-known way to cope with scalability problems in model-checking.

Moreover, recognizing real scenarios is not a purely deterministic process. Sensor performance, precision of image analysis, scenario descriptions may induce various kinds of uncertainty. While taking into account this uncertainty, we should still keep our model of time deterministic, modular, and formally verifiable. To formally describe probabilistic timed systems, the most popular approach involves probabilistic extension of timed automata. New model checking techniques can be used as verification means, but relying on model checking techniques is not sufficient. Model checking is a powerful tool to prove decidable properties but introducing uncertainty may lead to infinite state or even undecidable properties. Thus model checking validation has to be completed with non exhaustive methods such as abstract interpretation.

3.4.3. Model-Driven Engineering for Configuration and Control and Control of Video Surveillance systems

Model-driven engineering techniques can support the configuration and dynamic adaptation of video surveillance systems designed with our SUP activity recognition platform. The challenge is to cope with the many—functional as well as nonfunctional—causes of variability both in the video application specification and in the concrete SUP implementation. We have used *feature models* to define two models: a generic model of video surveillance applications and a model of configuration for SUP components and chains. Both of them express variability factors. Ultimately, we wish to automatically generate a SUP component assembly from an application specification, using models to represent transformations [58]. Our models are enriched with intra- and inter-models constraints. Inter-models constraints specify models to represent transformations. Feature models are appropriate to describe variants; they are simple enough for video surveillance experts to express their requirements. Yet, they are powerful enough to be liable to static analysis [69]. In particular, the constraints can be analyzed as a SAT problem.

An additional challenge is to manage the possible run-time changes of implementation due to context variations (e.g., lighting conditions, changes in the reference scene, etc.). Video surveillance systems have to dynamically adapt to a changing environment. The use of models at run-time is a solution. We are defining adaptation rules corresponding to the dependency constraints between specification elements in one model and software variants in the other [57], [74], [72].

4. Application Domains

4.1. Introduction

While in our research the focus is to develop techniques, models and platforms that are generic and reusable, we also make effort in the development of real applications. The motivation is twofold. The first is to validate the new ideas and approaches we introduce. The second is to demonstrate how to build working systems for real applications of various domains based on the techniques and tools developed. Indeed, Stars focuses on two main domains: **video analytic** and **healthcare monitoring**.

4.2. Video Analytics

Our experience in video analytic [6], [1], [8] (also referred to as visual surveillance) is a strong basis which ensures both a precise view of the research topics to develop and a network of industrial partners ranging from end-users, integrators and software editors to provide data, objectives, evaluation and funding.

For instance, the Keeneo start-up was created in July 2005 for the industrialization and exploitation of Orion and Pulsar results in video analytic (VSIP library, which was a previous version of SUP). Keeneo has been bought by Digital Barriers in August 2011 and is now independent from Inria. However, Stars continues to maintain a close cooperation with Keeneo for impact analysis of SUP and for exploitation of new results.

Moreover new challenges are arising from the visual surveillance community. For instance, people detection and tracking in a crowded environment are still open issues despite the high competition on these topics. Also detecting abnormal activities may require to discover rare events from very large video data bases often characterized by noise or incomplete data.

4.3. Healthcare Monitoring

Since 2011, we have initiated a strategic partnership (called CobTek) with Nice hospital [62], [75] (CHU Nice, Prof P. Robert) to start ambitious research activities dedicated to healthcare monitoring and to assistive technologies. These new studies address the analysis of more complex spatio-temporal activities (e.g. complex interactions, long term activities).

4.3.1. Research

To achieve this objective, several topics need to be tackled. These topics can be summarized within two points: finer activity description and longitudinal experimentation. Finer activity description is needed for instance, to discriminate the activities (e.g. sitting, walking, eating) of Alzheimer patients from the ones of healthy older people. It is essential to be able to pre-diagnose dementia and to provide a better and more specialized care. Longer analysis is required when people monitoring aims at measuring the evolution of patient behavioral disorders. Setting up such long experimentation with dementia people has never been tried before but is necessary to have real-world validation. This is one of the challenge of the European FP7 project Dem@Care where several patient homes should be monitored over several months.

For this domain, a goal for Stars is to allow people with dementia to continue living in a self-sufficient manner in their own homes or residential centers, away from a hospital, as well as to allow clinicians and caregivers remotely provide effective care and management. For all this to become possible, comprehensive monitoring of the daily life of the person with dementia is deemed necessary, since caregivers and clinicians will need a comprehensive view of the person's daily activities, behavioral patterns, lifestyle, as well as changes in them, indicating the progression of their condition.

4.3.2. Ethical and Acceptability Issues

The development and ultimate use of novel assistive technologies by a vulnerable user group such as individuals with dementia, and the assessment methodologies planned by Stars are not free of ethical, or even legal concerns, even if many studies have shown how these Information and Communication Technologies (ICT) can be useful and well accepted by older people with or without impairments. Thus one goal of Stars team is to design the right technologies that can provide the appropriate information to the medical carers while preserving people privacy. Moreover, Stars will pay particular attention to ethical, acceptability, legal and privacy concerns that may arise, addressing them in a professional way following the corresponding established EU and national laws and regulations, especially when outside France. Now, Stars can benefit from the support of the COERLE (Comité Opérationnel d'Evaluation des Risques Légaux et Ethiques) to help it to respect ethical policies in its applications.

As presented in 3.1, Stars aims at designing cognitive vision systems with perceptual capabilities to monitor efficiently people activities. As a matter of fact, vision sensors can be seen as intrusive ones, even if no images are acquired or transmitted (only meta-data describing activities need to be collected). Therefore new communication paradigms and other sensors (e.g. accelerometers, RFID, and new sensors to come in the future) are also envisaged to provide the most appropriate services to the observed people, while preserving their privacy. To better understand ethical issues, Stars members are already involved in several ethical organizations. For instance, F. Brémond has been a member of the ODEGAM - "Commission Ethique et Droit" (a local association in Nice area for ethical issues related to older people) from 2010 to 2011 and a member of the French scientific council for the national seminar on "La maladie d'Alzheimer et les nouvelles technologies - Enjeux Ã©thiques et questions de société" in 2011. This council has in particular proposed a chart and guidelines for conducting researches with dementia patients.

For addressing the acceptability issues, focus groups and HMI (Human Machine Interaction) experts, will be consulted on the most adequate range of mechanisms to interact and display information to older people.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

Abhijit Das, Antitza Dantcheva and Francois Brémond were winners of the Bias Estimation in Face Analytics (BEFA) Challenge at the European Conference on Computer Vision (ECCV 2018).

6. New Software and Platforms

6.1. 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, Thanh 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

6.2. 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

7. New Results

7.1. Introduction

This year Stars has proposed new results related to its three main research axes : perception for activity recognition, semantic activity recognition and software engineering for activity recognition.

7.1.1. Perception for Activity Recognition

Participants: François Brémond, Juan Diego Gonzales Zuniga, Abhijit Das, Antitza Dancheva, Furqan Muhammad Khan, Michal Koperski, Thi Lan Anh Nguyen, Remi Trichet, Ujjwal Ujjval, Srijan Das, Vikas Thamizharasan, Monique Thonnat.

The new results for perception for activity recognition are:

- Late Fusion of multiple convolutional layers for pedestrian detection (see 7.2)
- Deep Learning applied on Embedded Systems for People Tracking (see 7.3)
- Cross Domain Residual Transfer Learning for Person Re-identification (see 7.4)
- Face-based Attribute Classification (see 7.5)
- Face Attribute manipulation
- From attribute-labels to faces: face generation using a conditional generative adversarial network (see 7.6)
- Face analysis in structured light images (see 7.7)

7.1.2. Semantic Activity Recognition

Participants: François Brémond, Antitza Dantcheva, Farhood Negin, Thanh Hung Nguyen, Michal Koperski, Srijan Das, Kaustubh Sakhalkar, Arpit Chaudhary, Abhishek Goel, Abdelrahman Abubakr, Abhijit Das, Yaohui Wang, S L Happy, Alexandra König, Guillaume Sacco, Philippe Robert, Soumik Mallick, Julien Badie, Monique Thonnat.

For this research axis, the contributions are :

- Deep-Temporal LSTM for Daily Living Action Recognition (see 7.8)
- A New Hybrid Architecture for Human Activity Recognition from RGB-D videos (see 7.10)
- Where to focus on for Human Action Recognition? (see 7.11)
- Online temporal detection of daily-living human activities in long untrimmed video streams (see 7.12)
- Activity Detection in Long-term Untrimmed Videos (see 7.13)
- Video based face analysis for health monitoring (see 7.14)
- Mobile biometrics (see 7.15)
- Comparing methods for assessment of facial dynamics in patients with major neurocognitive disorders (see 7.16)
- Combating the issue of low sample size in facial expression recognition (see 7.17)
- Serious exergames for Cognitive Stimulation (see 7.18)
- Fully Automatic Speech-Based Analysis of the Semantic Verbal Fluency Task (see 7.19)
- Language Modelling in the Clinical Semantic Verbal Fluency Task (see 7.19.2)
- Telephone-based Dementia Screening I: Automated Semantic Verbal Fluency Assessment (see 7.19.3)
- Automatic Detection of Apathy using Acoustic Markers extracted from Free Emotional Speech and using Automatic Speech Analysis (see 7.19.4)
- Monitoring the Behaviors of Retail Customers (see 7.20)

7.1.3. Software Engineering for Activity Recognition

Participants: Sabine Moisan, Annie Ressouche, Jean-Paul Rigault, Ines Sarray, Daniel Gaffé, Julien Badie, François Brémond, Minh Khue Phan Tran.

The contributions for this research axis are:

- A Synchronous Approach to Activity Recognition (see 7.21)
- A Probabilistic Activity Description Language (see 7.22)

7.2. Late Fusion of Multiple Convolutional Layers for Pedestrian Detection

Participants: Ujjwal Ujjwal, François Brémond, Aziz Dziri [VEDECOM], Bertrand Leroy [VEDECOM].

One of the prominent problems in pedestrian detection is handling scale and occlusion. These problems are quite well aligned with the recent interests in autonomous vehicles. Successful detection of far-scale pedestrians can assist the vehicle in making safety maneuvers well ahead in time, thereby promoting a safer traffic environment. The same is true for surveillance systems in high security environment like airports and ports.

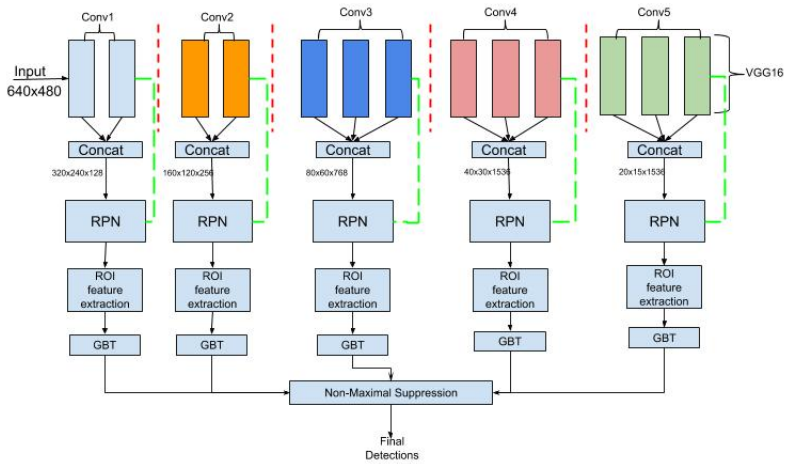


Figure 5. Block diagram of our proposed Multiple-RPN pedestrian detection system

We propose a system design for pedestrian detection by leveraging the power of multiple convolutional layers explicitly (see Figure 5). We quantify the effect of different convolutional layers on the detection of pedestrians of varying scales and occlusion level. We show that earlier convolutional layers are better at handling small-scale and partially occluded pedestrians. We take cue from these conclusions and propose a pedestrian detection system design based on Faster-RCNN which leverages multiple convolutional layers by late fusion. In our design, we introduce height-awareness in the loss function to make the network emphasize on pedestrian heights which are misclassified during the training process. The proposed system design achieves a log-average miss-rate of 9.25% on the caltech-reasonable dataset. This is within 1.5% of the current state-of-art approach, while being a more compact system. The work was published in the 15^{th} IEEE International Conference on Advanced Video and Signal-based Surveillance (AVSS)-2018 [51].

7.3. Deep Learning applied on Embedded Systems for People Tracking

Participants: Juan Diego Gonzales Zuniga, Thi Lan Anh Nguyen, Francois Brémond, Serge Tissot [KONTRON].

Keywords: Deep Learning, Embedded Systems, Multiple Object Tracking

One of the main issues with people detection and tracking is the amount of resources it consumes for real time applications. 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. The applications for an embedded hardware with these capabilities are limitless: automotive, security and surveillance, augmented reality and health-care just to name a few. But the state-of-the-art architectures are mostly focused on accuracy rather than resource consumption.

In our work, we have to consider improving the systems' accuracy and reducing resources for real-time applications. We are creating a shared effort of hardware adaptation and agnostic software optimization for all deep learning based solutions.

We here focus our work on two separated but linked problems.

First, we improve the feature representation of tracklets for the Multiple Object Tracking challenge. This is based on the concept of Residual Transfer Learning [44]. Second, we are creating a viable platform to run our algorithms on different target hardware, mainly, Intel Xeon Processors, FPGAs and AMD GPUs.

7.3.1. Residual Transfer Learning :

We present a smart training alternative for transfer learning based on the concept of ResNet [65]. In ResNet, a layer learns the estimate residual between the input and output signals. We cast transfer learning as a residual learning problem, since the objective is to close the gap between the initial network and the desired one. Achieving this goal is done by adding residual units for a number of layers to an existing model that needs to be transferred from one task to another. The existing model can thus be able to perform a new task by adding and optimizing residual units as shown in Figure 6. The main advantage of using residual units for transfer learning is the flexibility in terms of modelling the difference between two tasks.

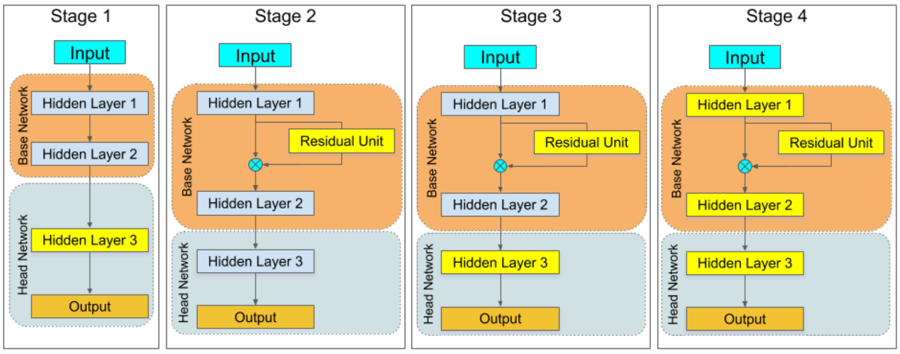


Figure 6. Training stages of Residual Transfer Learning method. Each stage only trains the layers shown in yellow, and fixes the layers in grey. The residual units are added at the second stage

7.3.2. Deep Learning Platform on Multiple Target Hardware :

Deep learning algorithms need an extensive allocation of resources to be executed, most of the research is accomplished under NVIDIA GPU's. This is limiting because it reduces the possibilities on how to optimize certain blocks that directly depend on the hardware configuration. The main cause is the lack of a flexible platform that would support different targets: AMD GPUs, Intel Xeon processors and specialized FPGAs.

We work with two hardware based platforms; ROCm and Openvino. The ROCm stack, shown in Figure 7, allows us to perform a variety of layer computations on AMD GPUs. We have managed to import different deep learning networks such as VGG16, ResNet and Inception to AMD's Radeon graphics card. On the other hand, Openvino's main goal is to reduce the inference time of a network. For this solution, we count on the Openvino Optimizer, shown in Figure 8, which main goal is to transform the network model from Caffe or Tensorflow into an Inference Model for Intel's processors and FPGAs.

We also built docker images on top of the above mention platforms, this is done to speed the deployment stage by being operating system independent.

7.4. Cross Domain Residual Transfer Learning for Person Re-identification

Participants: Furqan Khan, Francois Brémond.

Keywords: multi-shot person re-identification, transfer learning, residual unit

Person re-identification (re-ID) refers to the retrieval task where the goal is to search for a given person (query) in disjoint camera views (gallery). Performance of appearance based person re-ID methods depends on the similarity metric and the feature descriptor used to build a person's appearance model from given image(s).

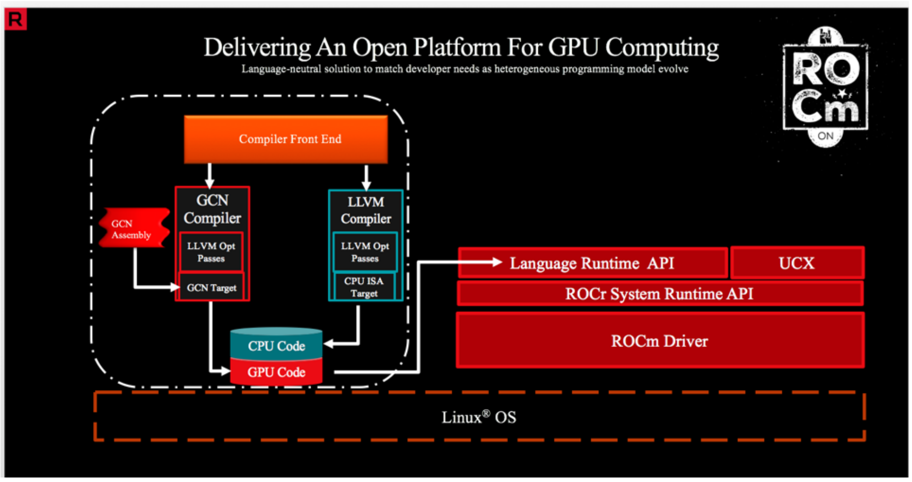


Figure 7. The ROCm System Runtime is language independent and makes heavy use of the Heterogeneous System Architecture.

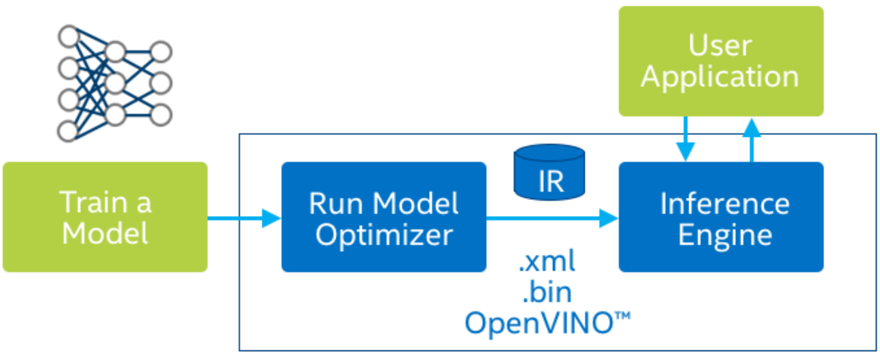


Figure 8. Openvino: When you run a pre-trained model through the Model Optimizer, your output is an Intermediate Representation of the network.

A novel way is proposed to transfer model weights from one domain to another using residual learning framework instead of direct fine-tuning. It also argues for hybrid models that use learned (deep) features and statistical metric learning for multi-shot person re-identification when training sets are small. This is in contrast to popular end-to-end neural network based models or models that use hand-crafted features with adaptive matching models (neural nets or statistical metrics). Our experiments demonstrate that a hybrid model with residual transfer learning can yield significantly better re-identification performance than an end-to-end model when training set is small. On iLIDS-VID [78] and PRID [67] datasets, we achieve rank1 recognition rates of 89.8% and 95%, respectively, which is a significant improvement over state-of-the-art.

7.4.1. Residual Transfer Learning

We use RTL to transfer a model trained on Imagenet [63] for object classification to perform person re-ID. We chose to use 16-layer VGG model due to its superior performance in comparison to AlexNet and overlooked ResNet for its extreme depth because our target datasets are small and do not warrant such a deep model for higher performance.

One advantage of using residual learning [66] for model transfer is that it allows more flexibility in terms of modeling the difference between two tasks through a number of residual units and their composition. We noted that when residual units are added to the network with a different network head, training loss is significantly higher in the beginning which pushes the network far away from pre-trained solution by trying to over compensate through residual units. To avoid this, we propose to train the network in 4 stages, with fourth stage being optional (Fig. 9). The proposed work has been published in [45].

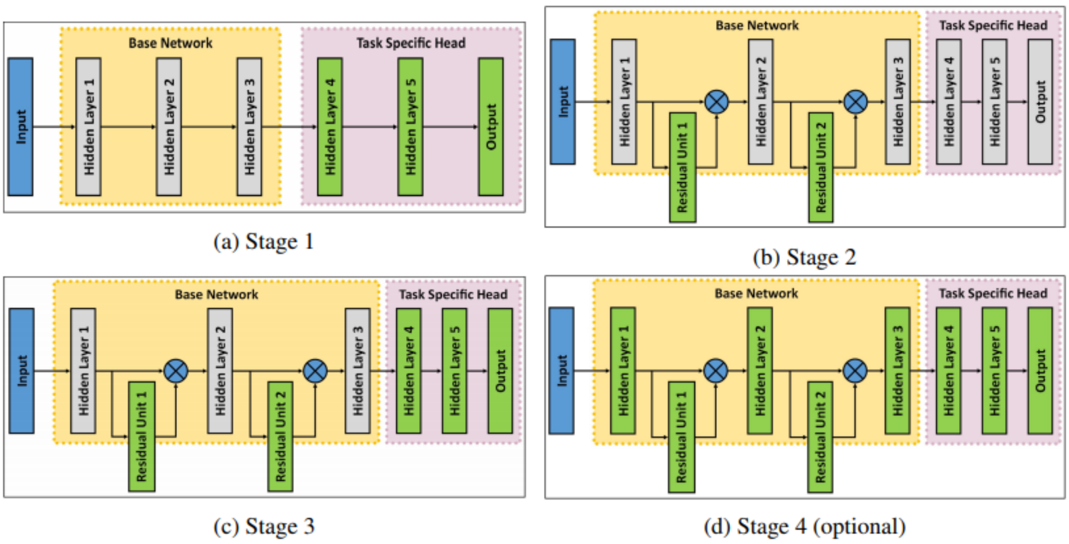


Figure 9. Residual Transfer Learning in 4 stages. During each stage only the selected layers (shown in green) are trained. Residual Units are added to the network after first stage of RTL.

- **Stage 1**: In the first stage, we replace original head of the network with a task specific head and initialize it randomly. At this stage, we do not add any residual units to the network and train only the parameters of the replaced head of the network. Thus only the head layers are considered to contribute to the loss. This allows the network to learn noisy high level representation for the desired task and decrease the network loss without affecting lower order layers.

- **Stage 2**: In the second stage, we add residual units to the network and initialize them randomly. Then we freeze all other layers, including the network head, and optimize the parameters of added residual units. As the head and other layers are fixed, residual units are considered as the source of loss. As we start with a reasonably low loss value, residual units are not forced to over compensate for the loss.
- **Stage 3**: In the third stage, we train the network by learning parameters of both added residual units and network head, thus allowing both the lower and higher order representations to adjust to the specific task.
- **Stage 4 (Optional)**: We noticed in our experiments on different datasets that the loss function generally gets low enough by the end of third stage. However, if needed, the whole network can be trained to further improve performance.

7.4.2. Conclusion

When using identity loss and large amount of training data, RTL gives comparable performance to direct fine-tuning of network parameters. However, the performance difference between two transfer learning approaches is considerably in favor of RTL when training sets are small. The reason is that when using RTL only a few parameters are modified to compensate for the residual error of the network. Still, the higher order layers of the network are prone to over-fitting. Therefore, we propose using hybrid models where higher order domain specific layers are replaced with statistical metric learning. We demonstrate that the hybrid model performs significantly better on small datasets and gives comparable performance on large datasets. The ability of the model to generalize well from small amount of data is crucial for practical applications because frequent data collection in large amount for training is nit possible.

7.5. Face-based Attribute Classification and Manipulation

Participants: Abhijit Das, Antitza Dantcheva, Francois Brémond.

Keywords: Face, Attribute, GAN, Biometrics

Due to the biasness of face analytic datasets, with respect to factors such as age, gender, ethnicity, pose and resolution, systems based on a skewed training dataset are bound to produce skewed results. Further, it has been exhibited in the literature [59] that such biases may have serious impacts on performance in challenging situations where the outcome is critical. In order to progress toward balanced face recognition and attribute estimation, the 1st International Workshop on Bias Estimation in Face Analytics was organized in conjunction with ECCV 2018. The workshop also organized a challenge to introduce a well-balanced dataset across multiple factors: age, gender, ethnicity, pose and resolution and requested for algorithms to estimate biases.

We proposed a Multi-Task Convolutional Neural Network (MTCNN) algorithm that jointly learned [37] gender, age and ethnicity by a loss function involving joint dynamic loss weight adjustment and was successful, as well as relatively unbiased in estimating age, gender and ethnicity. Our algorithm was found to be the best algorithm focusing the aim of the competition and the above mentioned research problem.

7.5.1. Generative Adversal Network (GAN)

models are autoregressive models depending on the global information, which can be potentially affected by its employment on local feature/ attribute-based erasuring. In addition, these models are typically trained depending on the maximum likelihood to find the intense difference between the regression domains, as a result after a certain limit of learning it can produce very naive development in the interpolation of the regression carried out for the purpose of local attribute removal. Hence, to mitigate an aforementioned couple of pitfalls we propose a method for localizing the Cycle GAN (C-GAN) for local feature-based regression. We trained the C-GAN with domain-specific local feature and end model was recurrently imposed on the testing images. We experimented the Local C-GAN (L-C-GAN) on facial attribute (eyeglass and moustache/ bearded) auto-regression. Our qualitative performance on partial CelebA dataset and a couple of datasets we collected is promising. Moreover, ensuring the facial attributes have also been found to achieve better performance accuracy with respect to the presence of these attributes.

7.6. From Attribute-labels to Faces: Face Generation using a Conditional Generative Adversarial Network ,

Participants: Yaohui Wang, Antitza Dantcheva, Francois Brémond.

Keywords: Generative Adversarial Networks, Face generation

Facial attributes are instrumental in semantically characterizing faces. Automated classification of such attributes (i.e., age, gender, ethnicity) has been a well studied topic. We here seek to explore the inverse problem, namely given attribute-labels the *generation of attribute-associated faces*. The interest in this topic is fueled by related applications in law enforcement and entertainment. In this work, we propose two models for attribute-label based facial image and video generation incorporating 2D (see Figure 10) and 3D (see Figure 11) deep conditional generative adversarial networks (DCGAN). The attribute-labels serve as a tool to determine the specific representations of generated images and videos. While these are early results (see Figure 12 and 13), our findings indicate the methods' ability to generate realistic faces from attribute labels.

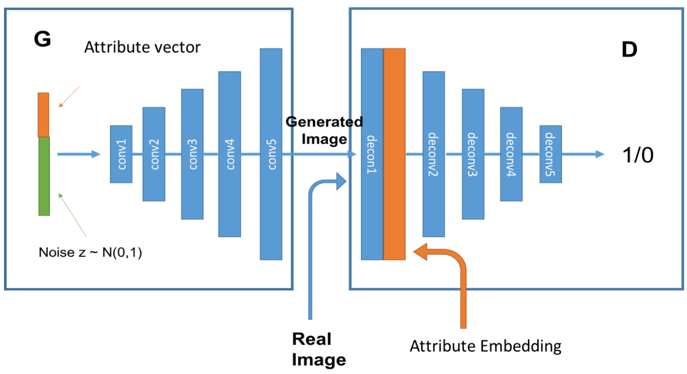


Figure 10. Architecture of proposed 2D method consisting of two modules, a discriminator D and a generator G. While D learns to distinguish between real and fake images, classifying based on attribute-labels, G accepts as input both, noise and attribute-labels in order to generate realistic face images.

7.7. Face Analysis in Structured Light Images

Participants: Vikas Thamizharasan, Antitza Dantcheva, Francois Brémond.

Keywords: Structured light, Face analysis

The main objective has been to perform face analysis tasks like authentication, gender, age and ethnicity classification by generating low-dimensional face embedding from the raw data acquired from structured light (see Figure 14) sensors using deep learning techniques. In this context we studied depth/disparity map extraction (see Figure 15), as well as other models.

7.8. Deep-Temporal LSTM for Daily Living Action Recognition

Participants: Srijan Das, Michal Koperski, Francois Brémond, Gianpiero Francesca.

Keywords: Temporal sequences, Appearance, LSTM

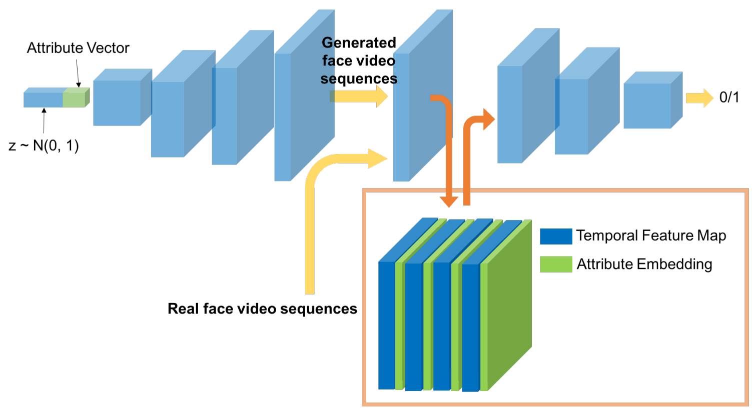


Figure 11. Architecture of proposed 3D model for face video generation

We have proposed to improve the traditional use of RNNs by employing a many to many model for video classification. We analyzed the importance of modeling spatial layout and temporal encoding for daily living action recognition. Many RGB methods focus only on short term temporal information obtained from optical flow. Skeleton based methods on the other hand show that modeling long term skeleton evolution improves action recognition accuracy. In this work, we proposed a deep-temporal LSTM architecture (see fig. 16) which extends standard LSTM and allows better encoding of temporal information. In addition, we have proposed to fuse 3D skeleton geometry with deep static appearance. We validated our approach on publicly available datasets (CAD60, MSRDailyActivity3D and NTU-RGB+D), achieving competitive performance as compared to the state-of-the art. The proposed framework has been published in AVSS 2018 [39].

7.9. Spatio-Temporal Grids for Daily Living Action Recognition

Participants: Srijan Das, Kaustubh Sakhalkar, Michal Koperski, Francois Brémond.

Keywords: Spatio-temporal, Grids, Multi-modal

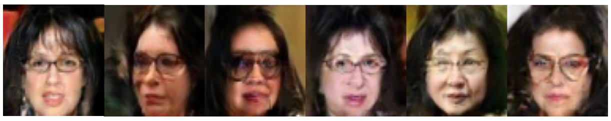
This work addresses the recognition of short-term daily living actions from RGB-D videos. Most of the existing approaches ignore spatio-temporal contextual relationships in the action videos. So, we have proposed to explore the spatial layout to better model the appearance. In order to encode temporal information, we divided the action sequence into temporal grids. We address the challenge of subject invariance by applying clustering on the appearance features and velocity features to partition the temporal grids. We validated our approach on four public datasets. The results show that our method is competitive with the state-of-the-art. The proposed architecture has been published in ICVGIP 2018 [40].

7.10. A New Hybrid Architecture for Human Activity Recognition from RGB-D videos

Participants: Srijan Das, Monique Thonnat, Kaustubh Sakhalkar, Michal Koperski, Francois Brémond, Gianpiero Francesca.

Keywords: Visual cues, Data fusion, RGB-D videos

(a) no glasses, female, black hair, smiling, young



(b) glasses, female, black hair, not smiling, old

(c) no glasses, male, no black hair, smiling, young

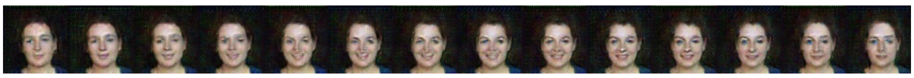
(d) glasses, male, no black hair, not smiling, old

Figure 12. Example images generated by the proposed 2D model.

(a) male, adolescent

(b) male, adult

(c) female, adolescent



(d) male, adult

Figure 13. Chosen output samples from 3DGAN

Figure 14. Structured light. A calibrated camera and projector (typically both near infrared) are placed at a fixed, known baseline. The structured light pattern helps establish correspondence between observed and projected pixels. Depth is derived for each corresponding pixel through triangulation. The process is akin to two stereo cameras, but with the projector system replacing the second camera, and aiding the correspondence problem.

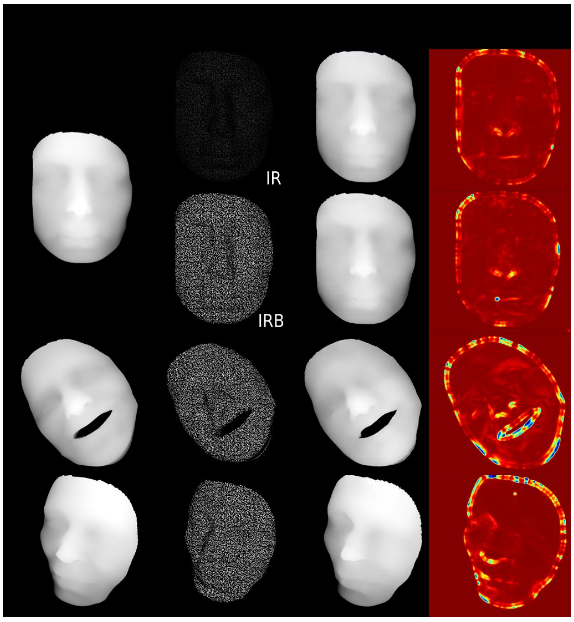


*Figure 15. *IR - Infrared image, IRB - Binarized Infrared image*

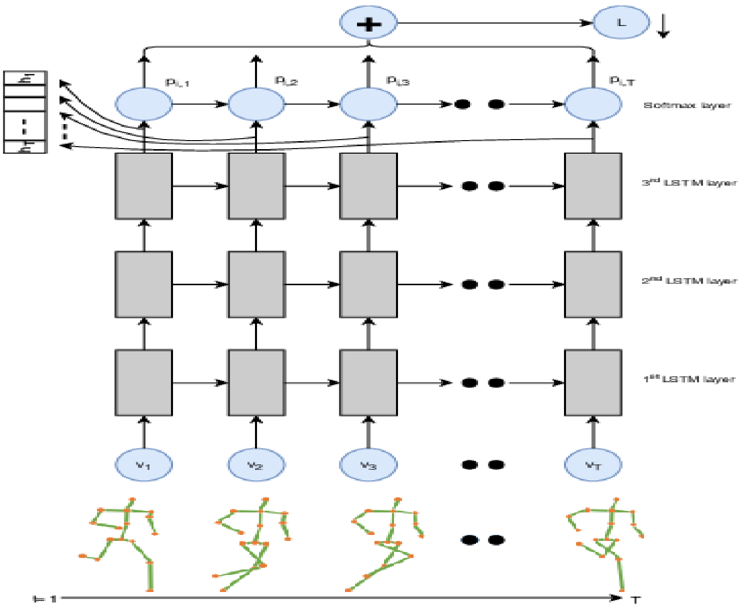


Figure 16. Framework of the deep-temporal LSTM proposed approach in [39]

Activity Recognition from RGB-D videos is still an open problem due to the presence of large varieties of actions. We have proposed a new architecture by mixing a high level handcrafted strategy and machine learning techniques. In order to address the problem of large variety of actions, we proposed a novel two level fusion strategy to combine motion, appearance and 3D pose information. For 3D pose information, we use the work published in AVSS 18 (described above). As similar actions are common in daily living activities, we also proposed a mechanism for similar action discrimination using dedicated SVMs. We validated our approach on four public datasets, CAD-60, CAD-120, MSRDailyActivity3D, and NTU-RGB+D improving the state-of-the-art results on them. The proposed architecture has been published in the industrial session of MMM 2019 [41].

7.11. Where to Focus on for Human Action Recognition?

Participants: Srijan Das, Arpit Chaudhary, Francois Brémond, Monique Thonnat.
Keywords: Spatial attention, Body parts, End-to-end

We proposed a spatial attention mechanism based on 3D articulated pose to focus on the most relevant body parts involved in the action. For action classification, we proposed a classification network compounded of spatio-temporal subnetworks modeling the appearance of human body parts and RNN attention subnetwork implementing our attention mechanism. Furthermore, we trained our proposed network end-to-end using a regularized cross-entropy loss, leading to a joint training of the RNN delivering attention globally to the whole set of spatio-temporal features, extracted from 3D ConvNets. Our method outperforms the State-of-the-art methods on the largest human activity recognition dataset available to-date (NTU RGB+D Dataset) which is also multi-views and on a human action recognition dataset with object interaction (Northwestern-UCLA Multiview Action 3D Dataset). The proposed framework will be published in WACV 2019. Sample visual results displaying the attention scores attained for each body parts can be seen in fig. 17.

7.12. Online Temporal Detection of Daily-Living Human Activities in Long Untrimmed Video Streams

Participants: Abhishek Goel, Abdelrahman G. Abubakr, Michal Koperski, Francois Brémond.
keywords: Daily-living activity recognition, Human activity detection, Video surveillance, Smarthome

Many approaches were proposed to solve the problem of activity recognition in short clipped videos, which achieved impressive results with hand-crafted and deep features. However, it is not practical to have clipped videos in real life, where cameras provide continuous video streams in applications such as robotics, video surveillance, and smart-homes. Here comes the importance of activity detection to help recognizing and localizing each activity happening in long videos. Activity detection can be defined as the ability to localize starting and ending of each human activity happening in the video, in addition to recognizing each activity label. A more challenging category of human activities is the daily-living activities, such as eating, reading, cooking, etc, which have low inter-class variation and environment where actions are performed are similar. In this work we focus on solving the problem of detection of daily-living activities in untrimmed video streams. We introduce new online activity detection pipeline that utilizes single sliding window approach in a novel way; the classifier is trained with sub-parts of training activities, and an online frame-level early detection is done for sub-parts of long activities during detection. Finally, a greedy Markov model based post processing algorithm is applied to remove false detection and achieve better results. We test our approaches on two daily-living datasets, DAHLIA and GAADRD, outperforming state of the art results by more than 10%. The proposed work has been published in [43].

7.12.1. The Work Flow of processing untrimmed videos is composed of three tasks:

- **Feature extraction** consists in extracting the Person-Centered CNN (PC-CNN) features as shown in fig. 18.
- **Classifier Training:** All training videos are first divided into relatively small windows of size W frames, which represent activity sub-videos (subparts). Then the features are generated for all these windows and the training is done with linear SVM classifier using all activities sub-videos.
- **Majority voting filtering**, as depicted in fig. 19, looks up for neighbors within a certain range that have the same label apply majority-voting between the labels

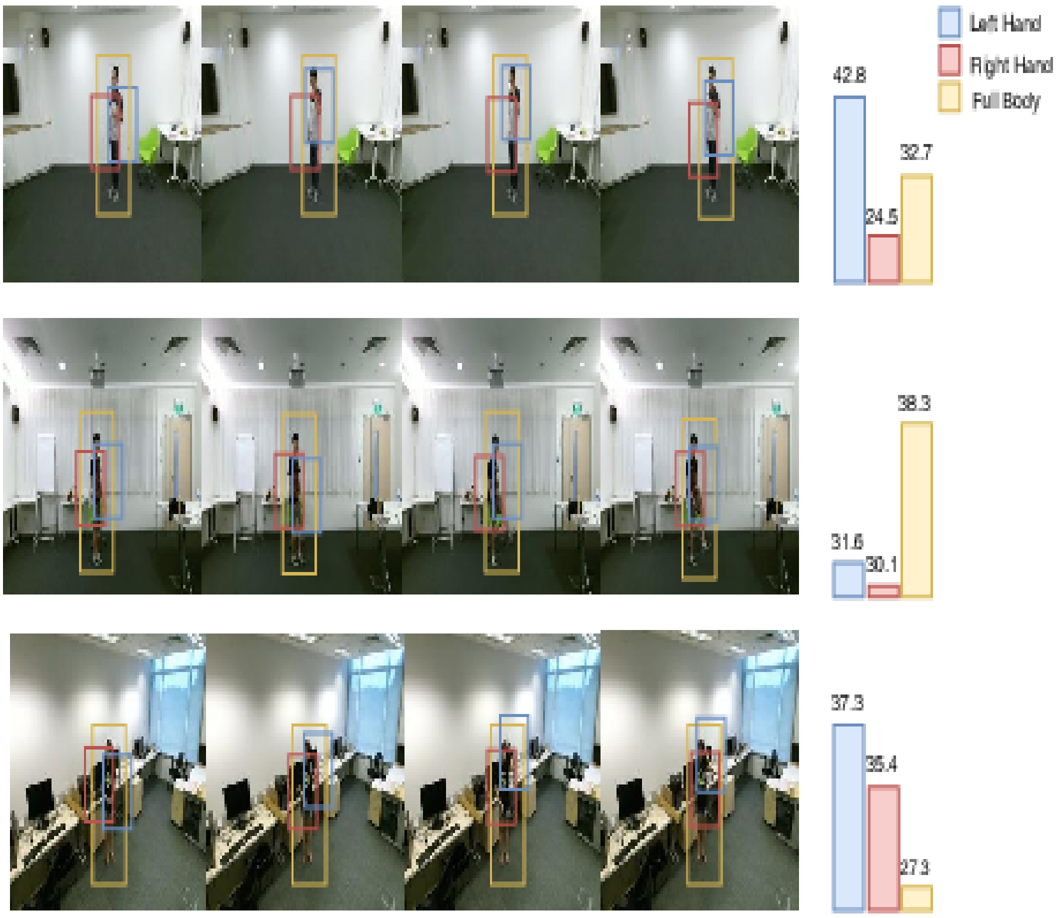


Figure 17. Example of video sequences with their respective attention scores. The action categories presented are drinking water with left hand (1st row), kicking (2nd row) and brushing hair with left hand (last row).

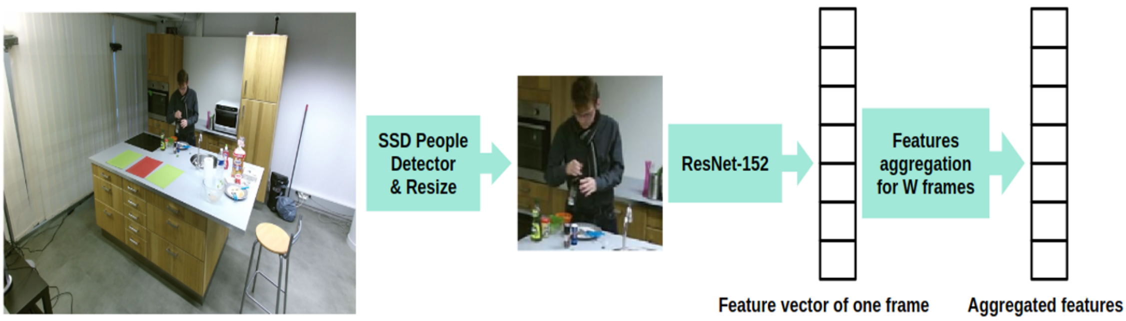


Figure 18. Extracting the Person-Centered CNN (PC-CNN) features

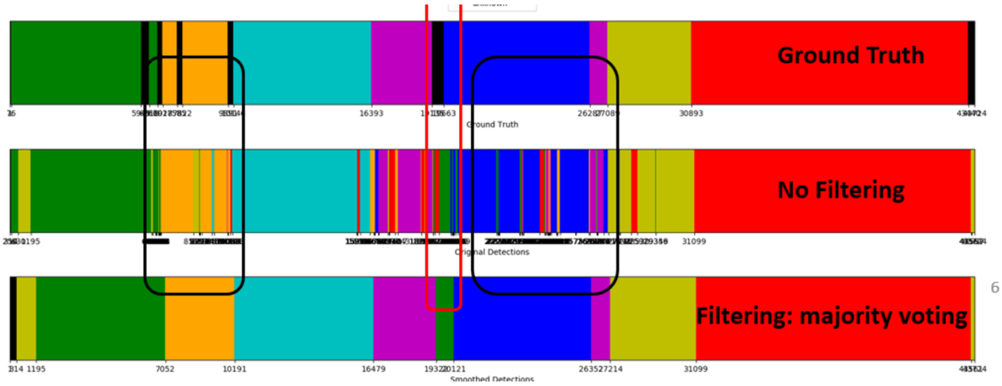


Figure 19. Post-filtering

7.13. Activity Detection in Long-term Untrimmed Videos by discovering sub-activities

Participants: Farhood Negin, Abhishek Goel, Abdelrahman G. Abubakr, Gianpiero Francesca, Francois Brémond.

Keywords: Activity detection, Semi-supervised learning, Sub-activity detection.

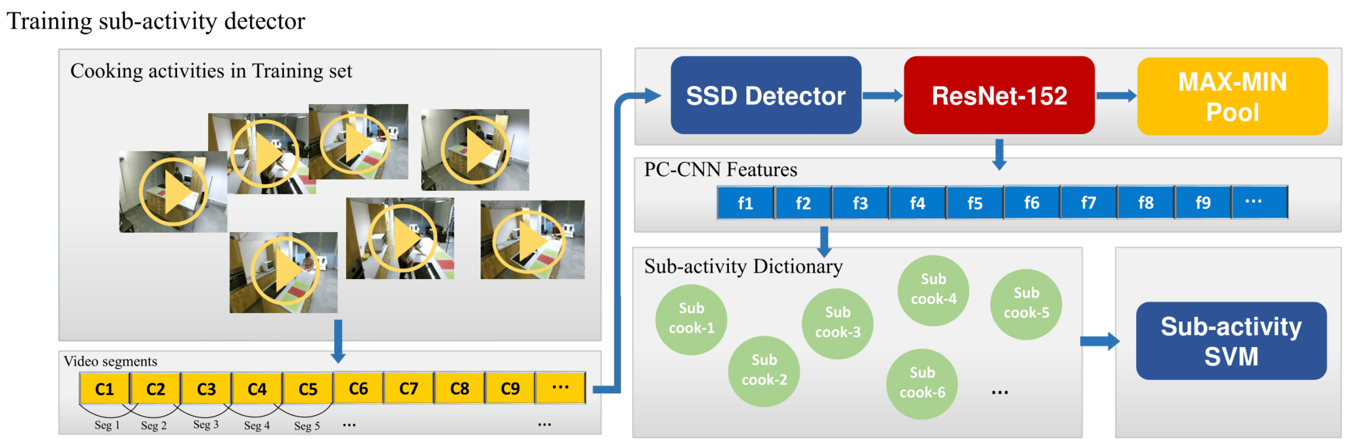


Figure 20. The process of extracting PC-CNN features and training of a weakly supervised sub-activity detector for the "Cooking" activity.

Detecting temporal delineation of activities is important to analyze large-scale videos. However, there are still challenges yet to be overcome in order to have an accurate temporal segmentation of activities. Detection of daily-living activities is even more challenging due to their high intra-class and low inter-class variations, complex temporal relationships of sub-activities performed in realistic settings. To tackle these problems, we propose an online activity detection framework based on the discovery of sub-activities. We consider a long-term activity as a sequence of short-term sub-activities. Our contributions can be summarized as follows:

- We introduce a new online frame-level activity detection pipeline which uses single-sized window approach. A weakly supervised classifier is trained directly on sub-activities discovered by clustering and operates on test videos to capture sub-activities of long videos within a fixed temporal window.
- To alleviate the noisy detections especially in activity boundaries, we propose a novel greedy post-processing method based on Markov models.
- We have extensively evaluated our proposed method on untrimmed videos from DAHLIA [68] and GAADRD [77] datasets and achieved state-of-the-art performances.

7.13.1. Proposed Method:

Our framework produces frame-level activity labels in an online manner by two major steps followed by a novel greedy post-processing technique. In order to handle long activities, activities are decomposed into a sequence of fixed-length overlapping temporal clips. We then extract deep features from the clips. We suggested a person-centric feature (PC-CNN) based on SSD detector that satisfies required processing efficiency of online systems. We then proposed a weakly-supervised method for the discovery of sub-activities of long-term activities which benefits from clustering and model selection methods to find the optimal sub-activities of the given activities. In order to characterize each activity with constituent sub-activities, we use K-means to cluster that activity's clips and construct a specific sub-activity dictionary. Therefore, we have one sub-activity dictionary for each main activity. We represent an activity sequence with sub-activity assignments using the trained dictionary. Then, for each activity class, we train a binary SVM classifier (one versus all) based on its sub-activities (Figure 20). The trained classifiers are then simultaneously used to produce frame-level activity labels with the help of a sliding window architecture. It should be noticed that unlike multi-scale sliding window methods, we only use a single fixed-size temporal window thanks to recognition of fixed length sub-activities. Finally, assuming temporal progression of sub-activities, we developed a greedy algorithm based on Markov models to refine noisy sub-activity proposals in middle and boundary regions of long activities. We evaluated the proposed method on two daily-living activity datasets and achieved state-of-the-art performances.

Table 1. The activity detection results obtained on the DAHLIA. Values in bold represent the best performance.

	ELS			**Max Subgraph Search**			**DOHT (HOG)**			**Sub Activity**		
	FA_1	F_score	IoU	FA_1	F_score	IoU	FA_1	F_score	IoU	FA_1	F_score	IoU
View 1	0.18	0.18	0.11	-	0.25	0.15	0.80	0.77	0.64	**0.85**	**0.81**	**0.73**
View 2	0.27	0.26	0.16	-	0.18	0.10	0.81	0.79	0.66	**0.87**	**0.82**	**0.75**
View 3	0.52	0.55	0.39	-	0.44	0.31	0.80	**0.77**	0.65	**0.82**	0.76	**0.69**

Table 2. Detection results obtained on the GAADRD dataset.

Method	FA_1	F_score	IoU
simple sliding window(HOG)	0.68	0.52	0.40
simple sliding window(PC-CNN)	0.61	0.55	0.44

Tables 1 and 2 show the results of applying the developed frameworks on DAHLIA and GAADRD respectively. It can be noticed that in DAHLIA dataset (compared to [71], [61], [60]), we significantly outperformed state-of-the-art results in all of the categories except in camera view 3 when the F-Score metric is used. We reported the results of GAADRD dataset with the two types of features HOG and PC-CNN. As it can be seen, even with hand-crafted features our framework produces comparable results. In future work, we are going to improve the sub-activity discovery algorithm by making it able to distinguish similar sub-activities in two different activities.

7.14. Video based Face Analysis for Health Monitoring

Participants: Abhijit Das, Antitza Dantcheva, Francois Brémond.

Keywords: Face, Attribute, GAN, Biometrics

Video based analysis in severely demented Alzheimer's Disease (AD) patients can be helpful for the analysis of their neuropsychiatric symptom such as apathy, depression. Even for the doctors it can be hard to know whether a person has depression or apathy. The main difference is that a person with depression will have feelings of sadness, be tearful, feel hopeless or have low self-esteem. Whereas, symptoms of person suffering from apathy can make the person's life less enjoyable. Therefore, a psychological protocol scenario can be used for video-based emotion analysis and facial movement can be used for discriminating apathetic person and non-apathetic person.

We proposed to use a) the facial expressions (neutral + 6 basic emotions: anger, disgust, happiness, surprise, sadness, fear) extracted using 50 layer Resnet, b) facial movements employing 68 facial landmark points, c) action unit intensity and frequency for AU 1, 2, 4, 5, 6, 7, 9, 10, 12, 14, 15, 17, 20, 23, 25, 26, and 45 using OpenFace and d) lip movements employing the 3D mouth open vector using the mean of upper lip and mean of bottom lip extracted from the facial landmarks detected around the lip as feature for each frame of the video. We post-process the features and calculated the amplitude, SD (Standard Deviations) and mean of each clip (10 seconds per clip) and these features were passed inputs to GRU. The GRU is connected to the Fully Connected layers, these fully connected features are mean pooled to get the apathy/non-apathy classification.

7.15. Mobile Biometrics

Participants: Abhijit Das, Antitza Dantcheva, Francois Brémond.

Keywords: Mobile biometrics

The prevalent commercial deployment of mobile biometrics as a robust authentication method on mobile devices has fueled increasingly scientific attention. Motivated by this, in this work [38] we seek to provide insight on recent development in mobile biometrics. We present parallels and dissimilarities of mobile biometrics and classical biometrics, enumerate related strengths and challenges. Further, we provide an overview of recent techniques in mobile bio-metrics, as well as application systems adopted by industry. Finally, we discuss open research problems in this field.

7.16. Comparing Methods for Assessment of Facial Dynamics in Patients with Major Neurocognitive Disorders

Participants: Yaohui Wang, Antitza Dantcheva, Francois Brémond.

Keywords: Face Analysis

Assessing facial dynamics in patients with major neurocognitive disorders and specifically with Alzheimer's disease (AD) has shown to be highly challenging. Classically such assessment is performed by clinical staff, evaluating verbal and non-verbal language of AD-patients, since they have lost a substantial amount of their cognitive capacity, and hence communication ability. In addition, patients need to communicate important messages, such as discomfort or pain. Automated methods would support the current healthcare system by allowing for telemedicine, *i.e.,* lesser costly and logistically inconvenient examination. In this work [52], we compare methods for assessing facial dynamics such as talking, singing, neutral and smiling in AD-patients, captured during music mnemotherapy sessions. Specifically, we compare 3D ConvNets (see Figure 21), Very Deep Neural Network based Two-Stream ConvNets (see Figure 22), as well as Improved Dense Trajectories. We have adapted these methods from prominent action recognition methods and our promising results suggest that the methods generalize well to the context of facial dynamics. The Two-Stream ConvNets in combination with ResNet-152 obtains the best performance on our dataset (Table 3), capturing well even minor facial dynamics and has thus sparked high interest in the medical community.

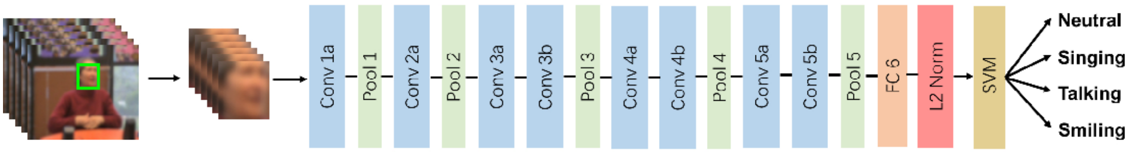
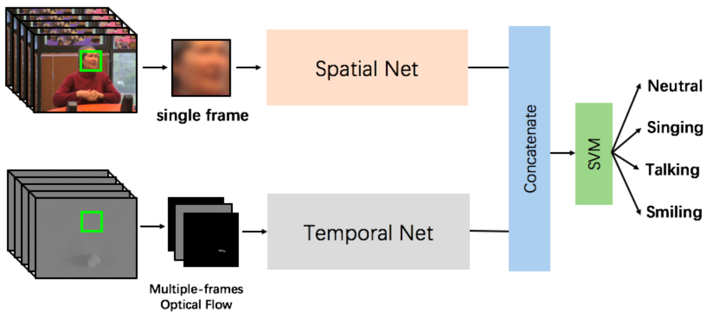
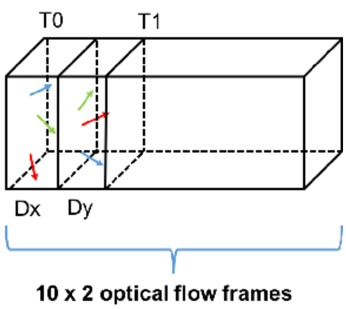


*Figure 21. **C3D based facial dynamics detection:** For each video sequence, faces are detected and the face sequences are passed into a pre-trained C3D network to extract a 4096-dim feature vector for each video. Finally a SVM classifier is trained to predict the final classification result. We have blurred the faces of the subject in this figure, in order to preserve the patient's privacy.*



(a) Two-Stream Architecture



(b) Stacked Optical Flow Field volume

Figure 22. (a) While the spatial ConvNet accepts a single RGB frame as input, the temporal ConvNet's input is the D_x and D_y of 10 consecutive frames, namely 20 input channels. Both described inputs are fed into the Two-stream ConvNets, respectively. We use in this work two variations of Very Deep Two Stream ConvNets, incorporating VGG-16 [76] ResNet-152 [65] for both streams respectively. (b) The optical flow of each frame has two components, namely D_x and D_y. We stack 10 times D_y after D_x for each frame to form a 20 frames length input volume.

Table 3. Classification accuracies of C3D, Very Deep Two-Stream ConvNets, iDT, as well as fusion thereof on the presented ADP-dataset. We report the Mean Accuracy (MA) associated to the compared methods. Abbreviations used: SN...Spatial Net, TN...Temporal Net.

Method	**MA (%)**
C3D	67.4
SN of Two-Stream ConvNets (VGG-16)	65.2
TN of Two-Stream ConvNets (VGG-16)	69.9
Two-Stream ConvNets (VGG-16)	76.1
SN of Two-Stream ConvNets (ResNet-152)	69.6
TN of Two-Stream ConvNets (ResNet-152)	75.8
Two-Stream ConvNets (ResNet-152)	76.4
iDT	61.2
C3D + iDT	71.1
Two-Stream ConvNets (VGG-16) + iDT	78.9
Two-Stream ConvNets (ResNet-152) + iDT	**79.5**

7.17. Combating the Issue of Low Sample Size in Facial Expression Recognition

Participants: S L Happy, Antitza Dantcheva, Francois Brémond.

Keywords: Face analysis, Expression recognition

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 contain images and videos with discrete disjoint labels of profound emotions, real-life data contain jointly occurring emotions and expressions of different intensities. Reliable data annotation is a major problem in this field, which results in publicly available datasets with low sample size. Transfer learning [73], [64] is usually used to combat the low sample size problem by capturing high level facial semantics learned on different tasks. However, 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 here propose a weakly supervised learning technique for expression classification, which leverages the information of unannotated data. In weak supervision scenarios, a portion of training data might not be annotated or wrongly annotated [79]. Crucial in our approach is that we first train a convolutional neural network (CNN) with label smoothing in a supervised manner and proceed to tune the CNN-weights with both labelled and unlabelled data simultaneously. The learning method learns the expression intensities in addition to classifying them into discrete categories. This bootstrapping of a fraction of unlabelled samples, replacing labelled data for model-update, while maintaining the confidence level of the model on supervised data improves the model performance.

Table 4. Cross database classification performance when using CK+ database for training.

Test databases	Percentage of training data		
	25%	50%	80%
CK+ (test-set)	88.79%	91.29%	95.16%
RaFD	64.25%	65.25%	78.46%
lifespan	35.13%	40.51%	60.83%

7.17.1. Experimental Results

Experiments were conducted on three publicly available expression datasets, namely CK+, RaFD, and lifespan. Substantial experiments on these datasets demonstrate large performance gain in cross-database performance,

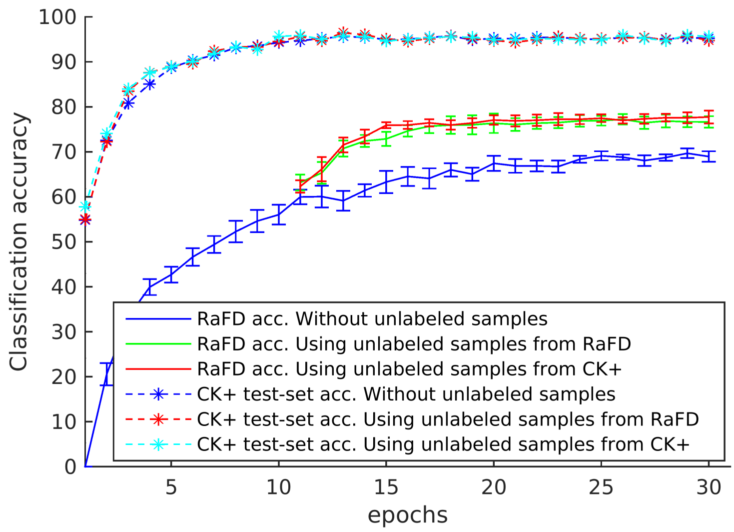


Figure 23. Cross-database experiments show significant performance improvement.

as well as show that the proposed method achieves to learn different expression intensities, even when trained with categorical samples. As can be seen in Fig. 23, when the model is trained on CK+ with unlabelled data, the model-performance improved by 11% in RaFD cross database evaluation. We observe that the use of unlabelled data from either CK+ or RaFD results in similar performances. Utilizing unlabelled images from CK+, the network sees varying expression-intensities and adapts to it. Table 4 reports the self and cross-database classification results with respect to varying number of training samples. Significant classification accuracy has been obtained with merely 25% of the training data. Use of a larger labelled training set strikingly boosts the cross-database performance. In future, we are planning to further improve the performance with unsupervised learning of expression patterns.

7.18. Serious Exergames for Cognitive Stimulation

Participants: Guillaume Sacco, Monique Thonnat.

Keywords: Neurocognitive disorders, Serious games, Geriatrics, Executive functions, Physical exercise, Cognitive training

A PhD thesis has been defended on the 8th of June at Nice University on this topic by Guillaume Sacco. This thesis presents a clinical and therapeutic approach aiming to create new care for patients with neurocognitive disorder. Serious exergames are serious video games integrating physical activity. Serious exergames could be tools to product enriched environment associating physical exercise and cognitive training. The aim of this thesis is to investigate whether serious exergames can contribute to the non-pharmacological management of neurocognitive disorders. In this thesis we have made two types of contributions. The first type are general contributions. One presents our integrative clinical approach associating physical exercise and cognitive training using serious exergames. The other one presents recommendations concerning the use of serious exergames. The second type of contributions are experimental. The first one aims to confirm a theoretical base of our clinical approach. The two other experiments assess the implementation of our approached in a population of patients with neurocognitive disorder. This year the integrative clinical approach associating physical exercise and cognitive training using serious exergames has been published [32] and presented at the International Conference on Gerontechnology ISG in Saint Petersburg, Florida, USA in May 2018.

7.19. Speech-Based Analysis for older people with dementia

Participants: Alexandra König, Philippe Robert, Nicklas Linz, Johannes Tröger, Jan Alexandersson.

Keywords: Alzheimer's disease, Dementia, Mild cognitive impairment, Neuropsychology , Assessment, Semantic verbal fluency, Speech recognition, Speech processing, Machine learning

7.19.1. Fully Automatic Speech-Based Analysis of the Semantic Verbal Fluency Task:

Semantic verbal fluency (SVF) tests are routinely used in screening for mild cognitive impairment (MCI). In this task, participants name as many items as possible of a semantic category under a time constraint. Clinicians measure task performance manually by summing the number of correct words and errors. More fine-grained variables add valuable information to clinical assessment, but are time-consuming. Therefore, the aim of this study is to investigate whether automatic analysis of the SVF could provide measures as accurate as the manual ones and thus, support qualitative screening of neurocognitive impairment.

Methods: SVF data were collected from 95 older people with MCI (n = 47), Alzheimer's or related dementias (ADRD; n = 24), and healthy controls (HC; n = 24). All data were annotated manually and automatically with clusters and switches. The obtained metrics were validated using a classifier to distinguish HC, MCI, and ADRD.

Results: Automatically extracted clusters and switches were highly correlated (r = 0.9) with manually established values, and performed as well on the classification task, separating HC from persons with ADRD (area under curve [AUC] = 0.939) and MCI (AUC = 0.758).

Conclusion: The results show that it is possible to automate fine-grained analyses of SVF data for the assessment of cognitive decline [70].

7.19.2. Language Modelling in the Clinical Semantic Verbal Fluency Task:

We employed language modelling (LM) as a natural technique to model production in this task. Comparing different LMs, we show that perplexity of a person's SVF production predicts dementia well (F1 = 0.83). Demented patients show significantly lower perplexity, thus are more predictable. Persons in advanced stages of dementia differ in predictability of word choice and production strategy - people in early stages differ only in predictability of production strategy (Linz et al., 2018a).

7.19.3. Telephone-based Dementia Screening I: Automated Semantic Verbal Fluency Assessment:

Despite encouraging results, there are still two main issues in leveraging pervasive sensing technologies for automatic dementia screening: significant hardware costs or installation efforts and the challenge of an effective pattern recognition. Conversely, automatic speech recognition (ASR) and speech analysis have reached sufficient maturity and allow for low-tech remote telephone-based screening scenarios. Therefore, we examine the technological feasibility of automatically assessing a neuropsychological test—Semantic Verbal Fluency (SVF)–via a telephone-based solution. We investigate its suitability for inclusion into an automated dementia frontline screening and global risk assessment, based on concise telephone-sampled speech, ASR and machine learning classification. Results are encouraging showing an area under the curve (AUC) of 0.85. We observe a relatively low word error rate of 33% despite phone-quality speech samples and a mean age of 77 years of the participants. The automated classification pipeline performs equally well compared to the classifier trained on manual transcriptions of the same speech data. Our results indicate SVF as a prime candidate for inclusion into an automated telephone-screening system [50].

7.19.4. Using Acoustic Markers extracted from Free Emotional Speech:

Apathy is a frequent neuropsychiatric syndrome in people with dementia. It leads to diminished motivation for physical, cognitive and emotional activity. Apathy is highly underdiagnosed since its criteria have been only recently established and rely heavily on the subjective evaluation of human observers. We analyzed speech samples from demented people with and without apathy. Speech was provoked by asking patients two emotional questions. Acoustic features were extracted and used in a classification task. The resulting models show performances of AUC = 0.71 and AUC = 0.63. This is a decent first step into the direction of automatic detection of apathy from speech. Usefulness of stimuli to elicit free speech is found to depend on patients' gender [46].

7.19.5. Using Automatic Speech Analysis:

Apathy is present in several psychiatric and neurological conditions and found to have a severe negative effect on patients' life. In older people, it can be a predictor of increased dementia risk. Current assessment methods seem insufficiently objective and sensitive, thus new diagnostic tools and broad-scale screening technologies are needed. This study is the first of its kind aiming to investigate whether automatic speech analysis could be used for characterization and detection of apathy.

Methods: A group of apathetic and non-apathetic patients (n = 60) was recorded while performing two short narrative speech tasks. Paralinguistic markers relating to prosodic, formant, source and temporal qualities of speech were automatically extracted, examined between the groups and compared to baseline assessments. Machine learning experiments were carried out to validate the diagnosis power of extracted markers.

Results: Correlations between apathy sub-scales and features revealed a relation between temporal aspects of speech and the subdomains of reduction in interest and initiative, as well as between prosody features and the affective domain. Group differences were found to vary for males and females, depending on the task. Differences in temporal aspects of speech were found to be the most consistent difference between apathetic and non-apathetic patients. Machine learning models trained on speech features achieved top performances of AUC = 0.88 for males and AUC = 0.77 for females (article under review).

An additional study in this context analyses transcripts of responses to emotional questions (positive and negative) for sentiment using a French emotion dictionary (FEEL) and for psycholinguistic properties (LIWC). Significant reductions in the number of words, the magnitude of sentiment, the overall sentiment and the range between sentiment in the positive and negative questions are found for the apathetic population. This effect is consistent between the positive and the negative stories. When training machine learning classifiers to detect apathy based on these features, the best model showed an AUC of 0.874 using only sentiment features. LIWC features mostly showed no predictive power. When ASR technology was introduced to automatically create transcripts, the performance of predictive models dropped slightly to AUC = 0.864. ASR errors were consistent over all categories of sentiment words. These results highlight the potential of computational linguistic analysis in screening for apathy (article under review).

7.20. Monitoring the Behaviors of Retail Customers

Participants: Soumik Mallick, Julien Badie, Francois Brémond.

Keywords: Ontology, Event detection, Multi-sensor data fusion, Real-time person tracking

The future shops will be connected and distributors as well as shopkeepers need to fulfill their promise to provide a personalized shopping experience to the customers, for example: advising and guiding customers in real time. It could not only enrich the productivity of the staffs but also increase the product sale. Implementing digital service and information in the store (like using beacons) is of primary importance. Sellers can keep their promise by providing the customer's contextual support tool in order to sell more product. To improve the performance of the store, this digital service can help to analyze customer displacement and the reaction to the product which can help to reduce the operational costs of the store by optimizing store process. It can also help to adjust store prices, merchandising and commercial operation. Thus connected digital store is a major level for new consumer services and an efficient way to manage the store.

We use multiple video cameras to detect customer in real-time inside the store. Furthermore, data are collected from different sensors like mobile phone, video camera, GPS location or Beacon. It helps to provide us with the trajectory information of the customer. A trajectory is composed of a set of points. The trajectory points are collected with the help of sensor API. Then, the calculation of distance of points in subsequent frames is performed. Every point has a minimum distance to a certain threshold of time. If there is a difference between a distance on a certain period of time that will be considered as a moving subject. For example, if we have

2 tracklets from different sensors (and generally with a different frequency of points), we cut both tracklets just to keep the intersection (in terms of time) and then apply Dynamic Time Warping (DTW) on this section. When we have the results for all tracklet pairs, we order them by distance and we decide to authorize to merge the data from the different sensors or not, with help of fusion algorithms to pass the information from the sensors to the ontology. After that, only one trajectory is sent to the ontology. Then we create a SPARQL request to extract trajectory-based events and execute it.

In this storeConnect project, we are investigating to improve the event recognition model. It will help to identify customer activity in the different zone inside the store as well as moving and stopping positions of the customer. Furthermore, inside the ontology, we want to add different attributes such as emotion, gender etc.

7.21. 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 artefacts), that follow the predefined model of an activity. We propose to describe activities as a series of actions, triggered and driven by environmental events.

Due to the large range of application domains (surveillance, safety, health care ...), we propose a generic approach to design activity recognition systems that interact continuously with their environment and react to its stimuli at run-time. Such recognition systems must satisfy stringent requirements: dependability, real time, cost effectiveness, security and safety, correctness, completeness ... To enforce most of these properties, our approach is to base the configuration of the system as well as its execution on formal techniques. We chose the *Synchronous Approach* which provides formal bases to perform static analysis, verification and validation, but also direct implementation.

Based on the synchronous approach, we designed a new user-oriented activity description language (named ADeL) to express activities and to automatically generate recognition automata. This language relies on two formal semantics, a behavioral and an equational one [48]. We also developed a component, called Synchronizer, to transform asynchronous sensor events into synchronous “instants”, necessary for the synchronous approach. This year, we mainly worked on the ADeL compiler to generate synchronous automata, on the graphical tool of this language and on the Synchronizer component.

7.21.1. ADeL Compilation:

To compile an ADeL program, we first transform it into an equation system which represents its synchronous automaton. Then we directly implement this equation system, transforming it into a Boolean equation system. This equation system provides an effective implementation of the initial ADeL program for our runtime recognition engine. The internal representation as Boolean equation systems also makes it possible to verify and validate ADeL programs, by generating a format suitable for a dedicated model checker such as the off-the-shelf NuSMV model-checker.

7.21.2. Synchronizer:

The role of the Synchronizer is to filter physical asynchronous events, to decide which ones may be considered as “simultaneous” and to aggregate the latter into logical instants. The sequence of these instants constitutes the logical time of our recognition systems. The runtime recognition engine interacts with the synchronizer and uses these instants to run the automata corresponding to the activities currently recognized. In general, no exact decision algorithm exists but several empirical strategies and heuristics may be used e.g., for determining instant boundaries. This year we completed the specification and implementation of a first version of the Synchronizer. It is parametrized by heuristics to manage events and data coming from various sensors, to define instant boundaries, and to cope with possible high level interruptions (preemptions).

Moreover, to facilitate the job of the synchronizer (to build the instants) and of the runtime engine (to wake up only the relevant automata), each automaton provides information about the awaited events at each state, i.e the events which may trigger transitions to a next state. The ADeL compiler has in charge to generate this information. In a first attempt, we computed statically all the awaited events in all states of an automaton. However, this approach implied to build the entire explicit automaton from an equation system, which was not realistic. Thus, this year we added specific equations to the equation systems of the operational semantics to compute the awaited events of each operator of the language. The information about next awaited events is now computed at runtine, when a state of the automaton is reached.

7.22. Probabilistic Activity Description Language

Participants: Elisabetta de Maria, Sabine Moisan, Jean-Paul Rigault.

Since the arrival of E. De Maria in the STARS team in September 2018, we work on the conception of a probabilistic framework for human behavior representation. The goal is to propose (i) a textual language for the description of activities which takes uncertainty into account; (ii) a formal probabilistic model to represent behaviors. Such a model will be tested and validated using experimental data coming from Alzheimer's patients. We will use temporal data resulting from different sensors and corresponding to patients playing with serious games. This will be the topic of T. L'Yvonnet's PhD starting in December. E. De Maria's main researches concern the investigation of the dynamic behavior of biological neuronal networks, using Leaky Integrate and Fire (LIF) neuronal networks, whose temporal dimension is crucial (the state of each neuron is computed taking into account not only present inputs but also past ones). This year, we used the PRISM language to model LIF neuronal networks as probabilistic reactive systems and we proposed an algorithm which aims at reducing the number of neurons and synaptical connections of these networks [42].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

- *Toyota:* (Action Recognition System): This project runs from the 1st of August 2013 up to 2019. 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) to better interact with the older adult. 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. These 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.
- *BluManta:* This contract is a CIFRE PhD grant and runs from August 2018 to August 2021. The aim is to develop an end-to-end 3D face analysis model, involving a unified deep neural network in charge of (a) creating a depth map, (b) extracting embeddings, (c) embeddings similarity estimation. This model will be targeted for high accuracy in tasks such as face authentication.
- *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.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

9.1.1.1. 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.

9.1.2. FUI

9.1.2.1. 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.

9.1.2.2. StoreConnect

Program: FUI

Project acronym: StoreConect.

Project title: StoreConnect.

Duration: September 2016 - September 2018.

Coordinator: Ubudu (Paris).

Other partners: Inria(Stars), STIME (groupe Les Mousquetaires (Paris)), Smile (Paris), Thevolys (Dijon).

Abstract: StoreConnect is an FUI project started in 2016 and will end in 2018. 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.

9.1.2.3. ReMinAry

Program: FUI

Project acronym: ReMinAry.

Project title: ReMinAry.

Duration: September 2016 - September 2019.

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 reeducative approach, through clinical trials centered on two pathologies with immobilization: post-traumatic (surgery of the shoulder) and neurodegenerative (amyotrophic lateral sclerosis).

9.2. International Initiatives

9.2.1. International Initiatives

FER4HM

Title: Facial expression recognition with application in health monitoring

International Partner (Institution - Laboratory - Researcher):

Chinese Academy of Sciences (China) Institute of Computing Technology - 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 [1-3], and some even their verbal communication ability (e.g., aphasia)2. 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 [9, 10]. 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.

SafEE

Title: Safe Easy Environment

International Partner (Institution - Laboratory - Researcher):

Duration: 2018 - 2020

Start year: 2018

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.

9.3. International Research Visitors

9.3.1. Visits to International Teams

Antitza Dantcheva visited Wael Abd-Almageed's laboratory at the Information Sciences Institute of the University of Southern California Viterbi School of Engineering in August 2018.

Antitza Dantcheva, Abhijit Das and Yaohui Wang visited the Institute of Computing Technology (ICT) at the Chinese Academy of Sciences (CAS) in August 2018.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

Francois Brémond was a General Chair for the 3rd IEEE International Conference on Image Processing, Applications and Systems (IPAS 2018).

10.1.1.2. Member of Organizing Committees

- Abhijit Das organized 5th Sclera Segmentation Benchmarking Competition 2018, in conjunction with International Conference on Biometrics 2018.
- Abhijit Das organized 1st Thai Student Signature and Name component Recognition and Verification Competition 2018 in conjunction with ICFHR 2018.
- Antitza Dantcheva and Abhijit Das organized Recent Advances in Biometric Technology for Mobile Devices (RABTMD 2018) in conjunction with the 9th IEEE International Conference on Biometrics: Theory, Applications, and Systems BTAS 2018.
- Antitza Dantcheva and Abhijit Das were local organizing co-chairs of IEEE International Conference on Image Processing, Applications and Systems (IPAS 2018).
- Alexandra Konig was member of the organizing committee of RaPID-2018 workshop (Resources and ProcessIng of linguistic, para-linguistic and extra-linguistic Data from people with various forms of cognitive/psychiatric impairments) 8th of May 2018, Miyazaki, Japan.

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

- Antitza Dantcheva was program Co-chair at the International Conference of the Biometrics Special Interest Group (BIOSIG) 2017 and 2018, September, 2018, Darmstadt, Germany.
- Alexandra Konig was program chair of 2nd Workshop on AI for Aging, Rehabilitation and Independent Assisted Living (ARIAL) @IJCAI'18 - In conjunction with 27th International Joint Conference on Artificial Intelligence and the 23rd European Conference on Artificial Intelligence,July 15, 2018, Stockholm, Sweden.

10.1.2.2. Member of Conference Program Committees

- Francois Brémond was program committee member of WACV18.
- Francois Brémond was a member of the AVSS Steering Committee for 2018
- Monique Thonnat was program committee member of the conference ICPRAM 2019
- Antitza Dantcheva was in the technical program committee of the IAPR International Conference on Biometrics (ICB) 2018
- Jean-Paul Rigault is a member of the *Association Internationale pour les Technologies à Objets* (AITO) which organizes international conferences such as ECOOP.

10.1.3. Reviews

- Francois Brémond was reviewer for many journals, such as IEEE Transactions on Circuits and Systems for Video Technology, for the journal Frontiers in Human Neuroscience, for the journal "revue Retraite et société" and Medical Engineering & Physics.
- Antitza Dantcheva was reviewer for a number of journals including 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), IET Biometrics, Pattern Recognition letters, Pattern Recognition.
- Francois Brémond was reviewer for many conferences including : CVPR2018, ECCV2018, VOT2018, ICCV2018, WACV2018-19, ISG18.
- Monique Thonnat is a reviewer for the journal Artificial Intelligence in Medicine AIIM (Elsevier).
- Sabine Moisan was reviewer for the 10th ICAART'18 International Conference on Agents and Artificial Intelligence.

10.1.4. Member of Editorial Boards

- Francois Brémond has been handling editor of the international journal "Machine Vision and Application" since 2014 and editor of a PANORAMA special issue of Journal of Electronic Imaging Letters (JEI): Ultra Wide Context and Content Aware Imaging.
- Antitza Dantcheva has been in the Editorial Board of the Journal Multimedia Tools and Applications (MTAP) since 2017.

10.1.5. Invited Talks

Francois Brémond was invited by:

- Prof. Vasek Hlavac (Czech Technical University in Prague) to give a talk at the Computer Vision Winter Workshops CVWW in Cesky Krumlov, 5th February 2018.
- Derek J Collins (Huawei) to give a talk at the 3rd Annual Computer Vision / Video Intelligence Forum in Dublin, 0ct. 2018.
- Nicolas Padoy (University of Strasbourg) to give a talk at the workshop MCV at CVPR, June 2018
- Dr Lauren CAURO (City of Nice) to give a talk at the workshop "Ethique en santé connectée : La santé connectée, un progrès pour tous? ", 26 Oct 2018
- Christophe ROUSSEAU (University of Nice) to give a talk at the SophIA Summit : IA et vision, 9 Nov 2018

- Monique Thonnat was invited by INGER to give a talk on Monitoring People with Video Analysis at the Franco-Mexican workshop AI Technology Applications and Research on Frailty and Dementia, Mexico, 22-23 November 2018.
- A. Dantcheva. “Facial analysis: from soft biometrics to healthcare” at Information Sciences Institute (ISI) at the University of Southern California (USC), Los Angeles, USA, September 2018.
- A. Dantcheva. “Facial analysis: from biometrics to healthcare” at Institute of Computing Technology (ICT) at the Chinese Academy of Sciences (CAS), Beijing, China, August 2018.
- Monique Thonnat has been invited to give a talk on Activity Recognition for Neurocognitive Disorders at the International Symposium on Smart Healthcare and Age-Friendly by Taichung Veterans General Hospital, Taichung, Taiwan, 4 December 2018.
- Monique Thonnat has been invited by Taipei Medical University to give a talk on An Approach with serious Exergames for Assessment and Stimulation of Patients with Neurocognitive Disorders at Bioinformatics vs Medecine: The Elderly Care in the Information Era, The Needs and Responses, Taipei, Taiwan, 6 December 2018.
- Francois Brémond has been invited to give a talk on Activity Recognition for People Monitoring at the International Symposium on Smart Healthcare and Age-Friendly by Taichung Veterans General Hospital, Taichung, Taiwan, 4 December 2018.
- Francois Brémond has been invited by Taipei Medical University to give a talk on Activity Recognition to Monitor Older People at Bioinformatics vs Medecine: The Elderly Care in the Information Era, The Needs and Responses, Taipei, Taiwan, 6 December 2018.

10.1.6. Leadership within the Scientific Community

- Francois Brémond was a member of the Evaluation Committee (i.e. HCERES) of the research laboratory LIPADE from Paris Descartes University, 15 March 2018.
- Francois Brémond was a member of the Evaluation Committee for the professor position in computer science of Lyon University, April 24th and May 15th 2018.
- Francois Brémond was a Reviewer for the AME Programmatic Proposal ”Human-Robot Collaborative AI for Advanced Manufacturing and Engineering” on behalf of (A*STAR) Singapore, 30th May 2018.
- Francois Brémond was an expert for a research program at the Campus for Research Excellence and Technological Enterprise (CREATE) from the National University of Singapore (NUS), Oct 2018.
- Francois Brémond was the working group Leader for reviewing a new Inria Project Team Proposal: CHORALE
- Francois Brémond is part of the Advisory Board of the V4Design EU project for the Horizon 2020 framework, ICT-20-2017 Call, Tools for smart digital content in the creative industries, 2018-21
- 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

10.2. Teaching - Supervision - Juries

10.2.1. Supervision

- PhD: Guillaume Sacco, Serious video games in gerontological practice: application to relationships between physical activity and cognition, Thèses, Université Côte d'Azur, June 2018.
- PhD: F. NEGIN, Toward Unsupervised Human Activity and Gesture Recognition in Videos, Theses, Universit´e Cote d'Azur, Sep 2018.
- PhD: L. A. NGUYEN, Long-term people trackers for video monitoring systems, Theses, Université Côte d'Azur, July 2018.
- PhD: M. K. PHAN TRAN, Maintaining the engagement of older adults with dementia while interacting with serious game, Theses, Université Côte d'Azur, April 2017,

10.2.2. Juries

Francois Brémond was part of several PhD and HDR Juries :

- Nicolas Padoy, HDR, University of Strasbourg, 19 January 2018
- Renato Baptista, University of Luxembourg, 29 January 2018
- Nicolas Chesneau, Inria Lear, Grenoble, 23 February 2018
- Dinh Van Nguyen, UPMC, Paris, 2 May 2018
- Riadh Ksantini, HDR, SUP'COM Tunis, 10 September 2018
- Yiqiang Chen, LIRIS, University of Lyon, 12 October 2018
- Katy Blanc, University of Nice, 17 December 2018
- Mohamed Adel Benamara, LIRIS, University of Lyon, 19 December 2018

Monique Thonnat was member of the selection board of professor PU27 at ENIB, Brest.

Monique Thonnat is member of the scientific board of ENPC, Ecole Nationale des Ponts et Chaussées since June 2008.

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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

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A5.6.1. - Virtual reality
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B3.3. - Geosciences
B5.1. - Factory of the future
B5.6. - Robotic systems
B5.7. - 3D printing
B8.3. - Urbanism and urban planning

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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. Applications

In addition to tackling enduring scientific challenges, our research on geometric modeling and processing is motivated by applications to computational engineering, reverse engineering, digital mapping and urban planning. The main deliverable of our research will be algorithms with theoretical foundations. Ultimately we 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-off company 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. theses and postdoctoral fellows on topics that match our research program.

5. Highlights of the Year

5.1. Highlights of the Year

The TITANE project-team has been evaluated by Inria in October 2018. We obtained three new ANR projects, the renewal of a collaborative contract with Google and a new Cifre PhD thesis with Dorea technology. Since September 2018 Pierre Alliez is head of science (délégué scientifique) of the Inria Sophia Antipolis center. He is also full paper co-chair of the Eurographics 2019 conference.

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. MeshMantics

KEYWORDS: Classification - 3D modeling
FUNCTIONAL DESCRIPTION: This software component enables the classification of surface meshes in accordance to common outdoor urban classes such as ground, facades, walls, roofs and vegetation.

- Participants: Florent Lafarge, Pierre Alliez and Yannick Verdié
- Contact: Pierre Alliez

6.4. 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

6.5. 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

6.6. 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/

6.7. Structure-preserving decimation

KEYWORDS: Mesh - 3D - Multi-View reconstruction

FUNCTIONAL DESCRIPTION: Structure-preserving decimation is a software that can simplify 3D meshes while preserving some of their structure. Simplification can be done either with a command line or with a graphical user interface that allows to combine several operations including several simplification methods.

- Participants: David Salinas, Florent Lafarge and Pierre Alliez
- Contact: David Salinas

7. New Results

7.1. Analysis

7.1.1. Planar Shape Detection at Structural Scales

Participants: Hao Fang, Mathieu Desbrun, Florent Lafarge [contact].

Shape detection, abstraction, man-made objects, point clouds, surface reconstruction.

Interpreting 3D data such as point clouds or surface meshes depends heavily on the scale of observation. Yet, existing algorithms for shape detection rely on trial-and-error parameter tunings to output configurations representative of a structural scale. We present a framework to automatically extract a set of representations that capture the shape and structure of man-made objects at different key abstraction levels. A shape-collapsing process first generates a fine-to-coarse sequence of shape representations by exploiting local planarity. This sequence is then analyzed to identify significant geometric variations between successive representations through a supervised energy minimization. Our framework is flexible enough to learn how to detect both existing structural formalisms such as the CityGML Levels Of Details, and expert-specified levels of abstraction. Experiments on different input data and classes of man-made objects, as well as comparisons with existing shape detection methods, illustrate the strengths of our approach in terms of efficiency and flexibility. Figure 1 illustrates the goal of our method. This work has been published in the proceedings of CVPR [16].

7.1.2. Multi-task Deep Learning for Satellite Image Pansharpening and Segmentation

Participants: Andrew Khalel, Onur Tasar, Yuliya Tarabalka [contact].

This work has been done in collaboration with Dr. Guillaume Charpiat (TAU team, Inria Saclay).

Segmentation, pansharpening, multi-task, joint learning

We proposed a novel multi-task framework to learn satellite image pansharpening and segmentation jointly. Our framework is based on encoder-decoder architecture, where both tasks share the same encoder but each one has its own decoder (see Fig. 2). We compare our framework against single-task models with different architectures. Results show that our framework outperforms all other approaches in both tasks.

7.1.3. Incremental Learning for Semantic Segmentation of Large-Scale Remote Sensing Data

Participants: Onur Tasar, Pierre Alliez, Yuliya Tarabalka [contact].

This work has been done in collaboration with CNES and ACRI-ST.

Incremental learning, catastrophic forgetting, semantic segmentation, convolutional neural networks

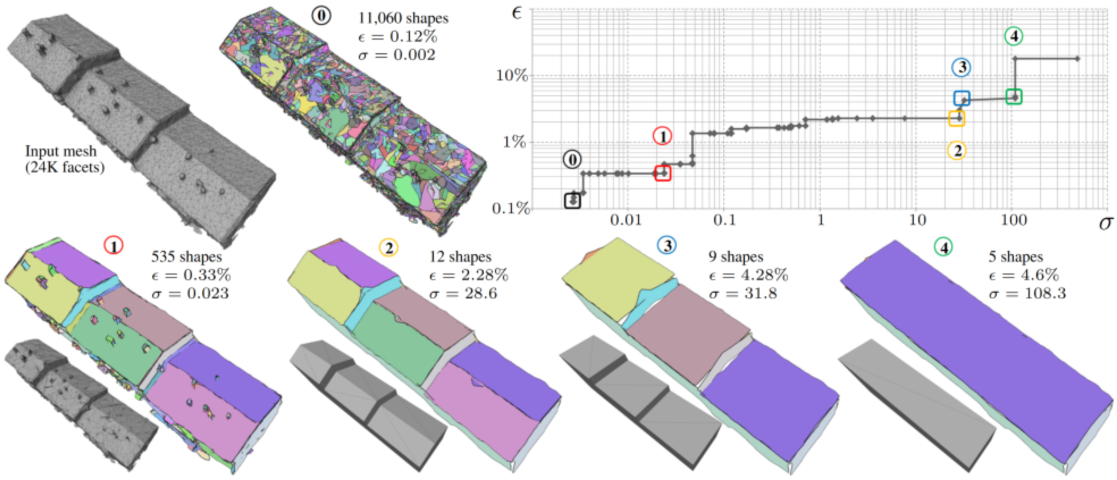


Figure 1. Planar shape detection at structural scales. Starting from 3D data (here a dense mesh generated by MultiView Stereo, top left), our algorithm produces a set of high-level representations with planar primitives (representations 1–4) describing the object at different representative structural scales (bottom). By progressively merging planar regions of an initial state (representation 0), one creates a sequence of representations whose further analysis allows for the extraction of a few structurally relevant representations (top right). Such shape representations can be used, for instance, as input for piecewise-planar reconstruction (see grey compact meshes). Note that each shape is displayed as a colored polygon computed as the α-shape of its inliers projected onto the shape.

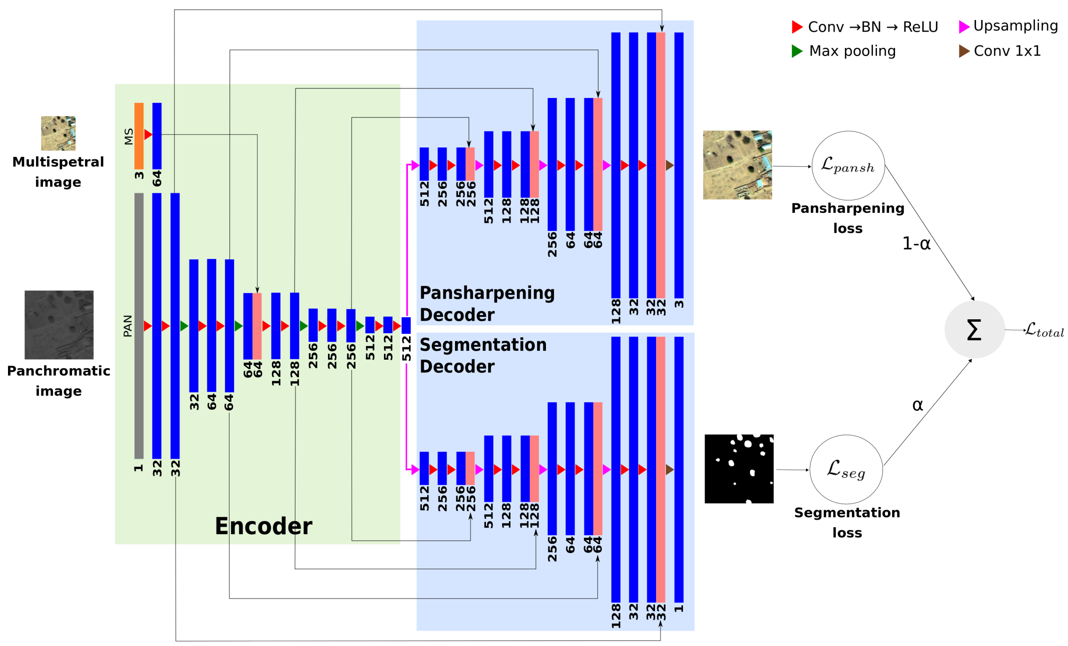


Figure 2. Overal framework for joint segmentation and pansharpening.

In spite of remarkable success of the convolutional neural networks on semantic segmentation, they suffer from catastrophic forgetting: 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. For remembering, we either regularly feed samples from the stored, little fraction of the previous data or use the memory network, depending on whether the new dat (see Fig. 3)a are collected from completely different geographic areas or from the same city. 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 submitted to IEEE Transactions on Geoscience and Remote Sensing (TGRS) and is currently on arXiV [25].

7.1.4. Multimodal Image Alignment through a Multiscale Chain of Neural Networks with Application to Remote Sensing

Participants: Nicolas Girard, Yuliya Tarabalka [contact].

This work has been done in collaboration with Armand Zampieri and Dr. Guillaume Charpiat (TAO team, Inria Saclay).

Multimodal, Alignment, Registration, Remote sensing

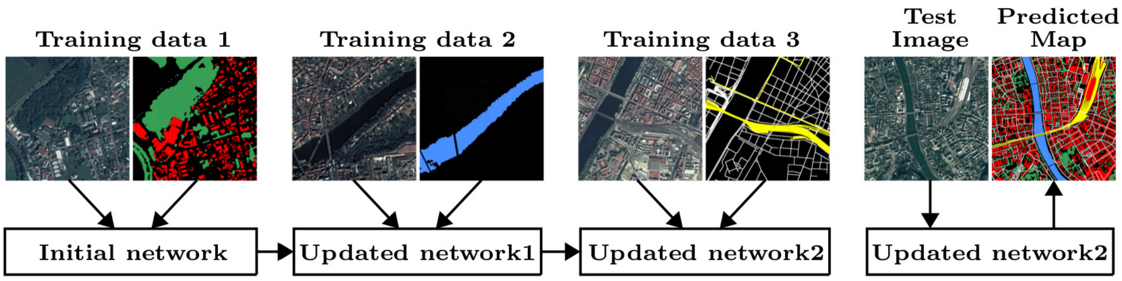


Figure 3. An example incremental learning scenario. Firstly, satellite images as well as their label maps for building and high vegetation classes are fed to the network. Then, from the second training data, the network learns water class without forgetting building and high vegetation classes. Finally, 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 comes, the network is able to detect all the classes.

We tackle here the problem of multimodal image non-rigid registration, which is of prime importance in remote sensing and medical imaging. The difficulties encountered by classical registration approaches include feature design and slow optimization by gradient descent. By analyzing these methods, we note the significance of the notion of scale. We design easy-to-train, fully-convolutional neural networks able to learn scale-specific features. Once chained appropriately, they perform global registration in linear time, getting rid of gradient descent schemes by predicting directly the deformation.

We show their performance in terms of quality and speed through various tasks of remote sensing multimodal image alignment. In particular, we are able to register correctly cadastral maps of buildings as well as road polylines onto RGB images, and outperform current keypoint matching methods (see Fig. 4). This work has been published in the proceedings of ECCV [20].

7.1.5. Aligning and Updating Cadaster Maps with Aerial Images by Multi-Task, Multi-Resolution Deep Learning

Participants: Nicolas Girard, Yuliya Tarabalka [contact].

This work has been done in collaboration with Dr. Guillaume Charpiat (TAO team, Inria Saclay).

Alignment, Registration, Multi-task, Multi-resolution

A large part of the world is already covered by maps of buildings, through projects such as OpenStreetMap. However when a new image of an already covered area is captured, it does not align perfectly with the buildings of the already existing map, due to a change of capture angle, atmospheric perturbations, human error when annotating buildings or lack of precision of the map data. Some of those deformations can be partially corrected, but not perfectly, which leads to misalignments. Additionally, new buildings can appear in the image. Leveraging multi-task learning, our deep learning model aligns the existing building polygons to the new image through a displacement output, and also detects new buildings that do not appear in the cadaster through a segmentation output (see Fig. 5). It uses multiple neural networks at successive resolutions to output a displacement field and a pixel-wise segmentation of the new buildings from coarser to finer scales. We also apply our method to buildings height estimation, by aligning cadaster data to the rooftops of stereo images.

7.2. Reconstruction

7.2.1. Kinetic Polygonal Partitioning of Images

Participants: Jean-Philippe Bauchet, Florent Lafarge [contact].

Polygons, image segmentation, object contouring, kinetic framework

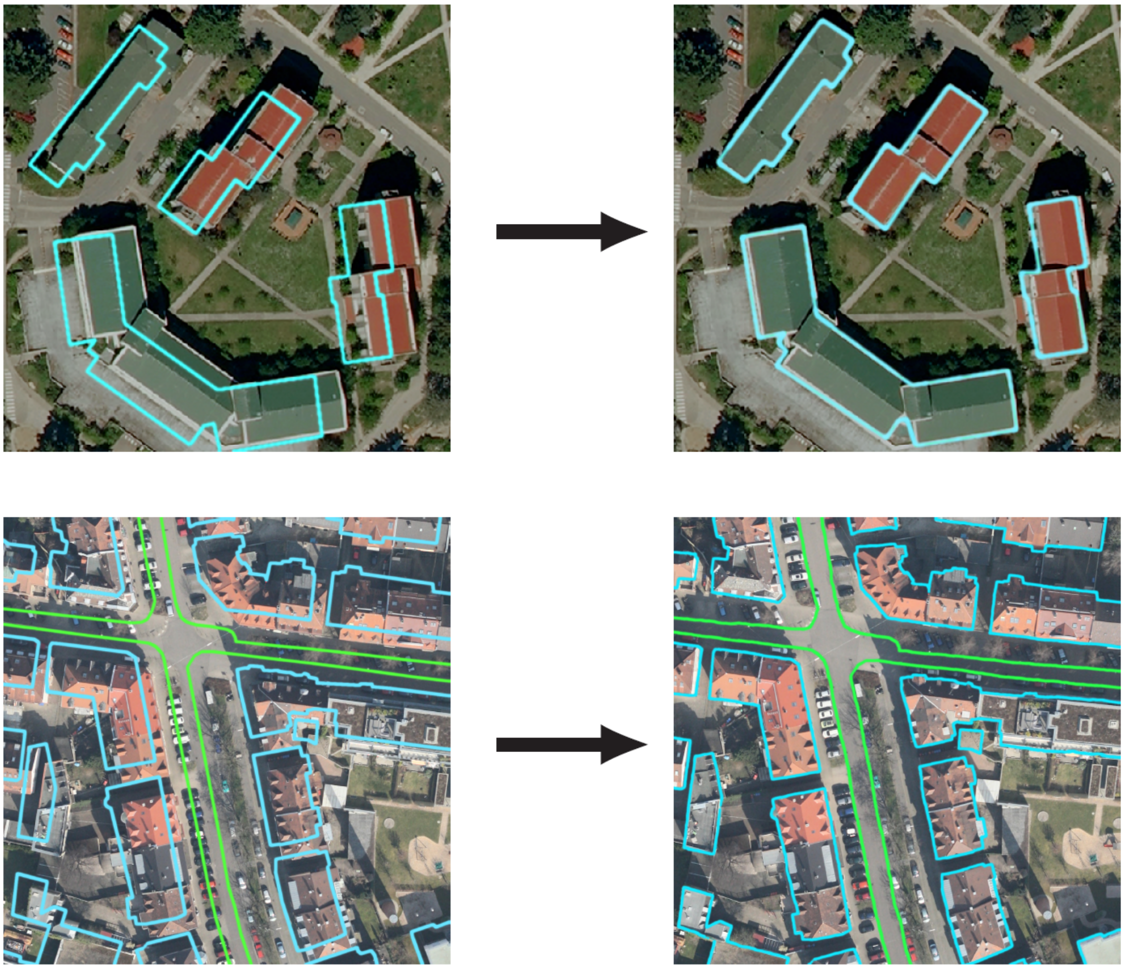


Figure 4. Multi-modal alignment.

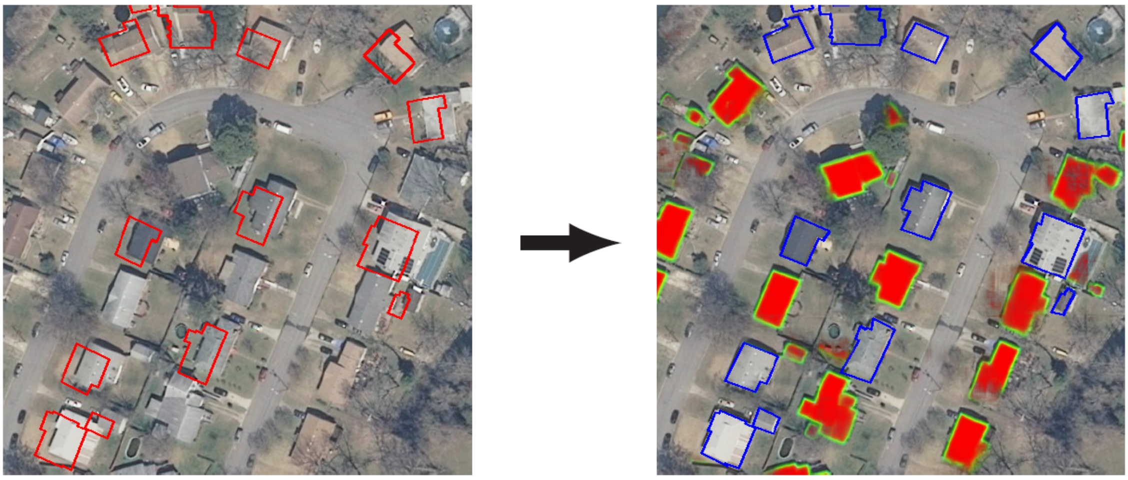


Figure 5. Multi-task learning with 2 tasks: multi-modal alignment and semantic segmentation.

Recent works showed that floating polygons can be an interesting alternative to traditional superpixels, especially for analyzing scenes with strong geometric signatures, as man-made environments. Existing algorithms produce homogeneously-sized polygons that fail to capture thin geometric structures and over-partition large uniform areas. We propose a kinetic approach that brings more flexibility on polygon shape and size. The key idea consists in progressively extending pre-detected line-segments until they meet each other. Our experiments demonstrate that output partitions both contain less polygons and better capture geometric structures than those delivered by existing methods. We also show the applicative potential of the method when used as preprocessing in object contouring. Figure 6 illustrates the goal of our method. This work has been published in the proceedings of CVPR [15].

7.2.2. Polygonization of Binary Classification Maps Using Mesh Approximation with Right Angle Regularity

Participants: Onur Tasar, Pierre Alliez, Yuliya Tarabalka [contact].

Work in collaboration with Emmanuel Maggiori.

Polygonization, vectorization, remote sensing, classification maps, mesh approximation, right angles

One of the most popular and challenging tasks in remote sensing applications is the generation of digitized representations of Earth's objects from satellite raster image data. A common approach to tackle this challenge is a two-step method that first involves performing a pixel-wise classification of the raster data, then vectorizing the obtained classification map. We propose a novel approach, which recasts the polygonization problem as a mesh-based approximation of the input classification map, where binary labels are assigned to the mesh triangles to represent the building class. A dense initial mesh is decimated and optimized using local edge and vertex-based operators in order to minimize an objective function that models a balance between fidelity to the classification map in ℓ_1 norm sense, right angle regularity for polygonized buildings, and final mesh complexity (see Fig. 7). Experiments show that adding the right angle objective yields better representations quantitatively and qualitatively than previous work and commonly used polygon generalization methods in remote sensing literature for similar number of vertices. This work was published at IGARSS [19].

7.2.3. End-to-End Learning of Polygons for Remote Sensing Image Classification

Participants: Nicolas Girard, Yuliya Tarabalka [contact].

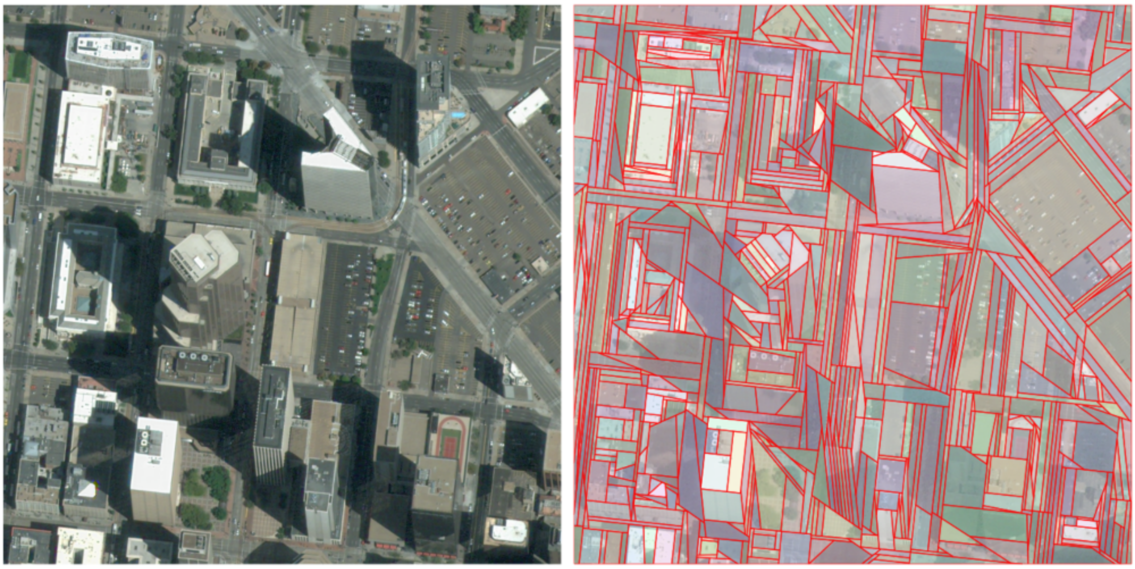
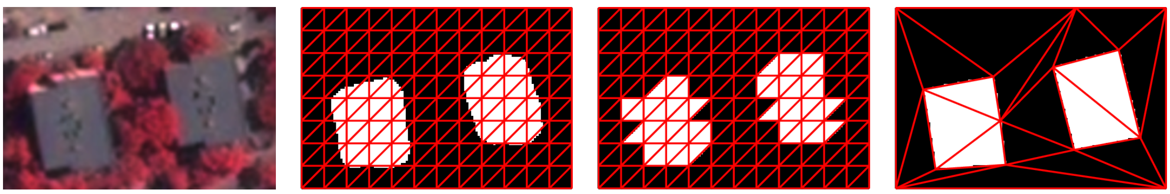


Figure 6. Kinetic partitioning into polygons. Our algorithm decomposes an image (left) into a partition of convex polygons (right). While superpixel-based methods impose homogeneously-sized regions, our polygons are more meaningful, capturing both large components and thin lineic structures that compose, for instance, urban scenes.



(a) (b) (c) (d)

Figure 7. Input image and example labeled meshes. (a) Input image, (b) Initial fine lattice, (c) Initial and (d) Optimized labeled triangle meshes. The triangles labeled as building are indicated by white.

High-resolution aerial images, polygon, vectorial, regression, deep learning, convolutional neural networks

While geographic information systems typically use polygonal representations to map Earth's objects, most state-of-the-art methods produce maps by performing pixelwise classification of remote sensing images, then vectorizing the outputs. This work studies if one can learn to directly output a vectorial semantic labeling of the image. We here cast a mapping problem as a polygon prediction task, and propose a deep learning approach which predicts vertices of the polygons outlining objects of interest. Experimental results on the Solar photovoltaic array location dataset show that the proposed network succeeds in learning to regress polygon coordinates, yielding directly vectorial map outputs (see Fig. 8). This work has been published in the proceedings of IGARSS [14].

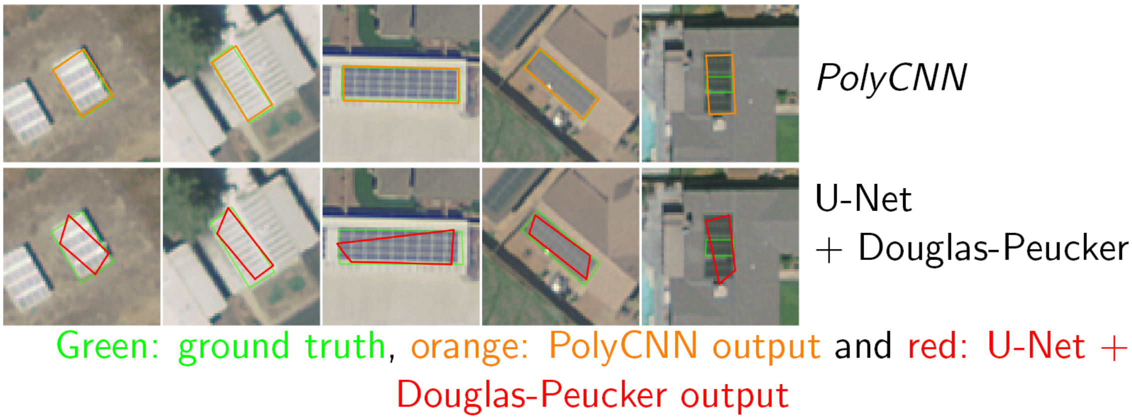


Figure 8. Results of polygon reconstruction with a deep neural network.

7.3. Approximation

7.3.1. Curved Optimal Delaunay Triangulation

Participants: Mathieu Desbrun, Pierre Alliez [contact].

Work in collaboration with Leman Feng (Ecole des Ponts ParisTech), Hervé Delingette (EPIONE) and Laurent Busé (AROMATH).

Higher-order meshing, Optimal Delaunay Triangulations, higher order finite elements, Bézier elements.

Meshes with curvilinear elements hold the appealing promise of enhanced geometric flexibility and higher-order numerical accuracy compared to their commonly-used straight-edge counterparts. However, the generation of curved meshes remains a computationally expensive endeavor with current meshing approaches: high-order parametric elements are notoriously difficult to conform to a given boundary geometry, and enforcing a smooth and non-degenerate Jacobian everywhere brings additional numerical difficulties to the meshing of complex domains. In this paper, we propose an extension of Optimal Delaunay Triangulations (ODT) to curved and graded isotropic meshes. By exploiting a continuum mechanics interpretation of ODT instead of the usual approximation theoretical foundations, we formulate a very robust geometry and topology optimization of Bézier meshes based on a new simple functional promoting isotropic and uniform Jacobians throughout the domain. We demonstrate that our resulting curved meshes can adapt to complex domains with high precision even for a small count of elements thanks to the added flexibility afforded by more control points and higher order basis functions (see Figure 9). This work has been published in the proceedings of ACM SIGGRAPH conference [12].

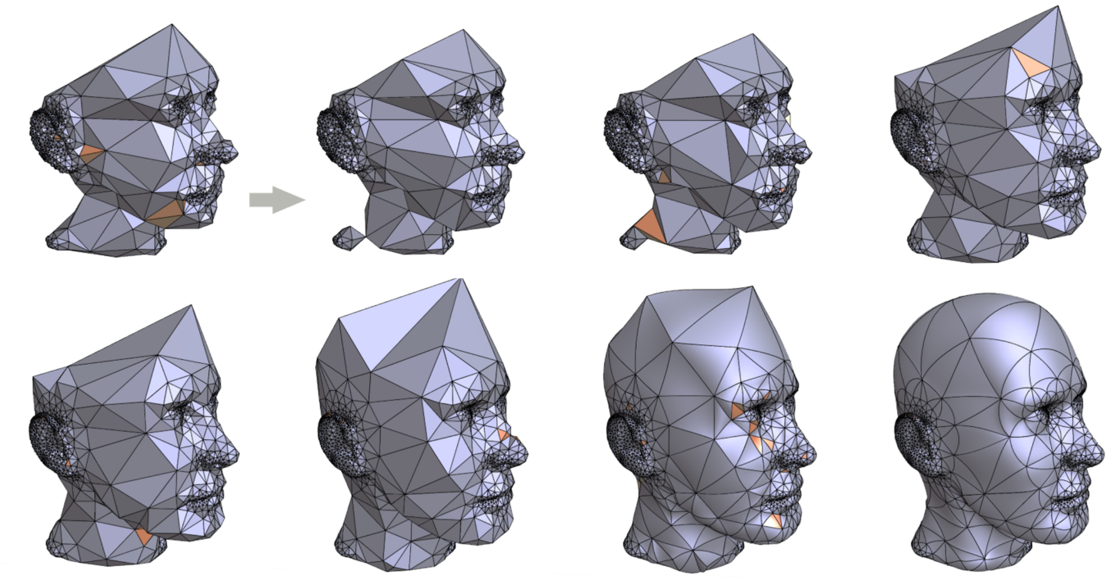


Figure 9. Generation of a curved optimal Delaunay triangulation.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Grants with Industry

8.1.1. Google Chrome University Research Programme

Participants: Pierre Alliez, Cédric Portaneri.

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 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 [contact].

In collaboration with SME Dorea Technology, our objective is to advance the knowledge on the 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. The project started in August 2018, for a total duration of 3 years.

8.1.3. Luxcarta

Participants: Jean-Philippe Bauchet, Florent Lafarge [contact].

The goal of this collaboration is to design automated approaches for producing city models from the last generation of satellites. The models should conform to the level 2 (LOD2) of the popular CityGML format. The project started in October 2016, for a total duration of 3 years.

8.1.4. CNES and Acri-ST

Participants: Onur Tasar, Pierre Alliez, Yuliya Tarabalka [contact].

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, Florent Lafarge [contact].

The goal of this recent collaboration is to develop methods for analyzing and exploring scale-spaces into urban 3D data. The project started in March 2016, 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 project 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 project 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 project 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.

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 project 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.

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 project started in February 2018, for a total duration of 4 years.

9.2. European Initiatives

9.2.1. FP7 & H2020 Projects

9.2.1.1. TITANIUM - Software Components for Robust Geometry Processing

ERC Proof of concept grant TITANIUM “Software Components for Robust Geometry Processing” (2017-2018), total 150 KE. Principal investigator: Pierre Alliez. Partner: Inria Spin-off Geometry Factory. Participants: Florent Lafarge, Dmitry Anisimov, Simon Giraudot and Andreas Fabri. We developed a software demonstrator for geometry processing and 3D urban modeling, in order to facilitate the pre-commercialization of novel software components for the CGAL Library. The outcome of TITANIUM is a versatile method for semantic classification of 3D point clouds and for semantic-aware reconstruction of urban scenes (in preparation).

9.3. International Initiatives

9.3.1. Inria International Partners

9.3.1.1. Declared Inria International Partners

We collaborated with Mathieu Desbrun from Caltech, David Bommes from Bern University (Switzerland), Gianmarco Cherchi and Riccardo Scateni from University of Cagliary (Sardinia).

9.4. International Research Visitors

9.4.1. Visits of International Scientists

- Mathieu Desbrun, Professor at Caltech, visited us from September to mid November.
- Michael Hemmer, research engineer at Google, visited us in December.
- Jorg Peters, Professor at University of Florida, visited us in October.

9.4.1.1. Internships

- Tong Zhao (Ecole des ponts ParisTech): geometric descriptors and robust principal component analysis. In collaboration with Mathieu Desbrun from Caltech.

- Vasudha Varadarajan (Birla Institute of Technology and Science, India): shape reconstruction using binary programming.
- Andrew Khalel (Cairo University, Egypt): Multi-task deep learning for simultaneous satellite image segmentation and pan-sharpening. In collaboration with Guillaume Charpiat.
- Andrii Zhygallo (TUM, Germany): Using deep learning for change detection from remote sensing images.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Organizing Committees

- Pierre Alliez: advisory committee of the EUROGRAPHICS annual conference 2018.
- Yuliya Tarabalka: Scientific Advisory Committee of the 2nd International Electronic Conference on Remote Sensing.

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

Pierre Alliez is full paper co-chair of

- EUROGRAPHICS 2019 conference, organized in Genova, May 2019.
- Solid and Physical Modeling 2019, organized in Vancouver, June 2019.

10.1.2.2. Member of the Conference Program Committees

- Pierre Alliez: EUROGRAPHICS Symposium on Geometry Processing, International Conference on Geometric Modeling and Processing, Shape Modeling International, EUROGRAPHICS Workshop on Graphics and Cultural Heritage.
- Florent Lafarge: Area chair of Asian Conference on Computer Vision (ACCV)
- Yuliya Tarabalka: SPIE in Remote Sensing conference, ACIVS conference.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- Pierre Alliez: associate editor of Computer Graphics Forum, Computer-Aided Geometric Design and Graphical Models. He is also a member of the editorial board of the CGAL open source project.
- Florent Lafarge: associate editor of The Visual Computer since 2015.
- Yuliya Tarabalka: associate editor for IEEE Transactions on image processing since 2018, Springer journal Sensing and Imaging since 2017, the International Journal of Computing since 2017 and journal Remote Sensing since 2017.

10.1.3.2. Reviewer - Reviewing Activities

- Pierre Alliez: reviewer for ACM Transactions on Graphics, ACM Siggraph conference, ACM Siggraph Asia conference, Computer Graphics Forum, CAGD, CAD, Symposium on Geometry Processing, Eurographics workshop on cultural heritage, Geometric Modeling and Processing, Shape Modeling International.
- Florent Lafarge: reviewer for the ISPRS journal of Remote Sensing and Photogrammetry.
- Yuliya Tarabalka: reviewer for the journals IEEE PAMI, IEEE TIP, IEEE TGRS, conferences IEEE IGARSS (student competition selection committee), ACIVS, SPIE, ECRS.

10.1.4. Invited Talks

- Pierre Alliez: invited talk at the Einstein Workshop on Geometry and Physics in Computer Graphics, organized in Berlin.
- Yuliya Tarabalka: keynote at the ACIVS 2018 conference (Advanced Concepts for Intelligent Vision Systems, Poitiers), TERRADATA workshop (Paris, 2018), conference “Challenges for imaging and modeling complex media and processes: The Earth’s interior and earthquake rupture” (Sophia Antipolis, 2018). She also gave an invited tutorial on machine learning at IEEE IGARSS 2018 conference.

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: reviewer for the European commission (two EU projects), ERC, evaluator for the French ANR, Belgium FNRS, Innovation Fund Denmark.
- Yuliya Tarabalka: expert evaluator for the ANR proposals and “Make Our Planet Great Again” CampusFrance proposals.

10.1.7. Research Administration

- Pierre Alliez: member of the scientific committee of the 3IA Côte d’Azur proposal.
- Yuliya Tarabalka: member of the scientific committee of the Academy 3 of the University Cote d’Azur since 2017.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master: Pierre Alliez and Florent Lafarge, 3D Meshes and Applications, 32h, M2, Ecole des Ponts ParisTech, France.

Master: Pierre Alliez and Florent Lafarge, Ingeniérie 3D, 21h, M2, university Nice Sophia Antipolis, France.

Master: Pierre Alliez and Florent Lafarge, Interpolation, 60h, M1, university Nice Sophia Antipolis, France.

Master: Pierre Alliez and Florent Lafarge, Mathématiques pour la géométrie, 30h, M1, EFREI, France.

Master: Florent Lafarge, Traitement d’images numériques, 6h, M2, university Nice Sophia Antipolis, France.

Master: Yuliya Tarabalka, Discrete inference and learning, 12h, M2 MVA, ENS Paris-Saclay & CentraleSupelec, France.

Master: Yuliya Tarabalka, Mathematical methods, 25h, MSc in data sciences and business analytics ESSEC-CS, CentraleSupelec, France.

Licence: Yuliya Tarabalka, Advanced algorithms, 28.5h, L2 Networks and Telecoms, IUT Nice Côte d’Azur, France.

10.2.2. Supervision

PhD defended:

Jean-Dominique Favreau, Compact image vectorization by stochastic approaches, Université Côte d’Azur, defended March 15 [11], Florent Lafarge and Adrien Bousseau.

PhDs in progress:

Hao Fang, Scale-space understanding in urban scenes, since March 2016, Florent Lafarge.

Jean-Philippe Bauchet, City modelling from high resolution satellite images, since October 2016, Florent Lafarge.

Lionel Matteo: From Pleiades images to very high resolution topography in complex zones, since September 2017, Yuliya Tarabalka and Isabelle Manighetti.

Onur Tasar, Using deep learning approaches to devise an efficient representation for large-scale satellite images, since October 2017, Yuliya Tarabalka and Pierre Alliez.

Nicolas Girard, How to structure satellite data, since November 2017, Yuliya Tarabalka.

Flora Quilichini, Geometry Compression, since January 2018, Pierre Alliez and Guillaume Lavoué (INSA Lyon).

Muxingzi Li, Image-based 3D reconstruction of indoor environments, since February 2018, Florent Lafarge and Renaud Marlet (ENPC).

Vincent Vadez, Geometric simplification of satellites for thermal simulation, since August 2018, Pierre Alliez.

10.2.3. Juries

Pierre Alliez:

- Thesis committee and president: Arnaud Bletterer (I3S Sophia Antipolis).
- HDR committee and president: Stefanie Wuhrer (Inria Grenoble).
- Comité de suivi doctoral: Simon Rodriguez (Inria Sophia Antipolis).
- Comité de suivi doctoral: Julien Renaudeau (Schlumberger).
- Comité de suivi doctoral: Oussama Ennafii (IGN).

Florent Lafarge:

- Thesis reviewer: Hassan Bouchiba (Ecole des Mines Paristech).

Yuliya Tarabalka:

- Thesis committee: Hariprasad Kannan (University Paris-Saclay), Nicolas Audebert (University Bretagne Sud and ONERA).
- Thesis reviewer: Praveer Singh (University Paris-Est), Lloyd Windrim (University of Sydney).

10.3. Popularization

Yuliya Tarabalka gave a seminar for the academic-industrial event “Les rendez-vous Université Côte d’Azur-Entreprise”, May 2018.

10.3.1. Internal or external Inria responsibilities

Pierre Alliez is head of science of the Inria Sophia Antipolis Center since September 2018, and member of the Inria evaluation committee.

10.3.2. Interventions

- Pierre Alliez gave a seminar and demo for the “fête de la science”, October 7th.

11. Bibliography

Major publications by the team in recent years

[1] D. Bommes, M. Campen, H.-C. Ebke, P. Alliez, L. Kobbelt.*Integer-Grid Maps for Reliable Quad Meshing*, in "ACM Transactions on Graphics", July 2013, vol. 32, n^{o} 4, https://hal.inria.fr/hal-00862648

[2] L. DUAN, F. LAFARGE.*Towards large-scale city reconstruction from satellites*, in "European Conference on Computer Vision (ECCV)", Amsterdam, Netherlands, October 2016, https://hal.inria.fr/hal-01352466

[3] J.-D. FAVREAU, F. LAFARGE, A. B. BOUSSEAU.*Photo2ClipArt: Image Abstraction and Vectorization Using Layered Linear Gradients*, in "ACM Transactions on Graphics", 2017, vol. 36, n^{o} 6, https://hal.inria.fr/hal-01581981

[4] S. GIRAUDOT, D. COHEN-STEINER, P. ALLIEZ.*Noise-Adaptive Shape Reconstruction from Raw Point Sets*, in "Computer Graphics Forum, Proceedings of EUROGRAPHICS Symposium on Geometry Processing", 2013, vol. 32, n^{o} 5, p. 229-238 [*DOI :* 10.1111/CGF.12189], https://hal.inria.fr/hal-00844472

[5] F. LAFARGE, P. ALLIEZ.*Surface Reconstruction through Point Set Structuring*, in "Computer Graphics Forum (Proceedings of Eurographics 2013)", May 2013, vol. 32, n^{o} 2, p. 225-234, https://hal.inria.fr/hal-00822763

[6] E. MAGGIORI, Y. TARABALKA, G. CHARPIAT, P. ALLIEZ.*High-Resolution Semantic Labeling with Convolutional Neural Networks*, in "IEEE Transactions on Geoscience and Remote Sensing", December 2017, https://hal.inria.fr/hal-01393279

[7] E. MAGGIORI, Y. TARABALKA, G. CHARPIAT.*Improved Partition Trees for Multi-Class Segmentation of Remote Sensing Images*, in "2015 IEEE International Geoscience and Remote Sensing Symposium - IGARSS 2015", Milan, Italy, IEEE, July 2015, https://hal.inria.fr/hal-01182772

[8] M. MANDAD, D. COHEN-STEINER, L. KOBBELT, P. ALLIEZ, M. DESBRUN.*Variance-Minimizing Transport Plans for Inter-surface Mapping*, in "ACM Transactions on Graphics", 2017, vol. 36, 14 [*DOI :* 10.1145/3072959.3073671], https://hal.inria.fr/hal-01519006

[9] Y. VERDIE, F. LAFARGE, P. ALLIEZ.*LOD Generation for Urban Scenes*, in "ACM Transactions on Graphics", 2015, vol. 34, n^{o} 3, 15, https://hal.inria.fr/hal-01113078

[10] Y. VERDIE, F. LAFARGE.*Detecting parametric objects in large scenes by Monte Carlo sampling*, in "International Journal of Computer Vision", January 2014, vol. 106, n^{o} 1, p. 57-75 [*DOI :* 10.1007/s11263-013-0641-0], https://hal.inria.fr/hal-00843022

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Doctoral Dissertations and Habilitation Theses

[11] J.-D. FAVREAU.*Compact image vectorization by stochastic approaches*, Université Côte d'Azur, March 2018, https://tel.archives-ouvertes.fr/tel-01818515

Articles in International Peer-Reviewed Journal

[12] L. FENG, P. ALLIEZ, L. BUSÉ, H. DELINGETTE, M. DESBRUN.*Curved Optimal Delaunay Triangulation*, in "ACM Transactions on Graphics", August 2018, vol. 37, n^{o} 4 [*DOI :* 10.1145/3197517.3201358], https://hal.inria.fr/hal-01826055

[13] P. GHAMISI, E. MAGGIORI, S. LI, R. SOUZA, Y. TARABALKA, G. MOSER, A. DE GIORGI, L. FANG, Y. CHEN, M. CHI, S. B. SERPICO, J. A. BENEDIKTSSON.*Frontiers in Spectral-Spatial Classification of Hyperspectral Images*, in "IEEE geoscience and remote sensing magazine", September 2018, vol. 6, n^{o} 3, p.

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[14] N. GIRARD, Y. TARABALKA.*End-to-End Learning of Polygons for Remote Sensing Image Classification*, in "IEEE International Geoscience and Remote Sensing Symposium – IGARSS 2018", Valencia, Spain, July 2018, https://hal.inria.fr/hal-01762446

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[15] J.-P. BAUCHET, F. LAFARGE.*KIPPI: KInetic Polygonal Partitioning of Images*, in "IEEE Conference on Computer Vision and Pattern Recognition (CVPR)", Salt Lake City, United States, June 2018, https://hal.inria.fr/hal-01740958

[16] H. FANG, F. LAFARGE, M. DESBRUN.*Planar Shape Detection at Structural Scales*, in "IEEE Conference on Computer Vision and Pattern Recognition (CVPR)", Salt Lake City, United States, 2018, https://hal.inria.fr/hal-01741650

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[20] A. ZAMPIERI, G. CHARPIAT, N. GIRARD, Y. TARABALKA.*Multimodal image alignment through a multi-scale chain of neural networks with application to remote sensing*, in "European Conference on Computer Vision (ECCV)", Munich, Germany, V. FERRARI, M. HEBERT, C. SMINCHISESCU, Y. WEISS (editors), Computer Vision – ECCV 2018, Springer International Publishing, September 2018, p. 679-696, https://hal.inria.fr/hal-01849389

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[21] N. GIRARD, G. CHARPIAT, Y. TARABALKA.*Aligning and Updating Cadaster Maps with Aerial Images by Multi-Task, Multi-Resolution Deep Learning*, in "Asian Conference on Computer Vision (ACCV)", Perth, Australia, December 2018, https://hal.archives-ouvertes.fr/hal-01923568

[22] S. LEFÈVRE, O. TASAR, D. SHEEREN.*Combining multiple segmentations through a flexible framework*, in "GEOBIA 2018 - From pixels to ecosystems and global sustainability ", Montpellier, France, Centre d'Etudes Spatiales de la BIOsphère (CESBIO) and Office national d'études et de recherches aérospatiales (ONERA) and Espace pour le développement (ESPACE DEV) and Société T.E.T.I.S, June 2018, http://hal.univ-reunion.fr/hal-01958983

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[23] B. BECKERS, P. ALLIEZ, D. ALIAGA (editors). *Editorial for Special issue on "Massive 3D Urban Models"*, Elsevier, Quito - Îles Galápagos, Ecuador, January 2018, vol. 95, p. 27-28 [*DOI :* 10.1016/J.GMOD.2017.07.001], https://hal.inria.fr/hal-01825907

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Project-Team TOSCA

TO Simulate and CAlibrate stochastic models

IN COLLABORATION WITH: Institut Elie Cartan de Lorraine (IECL)

IN PARTNERSHIP WITH:
CNRS

Université de Lorraine

RESEARCH CENTERS
Sophia Antipolis - Méditerranée
Nancy - Grand Est

THEME
Stochastic approaches

Table of contents

Project-Team TOSCA

Creation of the Project-Team: 2007 January 01, end of the Project-Team: 2018 December 31

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
B9.11.1. - Environmental risks
B9.11.2. - Financial risks

1. Team, Visitors, External Collaborators

Research Scientists

Denis Talay [Team leader, Inria, Senior Researcher, HDR]
Mireille Bossy [Inria, Senior Researcher, HDR]
Nicolas Champagnat [Inria, Senior Researcher, HDR]
Madalina Deaconu [Inria, Researcher, HDR]
Coralie Fritsch [Inria, Researcher]
Christophe Henry [Inria, Starting Research Position, from Nov 2018]
Antoine Lejay [Inria, Senior Researcher, HDR]
Etienne Tanré [Inria, Researcher]

Faculty Member

Denis Villemonais [Univ de Lorraine, Associate Professor]

External Collaborators

Areski Cousin [Univ de Claude Bernard]
Samuel Herrmann [Univ de Bourgogne, HDR]
Jean-Francois Jabir [Université étrangère]
Blandine L Heveder [Autre entreprise privée, until Jun 2018]
Nadia Maïzi [Ecole Nationale Supérieure des Mines de Paris]

Technical Staff

Victor Martin Lac [Inria, until Jun 2018]

PhD Students

Alexis Anagnostakis [Univ de Lorraine, from Oct 2018]
Lorenzo Campana [Univ. Côte d'Azur]
Quentin Cormier [Univ. Côte d'Azur]
Aurore Dupré [Laboratoire de météorologie dynamique]
Vincent Hass [Inria, from Oct 2018]
Pascal Helson [Univ Côte d'Azur]
Rodolphe Loubaton [Univ de Lorraine, from Oct 2018]
Milica Tomasevic [Inria, until Nov 2018]

Post-Doctoral Fellows

Ulysse Herbach [Inria, from Nov 2018]
Igor Honore [Inria, from Dec 2018]
Radu Maftei [Inria]
Hector Olivero-Quinteros [Univ Côte d'Azur, until July 2018]
Émilie Soret [Inria]

Visiting Scientists

Regis Briant [Laboratoire de météorologie dynamique, until Jun 2018]
Christophe Henry [Univ Côte d'Azur, from Aug 2018 until Oct 2018]
Kerlyns Martinez Rodriguez [Université étrangère]
Cyril Mokrani [Autre entreprise publique]

Administrative Assistants

Isabelle Blanchard [Inria]
Christine Faber [Inria, until Sep 2018]
Laurence Briffa [Inria, since Jun 2018]

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. Domain 1

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 Results

5.1. Probabilistic numerical methods, stochastic modelling and applications

Participants: Mireille Bossy, Nicolas Champagnat, Quentin Cormier, Madalina Deaconu, Olivier Faugeras, Coralie Fritsch, Pascal Helson, Antoine Lejay, Radu Maftei, Victor Martin Lac, Hector Olivero-Quinteros, Émilie Soret, Denis Talay, Etienne Tanré, Milica Tomasevic, Denis Villemonais.

5.1.1. Published works and preprints

- M. Bossy, J. Fontbona (Universidad de Chile, Chile) and H. Olivero-Quinteros (CIMFAV, Valparaíso, Chile) analysed mathematical model for the collective behavior of a fully connected network of finitely many neurons. They obtained that the whole system synchronize, up to some error controlled by the channels noise level. The associated nonlinear McKean-Vlasov equation concentrates, as time goes to infinity, around the dynamics of a single Hodgkin-Huxley neuron with a chemical neurotransmitter channel [42].
- M. Bossy, A. Dupré, P. Drobinski, L. Violeau and C. Briard (Zephyr ENR) obtained advances in stochastic Lagrangian approach for atmospheric boundary layer simulation, on the analysis of an optimal rate of convergence for the particle approximation method, and on validation case with the simulation of a Zephyr ENR wind farm site of six turbines [36].
- 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 obtained advances in stochastic Lagrangian approaches for the simulation of hydrokinetic turbines immersed in complex topography [33], [50].
- 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 [40].
- N. Champagnat and J. Claisse (Ecole Polytechnique) 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 [16].
- 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 [17].
- 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 distribution of the Fleming-Viot processes approaches a particular QSD, called minimal QSD. They proved that this holds true for general absorbed Markov processes with soft obstacles [48].

- N. Champagnat, K. Coulibaly-Pasquier (Univ. Lorraine) and D. Villemonais obtained general criteria for existence, uniqueness and exponential convergence in total variation to QSD for multi-dimensional diffusions in a domain absorbed at its boundary [37]. These results improve and simplify the existing results and methods.
- N. Champagnat and D. Villemonais obtained contraction properties in total variation of general penalized processes, including time-inhomogeneous Markov processes with absorption and Markov processes in varying environments [20]. Their method allows to improve significantly the former results of [62], [63].
- N. Champagnat and D. Villemonais studied with R. Schott (Univ. Lorraine) models of deadlocks in distributed systems. They use the approach developped recently by the first two authors to study quasi-stationary distributions in order to characterize and compute numerically the asymptotic behaviour of the deadlock time and the behaviour of the system before deadlock, both for discrete and for diffusion models [47].
- A. Lejay and A. Brault have followed their work on rough flow, which provides an unified framework to deal with the theory of rough paths from the points of view of flows. In particular, they have shown existence of flows even when the associated rough differential equations have multiple solutions [44], [45].
- A. Lejay and P. Pigato have provided an estimator of the diffusion and drift coefficients when they are discontinuous at a threshold. These estimators have been applied to financial data and exhibit leverage as well as mean-reversion effects on S&P 500 stocks' prices [57], [30]
- A. Lejay, L. Lenôtre and G. Pichot have proposed a new Monte Carlo method based on random exponential time steps to deal with discontinuous diffusions coefficients and drift [35], [56]
- A. Lejay, S. Haraketi and E. Haoula have shown how to construct a diffusion on the Sierpinski gasket lifted to the Heisenberg group [53].
- J. Bion-Nadal (Ecole Polytechnique) and D. Talay have pursued their work on a 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: cf. [41]. This solution is now shown to exist and be smooth even in cases where the infinitesimal generators of the considered diffusion processes are not strongly elliptic.

  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, the construction and analysis of an efficient stochastic algorithm are being in progress.
- In [60] D. Talay and M. Tomasevic have developed and analysed a new type of stochastic interpretation of the one-dimensional 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. At the mean-field level studied here, the McKean-Vlasov limit process interacts with all the past time marginals of its probability distribution. In [12] M. Tomasevic has proven that the two-dimensional parabolic-parabolic Keller-Segel system in the whole Euclidean space and the corresponding McKean-Vlasov stochastic differential equation are well-posed under some explicit conditions on the parameters of the model.
- D. Talay and M. Tomasevic are studying the well-posedness and the propagation of chaos of the particle system related to the two-dimensional parabolic-parabolic Keller-Segel system. The singularity of the interaction kernel being more critical than in the one-dimensional case, the preceding analysis [26] cannot be extended and a fully new methodology needs to be developed.

- V. Martin Lac, D. Talay and M. Tomasevic have worked on theoretical and algorithmic questions related to the simulation of the Keller–Segel particle systems. A preliminary version of a library has been developed.
- H. Olivero (Inria, now University of Valparaiso, Chile) and D. Talay have constructed and analysed an 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.
- 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 are ending and polishing the second volume of their series on Mathematical Foundation of Stochastic Simulation to be published by Springer.
- P-E. Jabin (University of Maryland) and D. Talay have ended their work on a mean-field game and shown the convergence of the joint density function of the controlled particle system. The construction of the limit has required the construction of suitable Sobolev spaces on sets of probability measures on Polish spaces.
- E. Tanré and Pierre Guiraud (Univ. of Valparaíso) have worked on the synchronization in a model of network of noisy biological neurons. Using a large deviation principle, they prove the stability of the synchronized state under stochastic perturbations. They also give a lower bound on the probability of synchronization for networks which are not initially synchronized. This bound shows the robustness of the emergence of synchronization in presence of small stochastic perturbations [25].
- 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 [52].
- 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 $n \to \infty$ [51].
- E. Tanré has worked with Patricio Orio (CINV, Chile) and Alexandre Richard (Centrale-Supelec) on the modelling and measurement of long-range dependence in neuronal spike trains. They exhibit evidence of memory effect in genuine neuronal data and compared a fractional integrate-and-fire model with the existing Markovian models [31].
- 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 Voltera equation satisfied by this rate. They used methods from integral equation to control finely the long time behavior of this firing rate [49].

- D. Villemonais collaborates with the Gerontology Service of CHRU Nancy on statistics of time evolution of telomere lengths in human blood cells. This is a collaboration with Anne Gégout Petit (IECL, Inria BIGS), Simon Toupance (CHRU Nancy), Eliane Albuisson (CHRU Nancy), Athanasios Benetos (CHRU Nancy), Daphnée Germain (Ecole des Mines de Nancy). They proposed in [32] a telomeric signature for human beings, stable along age evolution. Lionel Lenôtre works as a post-doc on this topic within the project GEENAGE of LUE.
- D. Villemonais studied with C. Coron (Univ. Paris-Saclay) and S. Méléard (École Polytechnique) the extinction probability before fixation for multi-dimensional models of Wright-Fisher type with mutations [21].
- In collaboration with E. Horton and A. Kyprianou (University of Bath), D. Villemonais studied the large-time asymptotic behaviour of the neutron transport equation in a three-dimensional domain [55]. This work is motivated by the simulation of the flow of particles in a nuclear tank.
- D. Villemonais studied with C. Mailler (University of Bath) the asymptotic behaviour of generalized measure-valued Polya urn models taking values in non-compact sets, using techniques from the theory of stochastic algorithms [58].

5.1.2. Other works in progress

- N. Champagnat, C. Fritsch and S. Billiard (Univ. Lille) are working on food web modeling.
- N. Champagnat and D. Villemonais are working with M. Benaïm (Univ. Neuchatel) on the convergence of stochastic algorithms to the quasi-stationary distribution of diffusion processes absorbed at the boundary of a domain.
- N. Champagnat is working with S. Méléard (École Polytechnique) and C. Tran Viet (Univ. Lille 1) on evolutionary models of bacteria with horizontal transfer. They study a scaling of parameters taking into account the influence of negligible but non-extinct populations, allowing to study specific phenomena observed in these models (re-emergence of traits, cyclic evolutionary dynamics and evolutionary suicide).
- Q. Cormier is investigating new methods to explore the long time behavior of the McKean-Vlasov SDE of [49], to go beyond the weak interactions case. The long time behavior of such McKean-Vlasov equations can be intricate as there can be multiple invariant measures or stable oscillations of the law of the process. The objective of this work is to develop (numerical and theoretical) methods to check the local stability of a given invariant measure of this non-linear SDE.
- 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 [34].
- C. Fritsch is working with Marianne Clausel (Univ. Lorraine) and Julien Trombini (Two-I) on the modeling of emotions spreading in a crowd.
- A. Lejay and A. Brault (U. Paris Descartes) continue their work to extend the framework of rough flows.
- O. Faugeras (MATHNEURO Inria Research Team), É. Soret (joint postdoc with MATHNEURO Inria Research Team) and É. Tanré are working on Mean-Field description of thermodynamics limits of large population of neurons with random interactions. They study the asymptotic behaviour for an asymmetric neuronal dynamics in a network of linear Hopfield neurons. They obtain the convergence in law of each component to a Gaussian process. The limit object is not a Markov process.
- P. Helson, E. Tanré and R. Veltz (MATHNEURO Inria team), are working on a neural network model of memory. The aim is to propose a new retrieval criterion and its mathematical analysis.

- E. Tanré has worked with Alexandre Richard (Centrale-Supelec) and Soledad Torres (Universidad de Valparaíso, Chile) on a one-dimensional fractional SDE reflected on the line. The existence and uniqueness of this process is known in the case where the Hurst parameter H of the noise (fBM) is larger than 0.5. They have proved the existence of a penalization scheme (suited to numerical approximation) to approach this object.

6. Bilateral Contracts and Grants with Industry

6.1. Bilateral Contracts with Industry

- 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.
- M. Bossy is the Coordinator of the POPART Industrial partnership project at UCA-JEDI on the modelling of fibre transport in turbulent flow. This partnership is granted by EDF and by UCA, and in collaboration with Observatoire de la Côte d'Azur.

7. Partnerships and Cooperations

7.1. Regional Initiatives

- 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.

7.2. National Initiatives

7.2.1. ANR

N. Champagnat is member of the ANR NONLOCAL (Phénomènes de propagation et équations non locales, 2014–2018) coordinated by F. Hamel (Univ. Aix-Marseille).

7.2.2. GDR

A. Lejay is leader of the GdR Project TRAG on rough path. This project has been accepted in October and should start on January 1st, 2019.

7.2.3. ITMO project

N. Champagnat, C. Fritsch and D. Villemonais 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.

7.2.4. PEPS

D. Villemonais has obtained a "PEPS jeune chercheur" grant.

7.3. European Initiatives

7.3.1. FP7 & H2020 Projects

- Mireille Bossy is involved in the VIMMP H2020 project, started in January 2018, as 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.

7.4. International Initiatives

7.4.1. Participation in Other International Programs

7.4.1.1. International Initiatives

Discrelongmem (C15E05)

Title: On discretization procedures in Non-Gaussian long memory processes with applications in non parametric statistics and time series analysis (C15E05)

International Partner (Institution - Laboratory - Researcher):

Universidad de Valparaiso (Chile) - CIMFAV – Facultad de Ingenieria

PI: E. Tanré (France), S. Torrès (Chile)

Duration: 2016 - 2018

Start year: 2016

Keywords: Approximations of non-Gaussian long-memory processes. Fractional Poisson processes (fPp). Skew Fractional Process (SfP).

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

7.5. International Research Visitors

7.5.1. Visits of International Scientists

- A. Kohatsu-Higa (Ritsumeikan University, Japan) - 1 month, with an invited professor position.

7.5.1.1. Internships

- Walid El Wahabi

  subject: processus de fragmentation pour les avalanches

  date: sept. 2018 - june. 2019

  institution: École des Mines de Nancy

- Vincent Hass

  Subject: Modèles de diffusion et estimation des dynamiques d'ADN tumoral circulant pour la détection d'une résistance à une thérapie ciblée

  Date: April 2018 - Sept. 2018

  Institution: Université Paris Sud

- Azer Mimouni

  subject: Méthodes de signature en apprentissage statistique

  date: sept. 2018 - june. 2019

  institution: École des Mines de Nancy

7.5.1.2. Sabbatical programme

D. Villemonais has obtained a *délégation CNRS* starting in September.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. 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).
- 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.

8.1.2. Scientific Events Organisation

8.1.2.1. General Chair, Scientific Chair

- Etienne Tanré was the General Chair of the Fourth International Conference on Mathematical Neuroscience https://icmns2018.inria.fr/, held in Antibes-Juan les Pins, June 11-13 2018.

8.1.2.2. Member of the Organizing Committees

- M. Bossy was a co-organizer of the workshop on Wasserstein calculus and related topics, ICMS, Edinburgh, UK- 19 to 23 November 2018.
- C. Fritsch co-organizes with Marianne Clausel (Univ. de Lorraine) the weekly Seminar of Probability and Statistics of IECL, Nancy.
- C. Fritsch co-organized the Ada Lovelace Day held at Inria Nancy – Grand Est, October 9.

8.1.3. Scientific Events Selection

8.1.3.1. Member of the Conference Program Committees

- M. Bossy is member of the SMAI2019 Conference Scientific Committee.
- D. Talay is serving as a member of the "Perturbation Techniques in Stochastic Analysis and Its Applications" Conference Program Committee (Luminy, France, 2019).

8.1.4. Journal

8.1.4.1. Member of the Editorial Boards

- 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*.
- A. Lejay is one of the three editors of the *Séminaire de Probabilités* and *Mathematics and Computers in Simulation* (MATCOM).
- D. Talay served as an Area Editor of *Stochastic Processes and their Applications*, and as an Associate Editor of *Probability, Uncertainty and Quantitative Risk*, *ESAIM Probability and Statistics*, *Stochastics and Dynamics*, *Journal of Scientific Computing*, *Monte Carlo Methods and Applications*, *Oxford IMA Journal of Numerical Analysis*, *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*.

8.1.4.2. Reviewer - Reviewing Activities

- N. Champagnat wrote reviews for *Annales de l'Institut Fourier*, *The Annals of Applied Probability* (three times this year), *Stochastic Processes and Their Applications*, *Electronic Journal of Probability* and *Frontiers of Mathematics in China*.

- C. Fritsch wrote reviews for *Applied Mathematics and Computation* and *PLOS ONE*.
- A. Lejay wrote reviews for *Proceedings of the Royal Society A*, *Mathematics and Computers in Simulation*, *Journal of Theoretical probability*, *Stochastic Processes and their Applications*, *Journal of computational physics*, *Journal of Functional Analysis*, *Electronic Journal of Probability*, *Journal of Optimization theory and applications*, *Physical Review E*, *Potential Analysis*, *Annals of Applied Probability*, *Annales de l'IHP, probabilités et statistique* and *Acta Mathematica Scientia*.
- 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.
- E. Tanré wrote reviews for *Annales Henri Lebesgue*, *The Annals of Applied Probability*, *Mathematics, MDPI*
- E. Tanré serves has a permanent reviewer of *Mathematical Reviews of the American Mathematical Society (MathSciNet)*.
- D. Villemonais wrote reviews for *Comptes-Rendus de l'Académie des Sciences de Paris*, *Journal of Advanced Probability*, *Electronic Journal of Probability*, *ESAIM: Probability & Statistics*, *Stochastic processes and applications*, *Markov Processes and Related Fields*, *The Annals of Applied Probability*.

8.1.5. Invited Talks

- N. Champagnat has been invited to give talks at the conference of *ANR NONLOCAL* in Chambéry in March, at the *Conference on Probability and Biological Evolution* at CIRM, Luminy in June, at *Journée mathématiques et informatique pour l'analyse des données et imagerie en oncologie* of the Cancéropôle Est at Institut de Cancérologie de Lorraine, Nancy in June, at the *MCQMC 2018* conference in Rennes in July, at the *Conference on Advances in Statistical Mechanics* at CIRM, Luminy in August, at the conference *Populations: Interactions and Evolution* at IHP, Paris in September and at the *ICMS workshop on Wasserstein calculus and related topics* at Bayes Center, Edinburgh in November.
- N. Champagnat has been invited to give a seminar talk at the *Groupe de travail PEIPS* at École Polytechnique in Palaiseau in February.
- N. Champagnat gave a colloquium talk at the *Colloquium - Mathematiques à Angers* in Angers in February.
- N. Champagnat has been invited to give a tutorial talk (mini-course) at the *Workshop on Mathematical Modeling with Measures: where Applications, Probability and Determinism Meet* at Lorentz Center, Leiden in December.
- Q. Cormier, P. Helson and E. Soret have presented three posters at the conference *International Conference on Mathematical Neuroscience* in Antibes Juan-les-Pins in June.
- C. Fritsch has been invited to give a plenary talk at the workshop *Modélisation stochastique et analyse en biologie* in Tours in May.
- C. Fritsch has been invited to give a plenary talk at the *third Mathematical Biology Modelling Days of Besançon* in June.
- C. Fritsch gave a talk at the *European Conference on Mathematical and Theoretical Biology* in Lisbonne in July.
- A. Lejay have been invited to give a mini-course "A short introduction to rough paths" in the *Rencontres Mathématiques de Rouen* in June 2018.
- A. Lejay have been invited to give a talk at the workshop *Random graphs and its applications for networks*, Saint-Étienne, October 2018.
- A. Lejay have been invited to give talks at the conference *Stochastics and PDE*, in Bucarest, September 2018 and at the conference *2th International Vilnius Conference on Probability Theory and Mathematical Statistics and 2018 IMS Annual Meeting on Probability and Statistics*, in Vilnius, June 2018.

- A. Lejay have been invited to give a seminar talk at the Mathematical Institute in Oxford, November 2018.
- E. Soret gave a lecture at the national conference *Journées de Probabilités* in Tours in June.
- D. Talay was an invited speaker at the ‘Symposium on Optimal Stopping in Honor of Larry Shepp’, Rice University in Houston, Texas, USA, 25-29 June 2018.
- D. Talay was an invited plenary speaker at the 9th International Conference on Stochastic Analysis and its Applications, Bielefeld, Germany, 3-7 September 2018.
- D. Talay was an invited speaker at the ‘Wasserstein Calculus and Related Topics’ Moscow-UK workshop on Stochastic Analysis, Edinburgh, UK, 19-23 November 2018.
- E. Tanré has given an invited talk at the *12th International Vilnius Conference on Probability Theory and Mathematical Statistics* and *2018 IMS Annual Meeting on Probability and Statistics* in Vilnius in July.
- E. Tanré has been invited to give a seminar talk in Lyon in October.
- M. Tomasevic gave a seminar at CMAP Laboratory, Ecole Polytechnique, France, in March.
- M. Tomasevic gave a lecture at the ‘Jps-2018: Jeunes Probabilistes et Statisticiens 2018’, Saint–Pierre d’Oléron, France, 13-18 May 2018.
- M. Tomasevic gave a lecture at the national conference *Journées de Probabilités* in Tours in June.
- M. Tomasevic gave a lecture at the 9th International Conference on Stochastic Analysis and its Applications, Bielefeld, Germany, 3-7 September 2018.
- M. Tomasevic gave a lecture at the ‘Journée francilienne d’accueil des postdoctorants en mathématiques’, Institut H. Poincaré, Paris, France, in October.
- D. Villemonais has been invited to give talks at the *Workshop on Particle systems and PDEs* at Bath University and at the conference *Populations: Interactions and Evolution* at IHP, Paris in September.
- D. Villemonais has been invited to give seminar talks at Warwick University, at the *Probability seminar* of London School of Economics and at the probability seminar of Université Paris-Descartes.

8.1.6. Leadership within the Scientific Community

- M. Bossy is serving as a vice president of the Inria Evaluation Committee.
- 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 served as a member of the scientific council of the Complex System academy of the UCA Idex.
- D. Talay served as a member of the committee in charge of preparing the application of Paris to the International Congress of Mathematicians 2022.
- 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.

8.1.7. Scientific Expertise

- M. Bossy served as a committee member for Pierre Lafitte Prize 2019.
- M. Bossy participated in a Associated Professor position recruitment committee at CMA Mines-ParisTech.
- M. Bossy was member of the hiring committee 26 PR at Université d’Evry.
- 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 served as a member of the HCERES evaluation committees for the LPSM Laboratory (Paris Sorbonne University) and the ENSTA mathematics department.
- D. Talay chaired the 2019 Pionneer ICIAM prize committee.

8.1.8. 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 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.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Master : M. Bossy *Stochastic Particle Methods for PDEs*, 18h, M2 Probabilité et Applications, Université Pierre et Marie Curie, France.

Master: N. Champagnat, *Introduction to Quantitative Finance*, 13.5h, 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, *Introduction to Quantitative Finance*, 3h, M1, École des Mines de Nancy, France.

Master: C. Fritsch, *Probability theory*, 61h, M1, École des Mines de Nancy, France.

Master: C. Fritsch, *Probability theory*, 40h, L3, École des Mines de Nancy, France.

Master: A. Lejay, *Simulation des marchés financiers*, 29h, M2, Master PSA, Université de Lorraine, France.

Master: D. Talay *Invariant measures of diffusion processes*, 18h, M2 Probabilité et Applications, Université Paris 6, 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) and M. Tomasevic (practical classes) *Numerical probability for mathematical finance*, 20h (8h + 12h), M2, Univ. Côte d'Azur (Master IMAFA), France.

8.2.2. Supervision

PhD in progress: Alexis Anagnostakis, *Étude du mouvement brownien collant*, Université de Lorraine, Octobre 2018, A. Lejay and D. Villemonais.

PhD: Antoine Brault, *Flots rugueux et inclusions différentielles perturbées*, Université Toulouse 3, Octobre 2018, A. Lejay and L. Coutin (Université Toulouse 3).

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).

PhD: M. Tomasevic, *On a Probabilistic Interpretation of the Keller-Segel Parabolic-Parabolic Equations*, Université Côte d'Azur, November 2018, D. Talay.

8.2.3. Juries

- M. Bossy served as a referee for the Ph.D. theses of Meïssam Bahlali, *Adaptation de la modélisation hybride eulérienne / lagrangienne stochastique de Code Satrne à la dispersion atmosphérique de polluants à l'échelle micro-météorologique et comparaison à la méthode eulérienne* Université Paris-Est, October 19, 2018, and of Alexandre Zhou, *Etude théorique et numérique de problèmes non linéaires au sens de McKean en finance*, Université Paris-Est, October 17, 2018.
- M. Bossy served as an examiner for the Ph.D. thesis of Isaque Santa Brigida Pimentel, *Valorisation optimale asymptotique avec risque asymétrique et applications en finance*, Université Paris Saclay, October 16, 2018.
- M. Bossy served as an examiner for the HDR of Dario Vincenzi, *Dynamique Lagrangienne en Turbulence et Turbulence Elastique*, Université Côte d'Azur, December 14, 2018.
- N. Champagnat served as a referee for the Ph.D. theses of Simon Girel, *Modélisation de la réponse immunitaire T-CD8: Analyse mathématique et modèles multiéchelles*, Univ. Lyon 1, November 13, 2018 and of Paulien Jeunesse, *Analyse statistique autour du taux de mortalité*, Université Paris Dauphine, January 8, 2019.
- N. Champagnat served as an examiner for the Ph.D. thesis of Rim Touibi, *Sur le comportement qualitatif des solutions de certaines équations aux dérivées partielles stochastiques de type parabolique*, Université de Lorraine, December 8, 2018.
- A. Lejay served as an examiner for the Ph.D. theses of Rim Touibi, *Sur le comportement qualitatif des solutions de certaines équations aux dérivées partielles stochastiques de type parabolique*, Université de Lorraine, December 8, 2018, of Antoine Brault, *Flots rugueux et inclusions différentielles perturbées*, Université Toulouse 3, October 8, 2018, and of Guillaume Copros, *Convergence of generic infinite products of nonexpansive and uniformly continuous operators*, Université Toulouse 3, October 2018.
- A. Lejay served as an examiner for the Habilitation thesis of Renaud Marty, *Quelques contributions à l'étude et aux applications des processus multifractionnaires et de la longue dépendance*, Université de Lorraine, February 2018.
- D. Talay served as an examiner for the Ph.D. thesis of Xiaoli Wei, *Problèmes de Contrôle de type McKean–Vlasov et Applications*, Université Paris Diderot, December 2018.
- D. Talay served as an examiner for the Habilitation thesis of Guillaume Bernis, *Modélisation Probabiliste des Marchés de Crédit*, université Paris Panthéon Sorbonne, January 2018.
- D. Talay served as an examiner for the Habilitation thesis of Ludovic Goudenège, *Algorithmes Numériques pour des Problèmes Stochastiques*, université Paris Saclay, December 2018.

- D. Talay served as a referee for Ph.D. thesis of Igor Honoré, *Estimations Non Asymptotiques de Mesures Invariantes et Régularisation par un Bruit Dégénéré de Chaînes d'Equations Différentielles Ordinaires*, université Paris Saclay, December 2018.

8.3. Popularization

8.3.1. Interventions

- M. Bossy gave the plenary lecture for the Academic Awards Ceremony of the Olympics of Geosciences and Mathematics 2018.
- Q. Cormier has animated the Inria desk at *Fête de la Science*.
- E. Tanré has presented his researches at *Journées Portes Ouvertes - Inria Sophia-Antipolis*.

9. Bibliography

Major publications by the team in recent years

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[3] M. Bossy, N. Maïzi, O. Pourtallier.*Game theory analysis for carbon auction market through electricity market coupling*, in "Commodities, Energy and Environmental Finance", M. Ludkovski, R. Sircar, R. Aid (editors), Fields Institute Communications, Springer, 2015, vol. 74, p. 335-370 [*DOI :* 10.1007/978-1-4939-2733-3_13], https://hal-mines-paristech.archives-ouvertes.fr/hal-01162832

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[12] M. TOMASEVIC.*On a probabilistic interpretation of the Keller-Segel parabolic-parabolic equations*, Universite Cote d'Azur, November 2018, https://hal.inria.fr/tel-01932777

Articles in International Peer-Reviewed Journal

[13] J. BION-NADAL, D. TALAY.*On a Wasserstein-type distance between solutions to stochastic differential equations*, in "Annals of Applied Probability", 2018, https://hal.inria.fr/hal-01943863

[14] M. BOSSY, J.-F. JABIR.*Particle approximation for Lagrangian Stochastic Models with specular boundary condition*, in "Electronic Communications in Probability", 2018, https://arxiv.org/abs/1504.07296 , https://hal.inria.fr/hal-01147441

[15] M. BOSSY, H. OLIVERO QUINTEROS.*Strong convergence of the symmetrized Milstein scheme for some CEV-like SDEs*, in "Bernoulli", 2018, vol. 24, n^o 3, p. 1995-2042, https://arxiv.org/abs/1508.04581 [*DOI :* 10.3150/16-BEJ918], https://hal.archives-ouvertes.fr/hal-01185353

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[33] C. MOKRANI, M. BOSSY, A. ROUSSEAU.*Towards a first validation of the SDM model for marine flows*, in "Simulation et Optimisation pour les Energies Marines Renouvelables", Paris, France, January 2018, https://hal.inria.fr/hal-01697596

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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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Project-Team WIMMICS

Creation of the Team: 2012 January 01, updated into Project-Team: 2013 July 01

WIMMICS is located on the SophiaTech Campus, Polytech Nice-Sophia Templiers 1 building.

Keywords:

Computer Science and Digital Science:

A1.2.9. - Social Networks
A1.3.4. - Peer to peer
A2.1. - Programming Languages
A2.1.1. - Semantics of programming languages
A3.1.1. - Modeling, representation
A3.1.2. - Data management, quering and storage
A3.1.3. - Distributed data
A3.1.4. - Uncertain data
A3.1.5. - Control access, privacy
A3.1.6. - Query optimization
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A3.2.1. - Knowledge bases
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A3.2.4. - Semantic Web
A3.2.5. - Ontologies
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A3.4.1. - Supervised learning
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A5.7.2. - Music
A5.8. - Natural language processing
A5.10.5. - Robot interaction (with the environment, humans, other robots)

A7.1.3. - Graph algorithms
A7.2.2. - Automated Theorem Proving
A8.2.2. - Evolutionary algorithms
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B2. - Health
B5.6. - Robotic systems
B5.8. - Learning and training
B6.3.1. - Web
B6.3.2. - Network protocols
B6.3.4. - Social Networks
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B8.2. - Connected city
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B8.5.1. - Participative democracy
B9. - Society and Knowledge
B9.1. - Education
B9.1.1. - E-learning, MOOC
B9.1.2. - Serious games
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B9.6.5. - Sociology
B9.6.8. - Linguistics
B9.6.10. - Digital humanities
B9.7. - Knowledge dissemination
B9.7.1. - Open access
B9.7.2. - Open data
B9.9. - Ethics
B9.10. - Privacy

1. Team, Visitors, External Collaborators

Research Scientists

Fabien Gandon [Team leader, Inria, Senior Researcher, HDR]
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Pinar Arslan [Inria, from Mar 2018]
Michele Corazza [Inria, from Feb 2018]
Erwan Demairy [Inria]
Franck Michel [CNRS]
Géraud Fokou Pelap [Inria, from Feb 2018]
Nicholas Halliwell [Inria, from Jul 2018]
Hai Huang [Inria, from May 2018]
Elmahdi Korfed [CNRS]
Roque Lopez Condori [Inria, Aug 2018]
Oscar Rodríguez Rocha [Inria, from Apr 2018, granted by U. numérique des sciences de la santé et du sport]

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Michael Fell [CNRS]
Raphaël Gazzotti [SynchroNext]
Abdoul Macina [Univ Côte d'Azur]
Tobias Mayer [Univ Côte d'Azur]
Duc Minh Tran [Univ de Nice - Sophia Antipolis, University of Danang, Vietnam, until Aug 2018]
Thu Huong Nguyen [Univ de Nice - Sophia Antipolis]
Emilie Palagi [Inria, from Sep 2018 until Nov 2018]
Mahamadou Toure [UGB]
Thuy Trieu [University of Timisoara, Romania, from Mar 2018 until Jul 2018]
Vorakit Vorakitphan [Inria, from Oct 2018]

Post-Doctoral Fellow

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Enrico Mensa [University of Torino, Italy, from May 2018 until Jul 2018]

Thanh Tuan Nguyen [Agence universitaire de la Francophonie, until May 2018]
Milagro Teruel [Universidad de Córdoba, Argentina, from Apr 2018 until Jun 2018]

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 [74]. 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 [73] 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

WIMMICS stands for Web-Instrumented Man-Machine Interactions, Communities, and Semantics.

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 the whole 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.fstandar

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

Serena Villata has been invited to deliver an Early Career Spotlight Talk at the main conference in Artificial Intelligence (IJCAI), namely the 27th International Joint Conference on Artificial Intelligence [0], on July 2018 in Stockholm (Sweden). The topic of this invited Early Career Spotlight Talk, *Artificial Argumentation for Humans*, is detailed in the related publication [62].
BEST PAPER AWARD :
[51]
O. RODRÍGUEZ ROCHA, C. FARON ZUCKER.*Automatic Generation of Quizzes from DBpedia According to Educational Standards*, in "The 3rd Educational Knowledge Management Workshop (EKM 2018)", Lyon, France, April 2018, https://hal.inria.fr/hal-01758737

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, 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

[0] https://www.ijcai-18.org/early-career-talks/

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 Milanesio
- Contact: Serena Villata Milanesio

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 Milanesio
- Contact: Elena Cabrio
- URL: http://www.qakis.org/

7. New Results

7.1. Users Modeling and Designing Interaction

7.1.1. User-centered Heuristics for the Control of Personal Data

Participants: Alain Giboin, Patrice Pena, Fabien Gandon.

This work (done in collaboration with Karima Boudaoud and Yoann Bertrand, SPARKS, I3S, in the context of the PadDOC FUI project) led to the elaboration and the evaluation of a set of user-centered heuristics and a procedure for designing and evaluating systems allowing the control of personal data. The elaboration of the heuristics was based on: (1) the transposal of Nielsen's heuristics and of Scapin and Bastien's ergonomic criteria to the control of personal data ; (2) the user centering of the Privacy-by-Design notion of integrated privacy; and (3) the integration of Altman's interaction approach to privacy.

7.1.2. Needs Analysis of the Target Users of the WASABI musical search platform

Participants: Alain Giboin, Isabelle Mirbel, Michel Buffa, Elmahdi Korfed.

In the context of the ANR project WASABI, we performed an analysis of the needs of the target users of the future WASABI platform. This analysis has been reported in an internal report.

7.1.3. Modeling the Users of Collaborative Ontology Building Environments

Participant: Alain Giboin.

We undertook a study on the evolution of the user model of collaborative ontology building environments (COBEs). By a user model – or a contributor model – we refer to the representation that COBEs designers have of the users of their systems and more generally of the actors contributing to the building of ontologies. This study aimed at emphasizing the importance to get a better knowledge of potential COBE contributors in order to design collaborative tools better suited to these contributors. The study was published in [55]. In this paper, we describe: (1) the method we used to study the evolution of the user/contributor model; (2) the evolution of the model (in terms of user types, user characterizations, and user's environment characterizations); (3) the parallel evolutions of: (a) the methods of COBEs design, (b) the systems themselves, and (c) the methods of collaborative ontology building; we mention some evolution perspectives envisioned by the designers.

7.1.4. Design of a User-Centered Evaluation Method for Exploratory Search Systems

Participants: Emilie Palagi, Alain Giboin, Fabien Gandon.

This work was undertaken in the context of the PhD of Emilie Palagi, in cooperation with Raphaël Troncy (EURECOM). Our method takes into account users' exploratory search (ES) behavior and is based on a cognitive model of an ES task. We specially work on Discovery Hub (Wimmics project – Inria) and 3cixty (EURECOM project) ESSs. During the third year of the PhD, we continued the evaluation of our model of exploratory search by comparing it to video records of seven other ES sessions on Discovery Hub, Frankenplace and 3cixty. We analyzed the videos with the same methodology: we wrote down the different chains of the different model's features used by the users in their ES session. For all the records we were able to identify the features of our model and extend our table of observed possible transitions between the model's features. From this analysis, we conclude that our model of ES can express the users' activity during an ES task. This work was partially published in [49].

Based on the ES model's features and the possible transitions between them, we designed two different evaluation and design methods of ES systems which do not necessarily involve users:

- Without users: Heuristics of ES and a procedure to use them. These heuristics are principles for the interaction design. The Heuristics of ES can be used several times along the design process of the ES system (in the design and evaluation phases). We presented the heuristics and evaluated them. This work was published in [48].
- With users: a guide for the elaboration of a customizable test protocol. The goal of the test is to analyze ES session records in order to find the model's features. In this guide, we give indications to customize the protocol and prepare users tests. We focused on two model-based elements of this customizable test protocol: a protocol for the elaboration of exploratory search tasks, and a video analysis grid for the evaluation of recorded exploratory search sessions.

7.1.5. Supporting Learning Communities with Intelligent services

Participants: Oscar Rodríguez Rocha, Catherine Faron Zucker.

The *Système Intelligent d'Enseignement en Santé 3.0* (SIDES 3.0), (Intelligent Health Education System 3.0), is a 3 years project funded by the French National Agency for Research (ANR) within the framework of the call for projects DUNE 2016. It builds upon a national Web platform, the *Système Informatique D'Evaluation en Santé (SIDES)* (Health Assessment Information System), used since 2013 by the faculties of medicine in France which enables them to perform all of their validation exams on tablets, providing them with automatic corrections. It contributes to the preparation of medical students to perform the *Epreuves Classantes Nationales (ECN) informatisées (ECNi)* (Computerized National Qualifying Events) which have been successfully held in France in June 2016 (8000 candidates simultaneously throughout France). The SIDES platform is administered by the 35 medicine faculties in France and is used by more than 70,000 students throughout their training. The system is also used to prepare students for *ECNi*. Over the last 3 years, more than 4 million clinical cases (made up of 15 questions each) have been performed by students (all activities combined).

Building on this success, the SIDES 3.0 project aims to upgrade the SIDES solution to an innovative solution providing the user with intelligent learning services based on a modelization of the pedagogical resources with Semantic Web models and technologies. It is coordinated by the *Université Numérique Thématique (UNT) en Santé et Sport*[0]. This structure offers an ideal national positioning for support and coordination of training centers (UFR) and also offers long-term financial sustainability. In this framework, we focus on developing and applying adaptive learning approaches to automatic quiz generation from existing questions, and quiz recommendation adapted to user profiles and learning contexts, to allow medical students to better achieve their educational objectives by answering quizzes [50], [51].

7.1.6. Explainable Predictions Using Product Reviews

Participants: Elena Cabrio, Fabien Gandon, Nicholas Halliwell, Freddy Lecue, Serena Villata.

This is a joint work between Accenture and Wimmics team, funded by Accenture. The goal of this project is to design a recommender system that returns explainable predictions to the user, incorporating text from the product reviews in the explanation. To start, we have replicated results from current state of the art methods. We then gathered a dataset of Amazon books and corresponding reviews, and ran the current state of the art algorithm on our dataset. The next steps will be to build a deep learning model to outperform the current state of the art algorithm, and develop a method to explain the predictions to the user using the product reviews.

7.1.7. Argument Mining

Participants: Elena Cabrio, Fabien Gandon, Claude Frasson, Andrea Tettamanzi.

We have published a survey paper about Argument Mining at IJCAI [61]. Argument mining is the research area aiming at extracting natural language arguments and their relations from text, with the final goal of providing

[0]http://www.uness.fr

machine-processable structured data for computational models of argument. This research topic has started to attract the attention of a small community of researchers around 2014, and it is nowadays counted as one of the most promising research areas in Artificial Intelligence in terms of growing of the community, funded projects, and involvement of companies. In this paper, we presented the argument mining tasks and we discussed the obtained results in the area from a data-driven perspective. An open discussion highlights the main weaknesses suffered by the existing work in the literature and proposes open challenges to be faced in the future.

Together with two colleagues from FBK Trento (Italy), we applied argumentation mining techniques, in particular relation prediction, to study political speeches in monological form, where there is no direct interaction between opponents. We argued that this kind of technique can effectively support researchers in history, social and political sciences, which must deal with an increasing amount of data in digital form and need ways to automatically extract and analyse argumentation patterns. We tested and discussed our approach based on the analysis of documents issued by R. Nixon and J. F. Kennedy during 1960 presidential campaign. We relied on a supervised classifier to predict argument relations (i.e., support and attack), obtaining an accuracy of 0.72 on a dataset of 1,462 argument pairs. The application of argument mining to such data allowed not only to highlight the main points of agreement and disagreement between the candidates' arguments over the campaign issues such as Cuba, disarmament and health-care, but also an in-depth argumentative analysis of the respective viewpoints on these topics. The results of this research have been published at AAAI [58].

In this direction, we have also, in collaboration with the Heron Lab of the University of Montreal, presented an empirical study about the relation between argumentative persuasion and emotions. Argumentative persuasion usually employs one of the three persuasion strategies: Ethos, Pathos or Logos. Several approaches have been proposed to model persuasive agents, however, none of them explored how the choice of a strategy impacts the mental states of the debaters and the argumentation process. We conducted a field experiment with real debaters to assess the impact of the mental engagement and emotions of the participants, as well as of the persuasiveness power of the arguments exchanged during the debate. Our results showed that the Pathos strategy is the most effective in terms of mental engagement. The results of this research have been published at FLAIRS [60].

Together with Souhila Kaci (LIRMM) and Leendert van der Torre (University of Luxembourg), we have proposed a formal framework to reason about preferences in abstract argumentation. Consider an argument A that is attacked by an argument B, while A is preferred to B. Existing approaches will either ignore the attack or reverse it. We introduced a new reduction of preference and attack to defeat, based on the idea that in such a case, instead of ignoring the attack, the preference is ignored. We compared this new reduction with the two existing ones using a principle-based approach for the four Dung semantics. The principle-based or axiomatic approach is a methodology to choose an argumentation semantics for a particular application, and to guide the search for new argumentation semantics. For this analysis, we also introduced a fourth reduction, and a semantics for preference-based argumentation based on extension selection. Our classification of twenty alternatives for preference-based abstract argumentation semantics using six principles suggests that our new reduction has some advantages over the existing ones, in the sense that if the set of preferences increases, the sets of accepted arguments increase as well. The results of this research have been published at COMMA [36].

Together with Celia da Costa Pereira (I3S) and Mauro Dragoni (FBK Trento), we presented SMACk, an opinion summary system built on top of an argumentation framework with the aim to exchange, communicate and resolve possibly conflicting viewpoints. SMACk allows the user to extract debated opinions from a set of documents containing user-generated content from online commercial websites, and to automatically identify the mostly debated positive aspects of the issue of the debate, as well as the mostly debated negative ones. The key advantage of such a framework is the combination of different methods, i.e., formal argumentation theory and natural language processing, to support users in making more informed decisions, e.g., in the context of online purchases. The results of this research have been published in the AI Communications journal [14].

7.2. Communities and Social Interactions Analysis

7.2.1. Argumentation and Emotion Detection with Adaptive Sentiment Analysis

Participants: Vorakit Vorakitphan, Serena Villata, Elena Cabrio.

This PhD work just started in the context of the ANSWER project with Qwant search engine. One of the main objectives of the ANSWER project is to use emotion detection algorithms within text inquiries and sentiment analysis to provide powerful enhancements in the search results from Qwant search engine. The final goal is to extract effective and scalable indicators of sentiment, emotions, and argumentative relations in order to offer the users additional means to filter the results selected by the search engine. Powerful algorithms in state-of-art will be focused to define new criteria for filtering search results, i.e., the expression of a feeling in the answers found by the search engine. By doing as mentioned, textual elements to which we wish to associate a polarity will no longer be considered in their individuality but connected to each other by polarized relations to be analyzed in a higher level setting. Currently, the work progress is in the survey of state-of-the-art based on emotion detection algorithms and implementation of sentiment analysis. Then the next target, classification models with multi-label features based on emotion detection, will be deeply explored as a starting point of this research. Moreover, NLP related to emotional news content will be taken into account to build a novel dataset based on emotion annotation from news articles in sentence-level.

7.2.2. Cyberbullying Events Prevention

Participants: Pinar Arslan, Michele Corazza, Elena Cabrio, Serena Villata.

In the CREEP EIT project, we built an emotion detection classifier to automatically identify the emotion for user-generated texts such as Twitter and Instagram posts. The correlation analysis that we carried out to get a better understanding of the associations between emotions and cyberbullying instances unveiled that certain emotions (e.g., anger, joy) would be good indicative features to detect cyberbullying instances. Hence, our pipeline firstly reveals automatically detected emotion labels for social media texts to be used to detect cyberbullying instances. The automatically predicted emotion labels were used as one of the predictors for our cyberbullying detection classifier. As part of the project, we successfully built a classifier for offensive language in social media interactions for English, Italian and German using neural networks. This classifier was evaluated by participating in two shared tasks: Germeval (German offensive language detection) and Evalita (Italian hate speech detection). For the Germeval Challenge [29], two systems for predicting message-level offensive language in German tweets were used: one discriminates between offensive and not offensive messages, and the second performs a fine-grained classification by recognizing also classes of offense. Both systems are based on the same approach, which builds upon Recurrent Neural Networks used with the following features: word embeddings, emoji embeddings and social-network specific features. The model combines word-level information and tweet-level information to perform the classification tasks. Our best performing model ranked 7th out of 51 submitted runs on the binary classification task, 5th out of 25 for the fine-grained classification task. For the Evalita Challenge shared tasks [28], our submissions were based on three separate classes of models: a model using a recurrent layer, an ngram-based neural network and a LinearSVC. For the Facebook task and the two cross-domain tasks we used the recurrent model and obtained promising results, especially in the cross-domain setting. For Twitter, we used an ngram-based neural network and the Linear SVC-based model. Our system ranked 1st in the Facebook to Twitter dataset, 2nd in the Twitter to Facebook dataset, 3rd in the Facebook dataset and 4th on the Twitter dataset.

7.2.3. Modeling of a Social Network of Service Providers

Participants: Molka Dhouib, Catherine Faron Zucker, Andrea Tettamanzi.

In the framework of a collaborative project with Silex France company and the CIFRE PhD thesis of Molka Dhouib, our aim is to model the social network of service providers and companies registered in the *software as a service* sourcing tool developed by Silex for the recommendation of the service providers that are best suited to meet the service requests expressed by companies. Our aim is to automate the matching of service requests and offers by reasoning on the social network of service providers and companies. We developed an automatic categorization of companies, service requests and service offers based on their textual descriptions. We conducted some experiments using state-of-the-art supervised Machine Learning techniques to classify Silex textual data into predefined categories, and to choose the best vector representations of the textual descriptions of service offers and requests in the Silex platform, and the best Machine Learning algorithm. This work has been presented at the French conference on applications of Artificial Intelligence APIA2018 [31].

7.3. Vocabularies, Semantic Web and Linked Data based Knowledge Representation

7.3.1. Modeling a Vocabulary of Professional Skills and Fields of Activities

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 a dedicated vocabulary of competences and fields of activities to semantically annotate B2B service offers. We started with the study of existing reference taxonomies representing skills, professions and fields of activities and we formalized them in SKOS. Then we built a SKOS vocabulary from the internal Silex repositories. Finally we performed a semi-automatic alignment of these vocabularies. This work has been presented at the French conference on Knowledge Engineering IC 2018 [53].

7.3.2. Representing and Querying a Knowledge Graph on Pedagogical Resources

Participants: Géraud Fokou Pelap, Catherine Faron Zucker, Fabien Gandon, Olivier Corby.

In the framework of the EduMICS (Educative Models Interactions Communities with Semantics) joint laboratory (LabCom) between the Wimmics team and the Educlever company, we built a knowledge graph from the database of the Educlever platform describing learning resources, and related knowledge and skills. We deployed our proposed Semantic Web based solution within the industrial environment of Educlever, using Web services, and we showed the added value of Semantic Web modelling enabling to implement new functionalities with SPARQL queries on the knowledge graph. This work has been presented at the SemWeb.Pro 2018 day [56] and at the WEBIST conference [34].

7.3.3. A Learnable Crawler for Linked Open Data

Participants: Hai Huang, Fabien Gandon.

This work is supported by the ANSWER project in cooperation with Qwant company. It consists of designing a learnable Linked Data crawler featured by a prediction component which is able to predict whether a newly discovered URI contains RDF data or not.

As the Web of Linked Open Data is growing exponentially, crawling for Linked Data has become increasingly important. Unlike normal Web crawlers, a Linked Data crawler performs selectively to collect linked RDF (including RDFa) data on the Web. From the perspectives of throughput and coverage, given a newly discovered URI, the key issue of Linked Data crawlers is to decide whether this URI is desirable to download (if it contains RDF data). Current solutions adopt heuristic rules aiming to filter irrelevant URIs. Unfortunately, it would hurt the coverage of crawling. In this work, we developed a learnable Linked Data crawler featured by a prediction component which is able to predict whether a newly discovered URI contains RDF data or not. We extracted useful features from the context RDF graph of the URI. The prediction model is based on FTRL-proximal [0] online learning algorithm. We evaluated it through extensive experiments in comparison with a number of baseline methods and demonstrated its efficiency.

7.3.4. Argument Mining on Clinical Trials

Participants: Tobias Mayer, Serena Villata, Elena Cabrio.

This work was done in the context of the PhD of Tobias Mayer, which is situated in the IADB project, "Intégration et Apprentissage sur les Données Biomédicales". We created a new annotated dataset of Randomized Controlled Tirals (RCT) about four different diseases (glaucoma, diabetes, hepatitis B, and hypertension), containing 976 argument components (697 containing evidence, 279 claims) together with a first approach for the argumentative component detection [39]. Empirical results are promising and show the portability of the proposed approach over different branches of medicine. Furthermore, we proposed a new sub-task of the argument component identification task: evidence type classification, which distinguishes the provided evidence on a more fine-grained level. To address it, we proposed a supervised approach and we tested it on our data set [40].

[0] FTRL: Follow The Regularized Leader

As a collaboration with ”Base, Corpus, Language” (BCL) at UCA within the IADB project, we anonymized and cleaned clinical reports (from CHU Nice), built a ”raw” French corpus from it and are currently working on transferring the above mentioned annotations and models to this data set.

7.3.5. Structure Detection in Song Lyrics

Participants: Michael Fell, Elena Cabrio, Fabien Gandon.

In the context of the WASABI ANR project, we work on the estimation of the structure of song lyrics. For this, we have built a predictive model that successfully segments song texts into their underlying paragraphs - a task called ”Lyrics Segmentation”. We have augmented existing state-of-the-art models for Lyrics Segmentation in two ways: (i) by applying convolutional neural networks to the task alongside of novel feature representations. This work resulted in a publication at the COLING conference [33]; (ii) by extending the feature representation with time-synchronized audio features, we improve the segmentation model performance. It can now also use audio cues when text cues are non-indicative; this improves segmentation performance. Our current endeavors aim at summarizing song texts so that journalists and musicologists can perform efficient searches under different perspectives (e.g. structure and semantic content).

7.3.6. Legal Information, Privacy

Participants: Elena Cabrio, Serena Villata.

Together with Valentina Leone and Luigi di Caro (University of Torino), we presented the *InvestigatiOnt* tool which aims to ease the interaction of end users with legal ontologies in order to spread the use of machine-processable legal information as well as its understanding. This research is addressed in the context of the EU H2020 MIREL project. The results of this research have been published as demo paper at ISWC [71].

Together with Sabrina Kirrane (Vienna University of Economics and Business) and Matthieu d’Aquin (National University of Ireland Galway), we examined 78 articles from dedicated venues, the Privacy Online workshop series, two SPOT workshops, as well as the broader literature that connects the Semantic Web research domain with issues relating to privacy, security and/or policies. Specifically, we classified each paper according to three taxonomies (one for each of the aforementioned areas), in order to identify common trends and research gaps. We concluded by summarising the strong focus on relevant topics in Semantic Web research (e.g. information collection, information processing, policies and access control), and by highlighting the need to further explore under-represented topics (e.g., malware detection, fraud detection, and supporting policy validation by data consumers). The results of this research have been published in the Semantic Web journal [16].

7.3.7. Semantic Web for Biodiversity

Participants: Franck Michel, Catherine Faron Zucker.

The collaboration initiated with the French National Museum of Natural History of Paris (MNHN) is now giving rise to the development of an activity related to biodiversity data sharing and integration.

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], the ontology Web portal for agronomy and agriculture. At the Biodiversity Information Standards conference (TDWG 2018), we presented some insights in the modelling of biodiversity Linked Data [45], we demonstrated how SPARQL Micro-Services can help in the integration of heterogeneous biodiversity-related data sources [43]. We also presented a poster on the Bioschemas.org initiative [46], a W3C community group that seeks the definition and adoption of common biology-related markup. In this context, we have proposed a first specification of the Taxon term [0] whose adoption as part of the official Schema.org vocabulary is currently being discussed with Google.

[0] http://lod-cloud.net/
[0] http://agroportal.lirmm.fr/ontologies/TAXREF-LD/
[0] http://bioschemas.org/devSpecs/Taxon/

We took part in the D2KAB ANR project submission that aims to turn agronomy and biodiversity data into semantically described, interoperable, actionable open-knowledge. The project has been accepted and is due to start in June 2019.

7.3.8. 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 published two contributions this year, together with Johan Montagnat from I3S.

First, we proposed a generic method to bridge the gap between the Semantic Web and NoSQL worlds [42]. To avoid defining yet another SPARQL translation method for each and every database, a SPARQL query is translated into a pivot abstract query, spanning all database-independent steps. Only then, the abstract query is translated into the target database query language while taking into account the specific database capabilities and constraints.

Second, we defined the SPARQL Micro-Service architecture that harnesses the Semantic Web standards to enable automatic combination of Linked Data and data residing in Web APIs (aka. REST Web services). A SPARQL micro-service is a lightweight, task-specific SPARQL endpoint that provides access to a small, resource-centric virtual graph, while dynamically assigning dereferenceable URIs to Web API resources that do not have URIs beforehand. The graph is delineated by the Web API service being wrapped, the arguments passed to this service, and the restricted types of RDF triples that this SPARQL micro-service is designed to spawn.

This work was presented at the ESWC conference [42] and the LDOW workshop at the Web Conference [44]. We also conducted an experimentation where we dynamically augment biodiversity Linked Data with data from multiple Web APIs: Flickr, Biodiversity Heritage Library, Encyclopedia of Life, Macauley scientific media archive, and MusicBrainz [43].

7.3.9. Linked Data Script Language

Participant: Olivier Corby.

We have designed and implemented LDScript, a programming language compatible with SPARQL that enables users to write extension functions that are directly executable in SPARQL queries.

We have leveraged pattern matching for structured objects such as lists where we can retrieve first elements, intermediate sublist and last elements. We have defined event driven processing where the SPARQL interpreter emits events which are processed by LDScript functions. The function definitions are annotated with event names. This enables users to trace query execution, to overload SPARQL statements such as "*order by, distinct*" and to extend SPARQL with new statements implemented as functions. In particular we are able to overload SPARQL operators for extension datatypes such as romain numbers or values with units. We are also able to trap and overload SPARQL execution errors with specific LDScript functions. In addition, we have introduced a second order "eval" function that enables us to evaluate the arguments of expressions that caused an error.

LDScript has been extended in order to process SPARQL Update in addition to SPARQL Query. Hence LDScript can be used to implement Semantic Web services with the following statements: SPARQL Query and Update, OWL RL entailment, RDF transformation to HTML.

This a follow up work on the formalism that was originally published at ISWC 2017 [72].

7.3.10. Graphic Display for RDF Graphs

Participants: Olivier Corby, Erwan Demairy.

This work has been done in the context of an Inria funding for software development (ADT).

In order to perform Linked Data visualisation, we connected the D3.js graphic display library to the Corese Web server. We designed an STTL transformation that generates D3 graph format with stylesheet from RDF graph. The graph display is performed thanks to SVG code generated by D3. The graph display can be interactive, that is hypertext navigation can be associated with a click on graph nodes. We have setup a demo with HAL open data server [0], see figure 1.

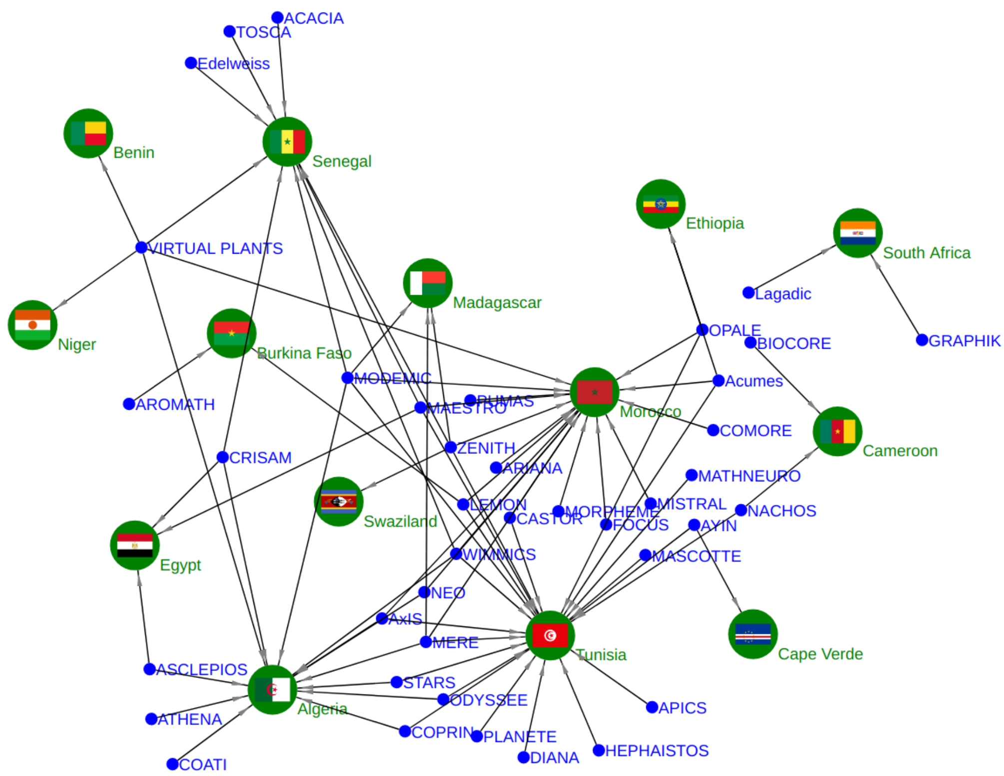

Figure 1. Inria Sophia Antipolis teams publishing with south American countries.

This work has been presented at the software development day at Inria Sophia Antipolis, November 14th.

7.3.11. Federated Query Scaler

Participant: Olivier Corby.

This work is done in the context of the *Federated Query Scaler* Inria exploratory research project (PRE) together with Olivier Dameron and Vijay Ingalalli from Dyliss team at Inria Rennes.

In this project, focused on SPARQL federated queries, Vijay Ingalalli designed a graph index for distributed SPARQL endpoints that enables us to predict whether joins between patterns can be performed within endpoints. We also wrote a compiler that generates a SPARQL query with service clauses from a federated query, that is a query annotated with several SPARQL endpoints URL.

[0] http://corese.inria.fr

We welcomed Vijay Ingalalli at Inria Sophia Antipolis, January 15-19, and Olivier Corby visited the Dyliss team in Rennes, March 4-6.

7.4. Analyzing and Reasoning on Heterogeneous Semantic Graphs

7.4.1. Distributed Artificial Intelligence for Revisable Linked Data Management

Participants: Ahmed El Amine Djebri, Andrea Tettamanzi, Fabien Gandon.

The aim of this PhD thesis is to study and to propose original solutions to many key aspects: Knowledge Representation in case of uncertain, incomplete and reviewable data; Uncertainty Representation in a data source, with provenance; Distributed Knowledge Revision and Propagation; Reasoning over Uncertain, Incomplete and distributed data-sources. Starting from an open Web of Data, this work tries to give the users more objective, exhaustive and certain views and information about their queries, based on distributed data sources with different levels of certainty and trustworthiness. We proposed a vocabulary to formalize uncertainty representation, and a framework to handle uncertainty mapping to sentences and contexts. This work has been presented as a poster at ISWS [68].

7.4.2. Learning Class Disjointness Axioms using Grammatical Evolution

Participants: Thu Huong Nguyen, Andrea Tettamanzi.

The aim of this research is to discover automatically class disjointness axioms from recorded RDF facts on the Web of Data. This may be regarded as a case of inductive reasoning and ontology learning. The instances, represented by RDF triples, play the role of specific observations, from which axioms can be extracted by generalization. We proposed the use of Grammatical Evolution, one type of evolutionary algorithm, for mining disjointness OWL2 axioms from an RDF data repository such as DBpedia. For the evaluation of candidate axioms against the DBpedia dataset, we adopt an approach based on possibility theory. We have submitted a paper to the conference EuroGP 2019.

7.4.3. Semantic Data for Image Recognition

Participants: Anna Bobasheva, Fabien Gandon.

This work is done in the context of the MonaLIA project with French Ministry of Culture, in collaboration with Frédéric Precioso, I3S, UCA. It consists of a preliminary study on image recognition of the Joconde database in connection with semantic data (JocondeLab).

The goal of this project is to exploit the cross-fertilization of recent advances in image recognition and semantic indexing on annotated image databases in order to improve the accuracy and the details of the annotation. The idea is, at first, to assess the potential of machine learning (including deep learning) and the semantic annotations on the Joconde database (350 000 illustrated artwork records from French museums). Joconde also contains metadata based on a thesaurus. In a previous project (JocondeLab) these metadata were formalized in Semantic Web formalism and were linking the iconographic Garnier thesaurus and DBpedia to the data of the Joconde database.

We developed SPARQL queries on Joconde database to extract the subset of images to train the Deep Learning classifier. We identified class subsets with enough labeled images for training, we balance number of images per class and we avoid images with intersected classes.

We tuned the pre-trained VGG16 implementation of the CNN classifier to classify the artwork images using well-known VGG16 with batch normalization [75] to train the classifier for the artwork images. We learned transfer from the training of the network on the ImageNet dataset to decrease the training time and we ran the classifier on many datasets and in different modes.

We developed another set of queries on the metadata to find the dependencies between the classification outcome and the artwork properties by applying statistical methods. We identified the usable (populated enough with reasonable number of categorical values) properties of the metadata. We used Recursive Feature Elimination (RFE) and Decision Tree to identify the top most statistically significant dependent variables and decision splitting values.

Results have been presented at a workshop of Ministry of Culture and Inria, November 22nd, at Bibliothèque Nationale de France in Paris.

7.4.4. Hospitalization Prediction

Participants: Catherine Faron Zucker, Fabien Gandon, Raphaël Gazzotti.

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. The first results of this project will be presented at the French EGC 2019 conference [54]. In this paper, we report and discuss the results of our first experiments on the database PRIMEGE PACA that contains more than 350,000 consultations carried out by 16 general practitioners. 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.

7.4.5. Fake News Detection

Participants: Jérôme Delobelle, Elena Cabrio, Serena Villata.

This work is part of the RAPID CONFIRMA (COntre argumentation contre les Fausses InfoRMAtion) DGA project aiming to automatically detect fake news and limit their diffusion. For this purpose, a framework will be 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, we will use methods from Natural Language Processing and Argumentation Theory to propose automatically extracted counter-arguments (adapted to target audience) from the existing reference press articles. These arguments allow to attack the false information detected in the fake news. Argument Mining techniques will make it possible to (1) analyse the argumentation in natural language, for example by looking for the argumentative structures, identifying the relations of support or attack between the arguments; (2) locate the data related to specific information (related to fake news) on the Web.

7.4.6. Mining and Reasoning on Legal Documents

Participants: Cristian Cardellino, Milagro Teruel, Serena Villata.

Together with Cristian Cardellino, Fernando Cardellino, Milagro Teruel and Laura Alonso Alemany from Univ. of Cordoba, we have proposed a methodology to improve argument annotation guidelines by exploiting inter-annotator agreement measures. After a first stage of the annotation effort, we have detected problematic issues via an analysis of inter-annotator agreement. We have detected ill-defined concepts, which we have addressed by redefining high-level annotation goals. For other concepts, that are well-delimited but complex, the annotation protocol has been extended and detailed. Moreover, as can be expected, we showed that distinctions where human annotators have less agreement are also those where automatic analyzers perform worse. Thus, the reproducibility of results of Argument Mining systems can be addressed by improving inter-annotator agreement in the training material. Following this methodology, we are enhancing a corpus annotated with argumentation, available online [0] together with guidelines and analyses of agreement. These analyses can be used to filter performance figures of automated systems, with lower penalties for cases where human annotators agree less. This research is addressed in the context of the EU H2020 MIREL project. The results of this research have been published at LREC [59].

[0] https://github.com/PLN-FaMAF/ArgumentMiningECHR

Together with some colleagues from Data61 Queensland (Australia) and Antonino Rotolo (University of Bologna), we proposed a formal framework that can instantiate in agents' dialogues moral/rational criteria, such as the maximin principle, Pareto efficiency, and impartiality, which were used, e.g., by John Rawls' theory or rule utilitarianism. Most ethical systems define how the individuals ought, morally, act being part of a society. The process of elicitation of a moral theory governing the agents in a society requires them to express their own norms with the aim to find a moral theory on which all may agree upon. This research is addressed in the context of the EU H2020 MIREL project. The results of this research have been published at DEON [57].

7.4.7. Argumentation

Participants: Serena Villata, Andrea Tettamanzi.

In collaboration with Mauro Dragoni of FBK and Célia da Costa Pereira of I3S, we have proposed the SMACk System, combining argumentation and aspect-based opinion mining [14].

7.4.8. Agent-Based Recommender Systems

Participants: Amel Ben Othmane, Nhan Le Thanh, Andrea Tettamanzi, Serena Villata.

We have proposed a spatio-temporal extension for our multi-context framework for agent-based recommender systems (CARS), to which we have added representation and algorithms to manage uncertainty, imprecision, and approximate reasoning in time and space [47].

7.4.9. RDF Mining

Participants: Duc Minh Tran, Andrea Tettamanzi.

In collaboration with Dario Malchiodi of the University of Milan and Célia da Costa Pereira of I3S, we have studied the use of a prediction model as a surrogate of a possibilistic score for OWL axioms [38], [37].

In collaboration with Claudia d'Amato of the University of Bari, 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 [52].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Joint Lab Inria - Qwant

Fabien Gandon is director of the joint Lab Inria - Qwant

8.1.2. Intelliquiz Carnot Project

Participants: Oscar Rodríguez Rocha, Catherine Faron Zucker.

Partner: Qwant/GAYAtech.

This project ended in March 2018. It was a joint project with GAYAtech (acquired by Qwant during the project) on the automatic generation of quizzes from the Web of Data. It is a continuation of a former collaborative project with GAYAtech on the recommendation of pedagogical resources based on ontology-based modelling and processing. We developed an approach to generate quizzes from DBpedia and we experimented it on the geographical domain for primary school students.

8.1.2.1. Joint Lab EduMICS

Catherine Faron Zucker is the scientific leader of the EduMICS (Educative Models Interactions Communities with Semantics) joint laboratory (LabCom, 2016-2018) between the Wimmics team and the Educlever company. Adaptive Learning, Social Learning and Linked Open Data and links between them are at the core of this LabCom. The purpose of EduMICS is both to develop research and technologies with the ultimate goal to adapt educational progressions and pedagogical resource recommendation to learner profiles. During the second year of the project, we continued the deployment of Semantic Web technologies within the industrial context of Educlever, showing the added value of Semantic Web modelling enabling ontology-based reasoning on a knowledge graph. To continue our collaboration, we submitted a project proposal to the call for projects *AAP Partenariat d'Innovation et Intelligence Artificielle*; we successfully passed the first phase.

8.1.3. 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) and UCA (post-doc). 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.

8.1.4. Synchronext Collaborative Project

Participants: Raphaël Gazzotti, Catherine Faron Zucker, Fabien Gandon.

Partner: Synchronext.

This project is funded by the ANRT (CIFRE PhD). Synchronext is a startup aiming at developing Semantic Web business solutions. The goal of this project is to develop a NLP and semantic Web based artificial agent for online support in the insurance domain. The objective is to reduce the dropout rate of Internet users on FAQs and to reduce the number of incoming calls and e-mails. This will enable to customer advisers to focus on more difficult questions. As a first step, we are working on automatically categorizing online requests to properly rout them.

8.2. Bilateral Grants with Industry

8.2.1. Accenture

Wimmics received two grants from Accenture to support work on explainable AI. They will fund the PhD of Nicholas Halliwell on that topic.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. ALDRAI UCA Project

At the center of the project, there is a triple ambition. The first is methodological and epistemological: it is a question of contributing to the development of the field of computational humanities via new tools of exploration of corpora, beyond the lexical approach (without excluding it, obviously, but in complementing) - it is a question of learning how to mobilize Artificial Intelligence to locate arguments, ideas and not simply terms, uses of terms, semantic fields. The second ambition is academic and transdisciplinary: the field studied in the project - administrative law from 1799 to today - concerns several disciplines (the history of law, administrative law, modern and contemporary history, philosophy, political science, administrative science) and the development of digital technology will make it possible to considerably widen the sources available for its study, both from the point of view of their analysis (thanks to the exploratory tools mentioned in the previous point) and from the point of view of their nature. The third ambition is professional: practitioners already use the available databases (such as ArianeWeb [0] - for administrative case law) but they need to be able to question them more finely, in relation to the theoretical questions they ask themselves. This need is all the stronger as the so-called *digital transformation of justice* is developing in the sense of automating decision-making processes, based on the disputes already settled through the implementation of systematic line of all court decisions (pursuant to the law of 7 October 2016 on the Digital Republic). Magistrates as lawyers therefore need new digital tools to work and several start-ups have appeared in the sector called Legal Tech.

Partners: UNS (faculté de lettres and faculté de droit), Inria, UCA, École Pratique des Hautes Études [0] and Institut des Systèmes Complexes de Paris IDF [0], duration: 2018-2019.

9.1.2. IADB UCA Project

IADB, *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 and BCL (Bases, Corpus, Language) Laboratory.

9.1.3. INCERTIMMO UCA Project

INCERTIMMO, *Uncertainty in Real Estate Spatial Modeling in the City*[0], is a research and development partnership funded by UCA and Kinaxia [0] company. UCA partners are: I3S, ESPACE [0], and IMREDD [0].

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.

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[0] http://arianeinternet.conseil-etat.fr/arianeinternet/
[0] https://www.ephe.fr/
[0] https://iscpif.fr/
[0] *Intégration et Apprentissage sur les Données Biomédicales*
[0] *Prise en compte de l'Incertitude pour une Modélisation Spatiale des Valeurs Immobilières dans la Ville*
[0] http://www.kinaxia.fr/
[0] http://univ-cotedazur.fr/laboratoires_old/espace
[0] http://imredd.fr/
[0] https://project.inria.fr/answer/
[0] http://www.qwant.com

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 1.0

Participants: Anna Bobasheva, Fabien Gandon.

The MonaLIA 1.0 project is a preliminary study on the coupling of learning methods (Deep Neural Networks) and knowledge-based methods (Semantic Web) for image recognition and the enhancement of descriptive documentary records. The approach is applied and evaluated on the collection and data in the Joconde database in order to identify the possibilities and challenges offered by this coupling in assisting in the creation and maintenance of such an annotated collection.

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 then explore these bases of musical knowledge and provide innovative applications for composers, musicologists, music schools and sound engineers, music broadcasters and journalists.

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. 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.

[0] http://side-sante.org/

Web site: http://dbpedia.fr

9.2.7. 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.

9.2.8. Qwant-Inria Joint Laboratory

Participants: Fabien Gandon, Alain Giboin.

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 identify possibilities of exploiting the Qwant search engine to improve the search for information in the digital cultural resources of the French Ministry of Culture. At the end of the project, some possibilities will be selected and will be the subject of research actions in the context a long-term project.

9.2.9. Inria Federated Query Scaler

Participant: Olivier Corby.

Federated Query Scaler is an Exploratory Research Project (PRE) funded by Inria, together with the Dyliss team at Inria Rennes. The topic of this project is the study of distributed SPARQL queries in the context of bioinformatics.

9.2.10. 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 [45].

Web site: http://www.cepam.cnrs.fr/zoomathia/

9.3. European Initiatives

9.3.1. CREEP EIT Project

The CREEP project (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). Partners: University of Trento, Fondazione Bruno Kessler, Inria, ExpertSystem, NeuroNation; duration: 2018-2020.

[0] http://lod-cloud.net/
[0] http://agroportal.lirmm.fr/ontologies/TAXREF-LD/

Web site: http://creep-project.eu/.

9.3.2. MIREL

MIREL, MIning and REasoning with legal text, is a Research and Innovation Staff Exchange (RISE) project, funded by Marie Skłodowska-Curie grant, duration: 2016-2019

The coordinator is Leendert van der Torre, University of Luxembourg

Other partners are: University of Bologna (Italy), University of Torino (Italy), University of Huddersfield (UK), Inria (France), APIS (Bulgaria), Nomotika s.r.l. (Italy), DLVSystem s.r.l. (Italy), Zhejiang University (China), Research Organization of Information and Systems (Japan), University of Cape Town (South Africa), National University of La Plata (Argentina), National University of Córdoba (Argentina), Universidad Nacional del Sur in Bahía Blanca (Argentina), National ICT Australia Ltd (Australia), Stanford University (USA).

The MIREL project will create an international and inter-sectorial network to define a formal framework and to develop 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, compliance checking, and decision support. MIREL addresses both conceptual challenges, such as the role of legal interpretation in mining and reasoning, and computational challenges, such as the handling of big legal data, and the complexity of regulatory compliance. It bridges the gap between the community working on legal ontologies and NLP parsers and the community working on reasoning methods and formal logic. Moreover, it is the first project of its kind to involve industrial partners in the future development of innovative products and services in legal reasoning and their deployment in the market. MIREL promotes mobility and staff exchange between SMEs to academies in order to create an inter-continental interdisciplinary consortium in Law and Artificial Intelligence areas including Natural Language Processing, Computational Ontologies, Argumentation, and Logic & Reasoning.

Web site: http://www.mirelproject.eu/

9.4. International Initiatives

9.4.1. Inria Associate Teams Not Involved in an Inria International Labs

MoReWAIS
MoReWAIS stands for Mobile Read Write Access and Intermittent to Semantic Web.

Partners: UGB (Senegal) - LANI - Moussa Lo; start year: 2016.

MoReWAIS proposes to explore the specificities (advantages and constraints) of mobile knowledge sharing. The mobile application targeted in MoReWAIS must allow communities and their users to enrich and access more easily the knowledge base using the user's context with its richness (e.g. location, other users close-by) and addressing its limitations (e.g. intermittent access, limited resources).

Web site: https://project.inria.fr/morewais/.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

Christian Cardellino: PhD, Universidad de Córdoba, Argentina, May and July.
Andrei Ciortea: PostDoc, University of Saint Gallen, Switzerland, Labex UCN@Sophia grant, November-December.
Kaladzavi Guidedi: PostDoc CEA-MITIC University of Maroua, Cameroon, MoreWAIS grant, November-December.
Phan Hieu Ho: PhD, Polytechnic Institute, Danang, Vietnam, April-July.
Milagro Teruel: PhD, Universidad de Córdoba, Argentina, May-June.
Thuy Trieu: PhD, University of Timisoara, Romania, March-July.

9.5.2. Research Stays Abroad

- Fabien Gandon visited CSIRO, Brisbane, Australia from July to August 2018. In the context of the project MIREL he worked on the problem of aligning semantic Web schemas (argumentation and generic schemas) to support interoperable and linked arguments on the Web as an extension of Web annotation and Web provenance.
- Raphaël Gazzotti visited the Natural Language Processing research group of the Universidad Nacional de Córdoba, Argentina, for two months as a secondment of the MIREL H2020 Project, March-April. We carried out information retrieval of medical test results within free text in french Electronic Medical Records by a symbolic approach. In a future step, we could annotate automatically free texts with this method then train a machine learning algorithm in order to have a better generalization of this extraction process. We also worked on a sequential machine learning modelization suited to Electronic Medical Records. This model exploits the potential of Conditional Random Fields and consequently allows us to interpret the decision made by the algorithm across all the different consultations of a patient, moreover, all medical test results can be considered with this modelization.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

Elena Cabrio was:

- Co-chair of CLiC-it: Fifth Italian Conference on Computational Linguistics, Turin, December.
- Challenge co-chair of The Web Conference (WWW), Lyon, France, April 23-27.

Catherine Faron Zucker was Program Chair together with Chiara Gandini of the 21st International Conference on Knowledge Engineering (EKAW 2018), November, Nancy.

Fabien Gandon was general co-chair of The Web Conference in Lyon, April, 2018.

Serena Villata was:

- Program Chair together with Eduardo Ferme of the 17th edition of the International Workshop on Non-Monotonic Reasoning (NMR), Tempe (Arizona), October,
- Chair together with Filip Radlinski of the “Poster and Demo” session of the Web Conference (WWW), Lyon, France, April,
- Chair together with Harko Verhagen, Mehdi Dastani and Jurgen Dix of the Dagstuhl Seminar on Normative Multi-Agent Systems NorMAS, April [67]

10.1.1.2. Member of the Organizing Committees

Michel Buffa organized the *WebAudio Plugins* Workshop at the Web Audio conference, Berlin, September 19-21.

Fabien Gandon was co-organizer of the Joint Day Inria Ministry of Culture 22/11/2018.

Alain Giboin was member of the organization committee of HCSE.

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

Olivier Corby was co-chair of the poster and demo track at EKAW, together with Philipp Cimiano.

Isabelle Mirbel was co-chair of the Doctoral Consortium at IEEE International Conference on Research Challenges in Information Science (RCIS).

10.1.2.2. Member of the Conference Program Committees

Michel Buffa: WebAudio Conference, ISWC.

Elena Cabrio: Association for Computational Linguistics conference (ACL), EMNLP, Extended Semantic Web Conference (ESWC), International Semantic Web Conference (ISWC), AAAI Conference on Artificial Intelligence.

Olivier Corby: The Web Conference 2019, IC, Digital Health, EKAW, ICCS, ISWC, QuWeDa.

Catherine Faron Zucker: The Web Conference (WWW) 2019, ICCS, ISWC, Web Science, ESWC, IJCAI, Semantics, Web Audio Conference WAC, workshop WWW Educational Knowledge Management EKM, workshop WWW Reasoning on Data RoD, EGC 2019, EIAH, IC, CNIA.

Fabien Gandon: The Web Conference (WWW), IJCAI, ISWC (Blue Sky), EGC, SemWeb.Pro.

Alain Giboin: ISWC, VOILA Workshop (at ISWC), IC.

Isabelle Mirbel: International Conference on Advanced Information Systems Engineering (CAISE).

Oscar Rodríguez Rocha: KEOD, KSE, EKAW, IJCAI, ECAI, Semantics.

Andrea Tettamanzi: AAAI-19, AAMAS, ACM (SWA Track), EGC 2019, EKAW, PPSN, TheWebConf 2019, Web Intelligence, WILF, WIVACE. He was also senior PC Member of IJCAI/ECAI and got a mention as distinguished PC Member.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

Catherine Faron Zucker: Revue d’Intelligence Artificielle.

Isabelle Mirbel: Ingénierie des Systèmes d’Information.

10.1.3.2. Reviewer - Reviewing Activities

Elena Cabrio: Journal Argument and Computation.

Catherine Faron Zucker: The Journal of Web Science, Journal of Web Semantics (JWS), International Journal on Semantic Web and Information Systems (IJSWIS), IEEE Transactions on Computational Social Systems (TCSS), IEEE’s Transactions on Learning Technologies (TLT), Multimodal Technologies and Interaction (MTI), Ingénierie des systèmes d’information (ISI).

Andrea Tettamanzi: Semantic Web Journal, IEEE Transactions on Evolutionary Computation.

Serena Villata: Journal of Logic and Computation, Argument & Computation, Artificial Intelligence.

10.1.4. Invited Talks

Michel Buffa: Presentation of the ANR WASABI project and of WebAudio technologies at the "Journée Ministère de la Culture - Inria" on 22/11 as part of the agreement between these two institutions, at the BnF.

Presentation of the WebAudio, WebMidi and WebAssembly W3C standards. Developer’s Day of the TPAC conference in Lyon, October, Lyon, France.

AZKAR Project, post-mortem presentation *Remote museum visits by an intelligent mobile robot*, during Mobility session: Autonomous and Connected Vehicle and Smart Cities, RoboPACA conference, Sophia Antipolis, France.

Elena Cabrio: *Argument Mining for Machine Translation*, 13th Machine Translation Marathon, Prague, September 6th.

From Linguistics to Computation across the Mountains to the Sea, FBK PhD Day, February 2nd, Trento (Italy).

Olivier Corby: *LDScript : a Linked Data Script Language*, Inria Montpellier, March 21st.

Semantic Web of Linked Data, Inria Rennes, April 5th.

Fabien Gandon: *Web Science, Artificial Intelligence and Intelligence Augmentation*, Invited Talk at Dagstuhl Perspectives Workshop 18262 - 10 Years of Web Science: Closing The Loop, 27/06/2018.

The revolutions of the Web planet, Invited talks I3S General Assembly, Nice, 5/07/2018.

Adding Missing Links to bridge Natural and Artificial Intelligence on the Web, Invited talks at University of Queensland, Brisbane, 08/08/2018.

A Web linking all kinds of intelligence, Invited talks at « Przemiany Festival », Copernicus Science Centre, French Embassy in Warsaw, 15/09/2018.

Towards a Web linking all kinds of intelligence, Invited Talk at SophI.A Summit, 07/11/2018.

Andrea Tettamanzi: Invited talk on *Guess What You Don't Know: Towards an Evolutionary Epistemology of Ontology Learning* at the 21st International Conference on Knowledge Engineering and Knowledge Management, Nancy, France, November 14th.

Conference on *Unsupervised Learning* at Amadeus, Sophia Antipolis, March 26th.

Tutorial talk on *Uncertainty in the Semantic Web: The case of axiom scoring* at the 12th International Conference on Scalable Uncertainty Management, Milan, Italy, October 3rd.

Conference on *Unsupervised Learning* at Amadeus, Sophia Antipolis, October 19th.

Serena Villata has been invited to deliver an Early Career Spotlight Talk at the main conference in Artificial Intelligence (IJCAI), namely the 27th International Joint Conference on Artificial Intelligence [0], in July in Stockholm (Sweden). The topic of this invited Early Career Spotlight Talk, *Artificial Argumentation for Humans* is detailed in the related publication [62].

10.1.5. Leadership within the Scientific Community

Fabien Gandon is:

- member of IW3C2 steering committee for The Web Conference (WWW series).
- member of SWSA steering committee for the ISWC conference (as general chair of ISWC 2019).
- member of ESWC conference steering committee.
- member of Web Science Trust Network

10.1.6. Scientific Expertise

Olivier Corby was reviewer for two project submissions at Université Gaston Berger, Senegal.
Catherine Faron Zucker:

- is the scientific referent of the Inria Learning Lab,
- was reviewer for the LabCom V3 2018 of the French Agence Nationale de la Recherche (ANR),
- was reviewer for the ARC6 call for projects of Auvergne Rhône Alpes region,
- was reviewer for the RIN call for projects of Normandie region.

Alain Giboin was reviewer for the Generic Call for Projects of the French Agence Nationale de la Recherche (ANR).

10.1.7. Research Administration

Olivier Corby is member of the scientific board of Université Côte d'Azur RISE academy (Network, Information, Digital Society) and member of the Scientific and Pedagogical committee of the Digital Systems for Humans, DS4H, graduate school at UCA.

Catherine Faron Zucker:

- is General Treasurer of the French Society for Artificial Intelligence (AFIA).
- was leading the steering committee of the AFIA college on Knowledge Engineering until June 2018.
- was member of the 2018 recruitment committee for young graduate scientists (CRCN) at Inria Lille.
- is member of the permanent commission of human resources (CPRH) of Université Nice Sophia Antipolis, section CNU 27

[0] https://www.ijcai-18.org/early-career-talks/

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”.
- was co-facilitator of the Idex Jedi Academy 5 initiative ”Humanités numériques” (with Arnaud Zucker, CEPAM).
- is member of the scientific committee of MSHS Axis 2 ”TIC, Usages et Communautés”.
- is co-facilitator of the initiative ”Artefacts et Coordination” of MSHS Axis 2.
- served as scientific correspondent for Inria Sophia Antipolis of COERLE (Inria Comité Opérationnel d’Evaluation des Risques Légaux et Ethiques), in tandem with the legal correspondent Nadège Camelio-Laurent.

Isabelle Mirbel was Vice-dean of the Science Faculty at University Nice-Sophia Antipolis until July 2018.

”Les lundis de l’ergonomie” is a cycle of seminars on Human Computer Interaction (HCI) and UX Design. Organized by Emilie Palagi and Louise Chaussade, this multidisciplinary series of talks attract academic and professional profiles but also anyone interested in social science’s approach to digital matters. This year, presentations took place with Naji Bouchiba, Guillene Ribière, Alessandro Trezzi, Manuel Boutet, Marc Relieu. The slides and some video records are available online [0].

10.1.8. Editorial Activities

Catherine Faron Zucker is among the scientific editors of the proceedings of the 21st International Conference on Knowledge Engineering and Knowledge Management, Nov 2018, Nancy, France. Lecture Notes in Computer Science 11313, Springer [65].

Serena Villata is among the authors of two editorial activities:

- Qingliang Chen, Paolo Torroni, Serena Villata: Preface. Fundam. Inform. 158(1-3): v-vii [13],
- Ugo Pagallo, Monica Palmirani, Pompeu Casanovas, Giovanni Sartor, Serena Villata: AI Approaches to the Complexity of Legal Systems - AICOL International Workshops 2015-2017: AICOL-VI@JURIX 2015, AICOL-VII@EKAW 2016, AICOL-VIII@JURIX 2016, AICOL-IX@ICAIL 2017, and AICOL-X@JURIX 2017, Revised Selected Papers. Lecture Notes in Computer Science 10791, Springer [66].

10.1.9. Standardization

- Michel Buffa is member of the WebAudio W3C working group and is Academic Representative of Université Côte d’Azur at W3C (AC Rep).
- Fabien Gandon is Advisory Committee representative of Inria at the World-Wide Web Consortium (W3C)

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Michel Buffa is director of MIAGE Nice-Sophia Antipolis: Licence, Master 1 and four Master 2 degrees, about 350 students [0].

[0] https://lundisergo.hypotheses.org/
[0] http://miage.unice.fr

Elena Cabrio is responsible of the internship program, 40 hours, (L3 and M2 MIAGE), University of Nice-Sophia Antipolis (UNS), France.
Catherine Faron Zucker is responsible of the Web option of the 5th year of Polytech Nice Sophia engineering school (Master degree) and is in charge of continuous training for the computer science department of Polytech Nice Sophia Antipolis.
Andrea Tettamanzi has managed the 3nd year of the *Licence* (Bachelor of Science) in Business Informatics (MIAGE) at the UFR Science of the University of Nice-Sophia Antipolis (UNS),

- License: Elena Cabrio, Web Server Programming, 45 hours, (L1 INFO), UNS, France.
- License: Elena Cabrio, Introduction to the Web, 40 hours, (L2MASS), UNS, France.
- Licence: Michel Buffa, JavaScript: L3 Miage (40h)
- License: Elena Cabrio, Internship supervision, 18 hours, (L3MIAGE), UNS, France.
- Licence: Isabelle Mirbel, Web programming (Persistency), 36h, L3, UNS, France.
- Licence: Andrea Tettamanzi, Algorithmics – Object Oriented Programmaing – Python, 50 h, L2, UNS, France.
- Licence: Andrea Tettamanzi, Advanced client side Web Programming, 39 h, L2, UNS, France.
- Licence: Andrea Tettamanzi, Web, 30 h, L3, UNS, France.
- Master: Elena Cabrio, WebScience, 10 hours, (M2IFI), 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: Olivier Corby, Catherine Faron Zucker, Oscar Rodríguez Rocha, Semantic Web of Data, 65h, M2, UNS, France.
- Master: Olivier Corby, Semantic Web, 3H, M2, University of Montpellier, France.
- Master: Catherine Faron Zucker, Oscar Rodríguez Rocha, Andrea Tettamanzi, Knowledge Engineering, 35h, M2, UNS, France.
- Master: Catherine Faron Zucker, Oscar Rodríguez Rocha, Web Languages, 35h, M1, UNS, France.
- Master: Fabien Gandon, Web Science, 3 h, M1, UNS, France.
- Master: Fabien Gandon, Integrating Semantic Web technologies in Data Science developments, 2*28 h, M2, DSTI, France.
- Master/PhD: Semantic Web and Linked Data Graphs, 3 h, Winter School on Complex Networks 2018 (5th edition), France.
- Master: Alain Giboin, Human-Computer-Interaction Design and Evaluation, 21h, M2, UNS.
- Master: Alain Giboin, Human-Computer-Interaction Adaptation of User Interfaces, 4h, M2, UNS.
- Master: Alain Giboin, Task and Activity Analysis for HCI design and evaluation, 6h, M2 Sociology and Ergonomics of Digital Technologies, UNS.
- Master: Alain Giboin, HCI Design and Evaluation, 10h, M2 Sociology and Ergonomics of Digital Technologies, UNS.
- Master: Alain Giboin, Digital Strategy (formerly: Economics and ICT) : Ergonomics, 13h, M2 Economics and ICT, ISEM, UNS.
- Master: Isabelle Mirbel, Project Management, 24h, M2, UNS, France.
- Master: Isabelle Mirbel, Requirement Engineering, 36h, M1, UNS, France.
- Master: Andrea Tettamanzi, Logic for AI, 30 h, M1, UNS, France.
- Master: Andrea Tettamanzi, Parallelism, 18 h, M1, UNS, France.
- Master: Andrea Tettamanzi, Web Science, 5 h, M1, UNS, France.
- Master: Andrea Tettamanzi, Data analysis in distributed environment, 18 h, M2, UNS, France.
- **E-learning**
  - Michel Buffa, MOOC *JavaScript Intro* EDx platform.
  - Michel Buffa, MOOC *HTML5 Coding Essentials and Best Practices*, Edx platform.
  - Michel Buffa, MOOC *HTML5 Apps and Games*, also on EDx platform.
  - Fabien Gandon, Catherine Faron Zucker, Olivier Corby, MOOC *Web sémantique*, FUN.
  - Fabien Gandon, Catherine Faron Zucker, Olivier Corby, MOOC *Web of Data*, FUN.
  - Fabien Gandon, Catherine Faron Zucker, Olivier Corby, MOOC *Web of Data*, Coursera [0],

to be run in 2019.

10.2.2. Supervision

HdR: **Michel Buffa**, *Des wikis aux simulations d'amplificateurs de guitare à lampes, le Web plateforme universelle*, UNS, December 12th, President : Fabien Gandon.

HdR: **Serena Villata**, *Explainable, Trustable and Emphatic Artificial Intelligence: from Formal Argumentation Theory to Argumentation for Humans*, UNS, July 4th, President : Fabien Gandon.

PhD: **Duc Minh Tran**, *Learning Ontologies from Linked Open Data*, Andrea Tettamanzi, UNS and Nguyen Thanh Binh, University of Danang, July [12].

PhD: **Emilie Palagi**, *Design of a Model-based Method for Evaluating Exploratory Search Systems*, UNS, Labex UCN@Sophia, Alain Giboin, Fabien Gandon with Raphaël Troncy (Eurecom), November 23rd.

PhD in progress: **Molka Dhouib**, *Modeling of a social network of service providers and companies and recommendation of service providers by reasoning on the social network*, UNS, Catherine Faron Zucker with Andrea Tettamanzi.

PhD in progress: **Ahmed El Amine Djebri**, *Distributed Artificial Intelligence for Linked Reviewable Data Management on the Semantic Web*, UNS, Andrea Tettamanzi, Fabien Gandon.

PhD in progress: **Michael Fell**, *Natural Language Processing of Song Lyrics*, UNS, Elena Cabrio, Fabien Gandon.

PhD in progress: **Raphaël Gazzotti**, *Modeling and Classification of Descriptions to Assist Decision Making*, UNS & SynchroNext, Catherine Faron Zucker, Fabien Gandon.

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**, *Mobile Access for the Web of Data*, Fabien Gandon, Pascal Molli and Moussa Lo, UGB, UNS.

PhD in progress: **Vorakit Vorakitphan**, *Argumentation and Emotions Emotion Detection with Adaptive Sentiment Analysis*, Elena Cabrio, Serena Villata, UCA.

Tobias Mayer attended:

- Advanced Course on Data Science & Machine Learning [0] (Siena, July 18-24)
- 3rd Summer School on Argumentation, [0] (Warsaw, September 06-10)

10.2.3. Juries

Catherine Faron Zucker was reviewer of the PhD thesis of

- Joe Raad, *Identity Management in Knowledge Graphs*, Université Paris Saclay, defended on 30/11/2018;
- Valentina Beretta, *Data veracity assessment: enhancing Truth Discovery using a priori knowledge*, Ecole des Mines Télécom IMT Mines Alès, defended on 30/10/2018;
- Landy Rajaonarivo, *Approche co-évolutive humain-système pour l'exploration de bases de données*, Ecole Nationale d'Ingénieurs de Brest (ENIB), defended on 29/06/2018;
- Manel Achichi, *Linking Heterogeneous Open Data – Application to the Musical Domain*, Université de Montpellier, defended on 15/02/2018.

[0] https://www.coursera.org/learn/web-data/
[0] https://acdl2018.icas.xyz/
[0] http://waw2018.argdiap.pl/summer-school/

Fabien Gandon was

- Jury Member for HDR Frédérique Segond, *Transformer les Données afin d'Etancher la Soif de l'Ere de la Connaissance*, University Grenoble Alpes, defended 17/01/2018
- Opponent for PhD Valentina Ivanova, *Fostering User Involvement in Ontology Alignment and Alignment Evaluation*, Linköping University Department of Computer and Information Science Division of Database and Information Techniques, defended 26/01/2018
- President for HDR Serena Villata, *Explainable, Trustable And Emphatic Artificial Intelligence From Formal Argumentation Theory To Argumentation For Humans*, University Côte d'Azur, defended 04/07/2018
- Reviewer for PhD Jörg Waitelonis, *Linked Data Supported Information Retrieval*, Karlsruher Institut für Technologie (KIT), defended 09/07/2018
- Reviewer for PhD Thesis Silvio Cardoso, *MAISA- Maintenance of Semantic Annotations*, Université Paris-Sud, LRI, and LIST Luxembourg, defended 30/11/2018
- President for HDR Michel Buffa, *Des wikis aux simulations d'amplificateurs de guitare à lampes, le Web plateforme universelle...*, University Côte d'Azur, defended 12/12/2018
- External Reviewer for PhD Thesis Luigi Asprino, *Engineering Background Knowledge for Social Robots*, University of Bologna, report sent the 15/12/2018
- Jury member for Tenure Track position for a Researcher in the field of Knowledge-based Systems in Healthcare at Bruno Kessler Foundation (FBK), 2018

Andrea Tettamanzi was:

- Jury member of the HDR theses of Giovanni Fusco, *Ville, Complexité, Incertitude. Enjeux de connaissance pour le géographe et l'urbaniste*, Université Côte d'Azur, February 5th;
- Jury member of the HDR theses of Chan Le Duc, *Raisonnement et révision pour des ontologies en logique de description*, Université Paris 8, November 29th.
- Chairman of the Jury for the PhD thesis of Abdoul Macina, UNS, December 17th on *SPARQL Distributed Query Processing over Linked Data*.
- Reviewer for the thesis of Victor Eduardo Fuentes, *Méta alignement méta heuristique*, whose defense was not authorized by Université du Québec, Montréal.

10.3. Popularization

10.3.1. Interventions

- Michel Buffa presented the WASABI ANR project during *La fête de la Science* in *L'esprit Sorcier* TV program [0].

11. Bibliography

Major publications by the team in recent years

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[2] E. Cabrio, S. Villata.*Natural Language Arguments: A Combined Approach*, in "20th European Conference on Artificial Intelligence (ECAI 2012)", Montpellier, France, August 2012, https://hal.inria.fr/hal-00724780

[0] https://youtu.be/-iExdePDsPA

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Doctoral Dissertations and Habilitation Theses

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[12] D. M. TRAN.*Discovering multi-relational association rules from ontological knowledge bases to enrich ontologies*, Université Côte d'Azur, July 2018, https://tel.archives-ouvertes.fr/tel-01926812

Articles in International Peer-Reviewed Journal

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International Conferences with Proceedings

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[23] M. BUFFA, J. LEBRUN.*Real-Time Emulation of a Marshall JCM 800 Guitar Tube Amplifier, Audio FX Pedals, in a Virtual Pedal Board*, in "WWW2018 - TheWebConf 2018 : The Web Conference, 27th International World Wide Web Conference", Lyon, France, April 2018 [*DOI :* 10.1145/3184558.3186973], https://hal.univ-cotedazur.fr/hal-01721463

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[31] M. T. DHOUIB, C. FARON ZUCKER, A. TETTAMANZI.*Categorization of B2B Service Offers: Lessons learnt from the Silex Use case*, in "4ème conférence sur les Applications Pratiques de l'Intelligence Artificielle APIA2018", Nancy, France, July 2018, https://hal.archives-ouvertes.fr/hal-01830905

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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

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THEME
Data and Knowledge Representation and Processing

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Project-Team ZENITH

Creation of the Team: 2011 January 01, updated into Project-Team: 2012 January 01

Keywords:

Computer Science and Digital Science:

A1. - Architectures, systems and networks
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Other Research Topics and Application Domains:

B1. - Life sciences
B1.1. - Biology
B1.1.7. - Bioinformatics
B6. - IT and telecom
B6.5. - Information systems

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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 produced through empirical observation and simulation. Such data must be processed (cleaned, transformed, analyzed) in all kinds of ways in order to draw new conclusions, prove scientific theories and produce knowledge. Similarly, digital humanities are faced with the problem of exploiting vast amounts of digitized cultural and historical data, such as broadcasted radio or TV content over decades. 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 are growing so fast that they will lead to collections of hundreds of exabytes by 2020.

Scientific data is very complex, in particular because of heterogeneous methods used for producing data, the uncertainty of captured data, the inherently multi-scale nature (spatial scale, temporal scale) of many sciences and the growing use of imaging (e.g. molecular imaging), resulting in data with hundreds of attributes, dimensions or descriptors. 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.

Despite their variety, we can identify common features of scientific data: big data; manipulated through complex, distributed workflows; typically complex, e.g. multidimensional or graph-based; 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).

Relational DBMSs, which have proved effective in many application domains (e.g. business transactions, business intelligence), are not efficient at dealing with scientific data or big data, which is typically unstructured. In particular, they have been criticized for their “one size fits all” approach. As an alternative , more specialized solutions are being developped such as NoSQL/NewSQL DBMSs and data processing frameworks (e.g. Spark) on top of distributed file systems (e.g. HDFS).

The three main challenges of scientific data management can be summarized by: (1) scale (big data, big applications); (2) complexity (uncertain, multi-scale data with lots of dimensions), (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, these solutions are in terms of architectures, models and algorithms that can be implemented in terms of components or services in specific computing environments, e.g. cloud. We design and validate our solutions by working closely with our scientific application partners such as CIRAD, INRA and IRD in France, or the National Research Institute on e-medicine (MACC) in Brazil. 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; data semantics to improve information retrieval and automate data integration; declarative languages to manipulate data and workflows; and highly distributed and parallel environments such as P2P, cluster and cloud. We also exploit machine learning, probabilities and statistics for high-dimensional data processing, data analytics and data search. To reflect our approach, we organize our research program in five complementary themes:

- Data integration, including data capture and cleaning;
- Data management, in particular, indexing and privacy;
- Scientific workflows, in particular, in grid and cloud;
- Data analytics, including data mining and statistics;
- Machine learning for high-dimensional data processing and 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 is a centralized server that 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. Data mining provides methods to discover new and useful patterns from very large datasets. These patterns may take different forms, depending on the end-user's request, such as:

- **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. This problem was first motivated by commercial and marketing purposes (*e.g.* discovering frequent correlations between items bought in a shop, which could help selling more). 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 $i+j+k$". Discovering frequent sequences has become critical in marketing, as well as in security (e.g. detecting network intrusions), in web usage analysis and any domain where data come in a specific order, typically given by timestamps.
- **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.).

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 and one core activity of Zenith in this context is the use of probability theory to quantify uncertainty and to 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 research is hence oriented towards computationally effective methods.
- **Deep neural networks**. A major breakthrough in machine learning performance has been witnessed in the last ten years through the advent of deep neural nets. These models are characterized by a huge amount of parameters, that routinely reach dozens of millions, and by scalable learning procedures. Researchers in Zenith are striving towards proposing original architectures and methods that are theoretically grounded and offer state-of-the-art performance for data search and data 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 core communities are targetted, which are: botany, and digital humanities. In both cases, the key observation done by Zenith 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. The team is active at the international level in organizing popular evaluation campaigns that allow machine learning researchers to propose new methods while solving important applicative problems. This activity has two distinct aspects: managing datasets, and offering tools to ease interoperability.

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 (e.g. in Brazil or the USA).

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 is estimated to reach 100TB very soon. 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. VLDB Conference

The VLDB conference (http://vldb2018.lncc.br) was in Rio de Janeiro. Its organization is a major outcome of the SciDISC associate team, with key positions held by members of the project: F. Porto: general chair, P. Valduriez: sponsor chair and many SciDISC members in the local organization. E. Ogasawara and P. Valduriez were chairs of the LADaS VLDB workshop. E. Pacitti was chair of the VLDB workshop on Big Social Data and Urban Computing (BiDU). The VLDB conference was a great success with about 700 participants.

5.1.2. New Book

A. Joly co-authored the book "Multimedia Tools and Applications for Environmental & Biodiversity Informatics" [69], which demonstrates how the latest advancements in data science impact the wide range of environmental and biodiversity studies.

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

- Participants: Maximilien Servajean and Alexis Joly
- Contact: Alexis Joly
- Publication: Crowdsourcing Thousands of Specialized Labels: A Bayesian Active Training Approach

6.3. Snoop

KEYWORDS: Content-based Image Retrieval - Deep learning

FUNCTIONAL DESCRIPTION: Snoop is a C++ framework dedicated to large-scale content-based image retrieval. Its main features are (i) the extraction and efficient indexing of visual features (hand-crafted or learned through deep learning), (ii) the search of similar images through approximate k-nearest neighbors and (iii), the supervised recognition of trained visual concepts. The framework can be used either as a set of C++ libraries or as a set of web services through a RESTFUL API. Snoop is the visual search engine used by the Pl@ntNet applications (very large audience).

- Participants: Alexis Joly, Jean-Christophe Lombardo and Olivier Buisson
- Partner: INA (Institut National de l'Audiovisuel)
- Contact: Alexis Joly
- Publication: Random Maximum Margin Hashing

6.4. 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

6.5. 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: Vítor 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

6.6. 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

6.7. 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

6.8. 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 Porgramming, ...) to analyse and simulate shapes and their development.

- Participants: Christian Fournier, Christophe Godin, Christophe Pradal, Frédéric Boudon, Patrick Valduriez, Esther Pacitti and Yann Guedon
- 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

6.9. FP-Hadoop

Fast Parallel Hadoop

KEYWORDS: Hadoop - Data parallelism
FUNCTIONAL DESCRIPTION: FP-Hadoop makes the reduce side of Hadoop MapReduce more parallel and efficiently deals with the problem of data skew in the reduce side. In FP-Hadoop, there is a new phase, called intermediate reduce (IR), in which blocks of intermediate values, constructed dynamically, are processed by intermediate reduce workers in parallel. Our experiments using FP-Hadoop using synthetic and real benchmarks have shown excellent performance gains compared to native Hadoop, e.g. more than 10 times in reduce time and 5 times in total execution time.

- Participants: Reza Akbarinia, Miguel Liroz-Gistau and Patrick Valduriez
- Contact: Reza Akbarinia
- Publication: FP-Hadoop: Efficient Execution of Parallel Jobs Over Skewed Data

6.10. Hadoop_g5k

KEYWORD: Cluster
FUNCTIONAL DESCRIPTION: Hadoop_g5k is a tool that makes it easier to manage Hadoop and Spark clusters and prepare reproducible experiments in the Grid 5000 platform. Hadoop_g5k offers a set of scripts to be used in command-line interfaces and a Python API to interact with the clusters. It is currently active within the G5k community, facilitating the preparation and execution of experiments in the platform.

- Participants: Reza Akbarinia, Miguel Liroz-Gistau and Patrick Valduriez
- Contact: Reza Akbarinia
- URL: https://www.grid5000.fr/mediawiki/index.php/Hadoop_On_Execo

6.11. 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

6.12. SON

Shared-data Overlay Network
KEYWORDS: Sharing - Ibuted exchange - Peer-to-peer.
FUNCTIONAL DESCRIPTION: SON is a development platform for P2P networks using web services, JXTA and OSGi. The development of a SON application is done through the design and implementation of a set of components. Each component includes a technical code that provides the component services and a code component that provides the component logic (in Java). The complex aspects of asynchronous distributed programming are separated from code components and automatically generated from an abstract description of services for each component by the component generator.

- Participants: Didier Parigot, Esther Pacitti and Patrick Valduriez
- Contact: Didier Parigot
- Publication: A Lightweight Middleware for developing P2P Applications with Component and Service-Based Principles
- URL: http://www-sop.inria.fr/members/Didier.Parigot/pmwiki/SON/index.php

6.13. SciFloware

Scientific Workflow Middleware

KEYWORDS: Bioinformatics - Distributed Data Management

FUNCTIONAL DESCRIPTION: SciFloware is a middleware for the execution of scientific workflows in a distributed and parallel way. It capitalizes on our experience with the Shared-Data Overlay Network and an innovative algebraic approach to the management of scientific workflows. SciFloware provides a development environment and a runtime environment for scientific workflows, interoperable with existing systems. We validate SciFloware with workflows for analyzing biological data provided by our partners CIRAD, INRA and IRD.

- Participants: Didier Parigot, Dimitri Dupuis and Patrick Valduriez
- Contact: Didier Parigot
- Publication: InfraPhenoGrid: A scientific workflow infrastructure for Plant Phenomics on the Grid
- URL: http://www-sop.inria.fr/members/Didier.Parigot/pmwiki/Scifloware

6.14. WebSmatch

Web Schema Matching

KEYWORD: Data integration

FUNCTIONAL DESCRIPTION: WebSmatch is a flexible, open environment for discovering and matching complex schemas from heterogeneous Web data sources. It provides three basic functions: (1) metadata extraction from data sources, (2) schema matching, (3) schema clustering to group similar schemas together. WebSmatch is delivered through Web services, to be used directly by data integrators or other tools with RIA clients. It is implemented in Java, delivered as Open Source Software (under LGPL). WebSmatch has been used by Data Publica and CIRAD to integrate public and private data sources.

- Participants: Emmanuel Castanier, Patrick Valduriez and Rémi Coletta
- Contact: Patrick Valduriez
- Publication: WebSmatch: a tool for Open Data
- URL: http://websmatch.gforge.inria.fr/

7. New Results

7.1. Query Processing

7.1.1. 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 this work, we address the problem of top-k query processing over encrypted data. Top-k queries are important for many applications such as information retrieval, spatial data analysis, temporal databases, graph databases, etc. We consider two cases for top-k query processing over encrypted data: 1) centralized: the encrypted data are stored at a single node of a data center, which is useful if the database can fit at one node; 2) distributed: the encrypted data are partitioned and the partitions are encrypted and distributed across multiple nodes, which is useful if the database is very big.

In [52], we address the distributed case, and propose a system, called SD-TOPK, for top-k query processing over encrypted data distributed across several nodes of the cloud. SD-TOPK comes with a distributed top-k query processing algorithm that is executed in the nodes, and finds a set including the encrypted top-k data items. It also has an efficient filtering algorithm that removes most of the false positives included in the set returned by the top-k query processing algorithm. This filtering is done without needing to decrypt the data in the cloud.

In [51], we propose a complete system, called *BuckTop*, for the centralized case. BuckTop is able to efficiently evaluate top-k queries over encrypted data outsourced to a singe node, without having to decrypt it in that node. It includes a top-k query processing algorithm that works on the encrypted data stored in the cloud node, and returns a set that is proved to contain the encrypted data corresponding to the top-k results. We implemented BuckTop and compared its performance for processing top-k queries over encrypted data with that of the popular threshold algorithm (TA) over original (plaintext) data. The results show the effectiveness of BuckTop for outsourcing sensitive data in the cloud and answering top-k queries.

7.1.2. Privacy Preserving Index for Range Query Processing in the Clouds

Participants: Reza Akbarinia, Esther Pacitti.

During the last decade, a large body of academic work has tackled the problem of outsourcing databases to an untrusted cloud while maintaining both privacy and SQL-like querying functionality (at least partially). Range query is an important kind of query that expresses a bounded restriction over the retrieved records. In the database management systems, these queries are usually answered by using efficient indexes. However, developing privacy preserving indexes for untrusted environments is very challenging.

In [55], we propose a differentially private index to an outsourced encrypted dataset. Efficiency is enabled by using a plaintext index structure to perform range queries. Security relies on both differential privacy (of the index) and semantic security (of the encrypted dataset). Our solution, called PINED-RQ, develops algorithms for building and updating the differentially private index. Compared to state-of-the-art secure index based range query processing approaches, PINED-RQ executes queries in the order of at least one magnitude faster. The security of PINED-RQ is proved and its efficiency is assessed by an extensive experimental validation.

7.1.3. Constellation Queries to Analyze Geometrical Patterns

Participants: Dennis Shasha, Patrick Valduriez.

Constellation queries are useful to analyze geometrical patterns. A geometrical pattern is a set of points with all pairwise distances (or, more generally, relative distances) specified. Finding matches to such patterns, i.e. constellations, has applications to spatial data in seismic, astronomical, and transportation contexts. Finding geometric patterns is a challenging problem as the potential number of sets of elements that compose shapes is exponentially large in the size of the dataset and the pattern. In [53], we propose algorithms to find patterns in large data applications using constellation queries. Our methods combine quadtrees, matrix multiplication, and bucket join processing. Our distributed experiments show that the choice of the composition algorithm (matrix multiplication or nested loops) depends on the freedom introduced in the query geometry through the distance additive factor. Three clearly identified blocks of threshold values guide the choice of the best composition algorithm. Answering complex constellation queries, i.e. isotropic and non-isotropic queries, is challenging because scale factors and stretch factors may take any of an infinite number of values. In [53], we propose practically efficient sequential and distributed algorithms for pure, isotropic, and non-isotropic constellation queries. As far as we know, this is the first work to address isotropic and non-isotropic queries.

7.1.4. Parallel Polyglot Query Processing

Participants: Boyan Kolev, Oleksandra Levchenko, Esther Pacitti, Patrick Valduriez.

The blooming of different cloud data stores has turned polystore systems to a major topic in the nowadays cloud landscape. Especially, as the amount of processed data grows rapidly each year, much attention is being paid on taking advantage of the parallel processing capabilities of the underlying data stores. To provide data federation, a typical polystore solution defines a common data model and query language with translations to API calls or queries to each data store. However, this may lead to losing important querying capabilities. The polyglot approach of the CloudMdsQL query language allows data store native queries to be expressed as inline scripts and combined with regular SQL statements in ad-hoc integration queries. Moreover, efficient optimization techniques, such as bind join, can still take place to improve the performance of selective joins. In [47], we introduce the distributed architecture of the LeanXcale query engine that processes polyglot queries in the CloudMdsQL query language, yet allowing native scripts to be handled in parallel at data store shards, so that efficient and scalable parallel joins take place at the query engine level. The experimental evaluation of the LeanXcale parallel query engine on various join queries illustrates well the performance benefits of exploiting the parallelism of the underlying data management technologies in combination with the high expressivity provided by their scripting/querying frameworks

7.2. Scientific Workflows

7.2.1. In Situ Analysis of Simulation Data

Participants: Vitor Silva, Patrick Valduriez.

In situ analysis and visualization have been used successfully in large-scale computational simulations to visualize scientific data of interest, while data is in memory. Such data are obtained from intermediate (or final) simulation results, and once analyzed are typically stored in raw data files. However, existing in situ data analysis and visualization solutions (e.g. ParaView/Catalyst, VisIt) have limited online query processing and no support for dataflow analysis. The latter is a challenge for exploratory raw data analysis. In the context of the SciDISC associate team with Brazil [38], we propose a solution that integrates dataflow analysis with ParaView Catalyst for performing in-situ data analysis and monitoring dataflow from simulation runs [25].

In [21], we propose a solution (architecture and algorithms), called Armful, to combine the advantages of a dataflow-aware SWMS and raw data file analysis techniques to allow for queries on raw data file elements that are related but reside in separate files. Its main components are a raw data extractor, a provenance gatherer and a query processing interface, which are all dataflow-aware.

An instantiation of Armful is DfAnalyzer [34], a library of components to support online in-situ and in-transit data analysis. DfAnalyzer components are plugged directly in the simulation code of highly optimized parallel applications with negligible overhead. With support of sophisticated online data analysis, scientists get a detailed view of the execution, providing insights to determine when and how to tune parameters or reduce data that does not need to be processed [35]. The source code of the DfAnalyzer implementation for Spark is available on github (github.com/hpcdb/RFA-Spark).

7.2.2. Scheduling of Scientific Workflows in Multisite Cloud

Participants: Esther Pacitti, Patrick Valduriez.

In [30], we consider the problem of efficient scheduling of a large SWf in a multisite cloud, i.e. a cloud with geo-distributed cloud data centers (sites). The reasons for using multiple cloud sites to run a SWf are that data is already distributed , the necessary resources exceed the limits at a single site, or the monetary cost is lower. In a multisite cloud, metadata management has a critical impact on the efficiency of SWf scheduling as it provides a global view of data location and enables task tracking during execution. Thus, it should be readily available to the system at any given time. While it has been shown that efficient metadata handling plays a key role in performance, little research has targeted this issue in multisite cloud. Then we propose to identify and exploit hot metadata (frequently accessed metadata) for efficient SWf scheduling in a multisite cloud, using a distributed approach. We implemented our approach within a scientific workflow management system, which shows that our approach reduces the execution time of highly parallel jobs up to 64% and that of the whole SWfs up to 55%.

7.2.3. Distributed Management of Scientific Workflows for Plant Phenotyping

Participants: Gaetan Heidsieck, Christophe Pradal, Esther Pacitti, Patrick Valduriez.

In the last decade, high-throughput phenotyping platforms have allowed acquisition of quantitative data on thousands of plants required for genetic analyses in well-controlled environmental conditions.The seven facilities of Phenome produce 200 terabytes of data annually, which are heterogeneous (images, time courses), multiscale (from the organ to the field) and originate from different sites. Hence, the major problem becomes the automatic analysis of these massive datasets and the ability to reproduce large and complex in-silico experiments.

In [31], we propose a solution (infrastructure) to distribute the computation of scientific workflows on very large grid computing facilities (EGI/France Grilles) to the 3D reconstruction, segmentation and tracking of plant organs. This infrastructure, InfraPhenoGrid, is based on OpenAlea, SciFloware and SON, a set of software and technology developed in the team. We have used this solution in [27] to dissect the genetic and environmental influence of biomass accumulation in complex multi-genotype maize canopies.

7.3. Data Analytics

7.3.1. 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 [36], we consider the problem of finding highly correlated pairs of time series across multiple sliding windows. Doing this efficiently and in parallel could help in applications such as sensor fusion, financial trading, or communications network monitoring, to name a few. We have developed a parallel incremental random vector/sketching approach, called ParCorr, to this problem and compared it with the state-of-the-art nearest neighbor method iSAX. Whereas iSAX achieves 100% recall and precision for Euclidean distance, the sketching approach is, empirically, at least 10 times faster and achieves 95% recall and 100% precision on real and simulated data. For many applications this speedup is worth the minor reduction in recall. Our method scales up to 100 million time series and scales linearly in its expensive steps (but quadratic in the less expensive ones).

In [48], we propose a demonstration of our sketch-based solution to efficiently perform both the parallel indexing of large sets of time series and a similarity search on them. Because our method is approximate, we explore the tradeoff between time and precision. A video showing the dynamics of the demonstration can be found at http://parsketch.gforge.inria.fr/video/parSketchdemo_720p.mov.

7.3.2. Parallel Mining of Maximally Informative k-Itemsets in Data Streams

Participants: Mehdi Zitouni, Reza Akbarinia, Florent Masseglia.

The discovery of informative itemsets is a fundamental building block in data analytics and information retrieval. While the problem has been widely studied, only few solutions scale. This is particularly the case when the dataset is massive, or the length k of the informative itemset to be discovered is high.

In [63], we address the problem of mining maximally informative k-itemsets (miki) in data streams based on joint entropy. We propose PentroS, a highly scalable parallel miki mining algorithm. PentroS renders the mining process of large volumes of incoming data very efficient. It is designed to take into account the continuous aspect of data streams, particularly by reducing the computations of need for updating the miki results after arrival/departure of transactions to/from the sliding window. PentroS has been extensively evaluated using massive real-world data streams. Our experimental results confirm the effectiveness of our proposal which allows excellent throughput with high itemset length.

7.3.3. Spatio-Temporal Data Mining

Participants: Esther Pacitti, Florent Masseglia.

The problem of discovering spatiotemporal sequential patterns affects a broad range of applications. Many initiatives find sequences constrained by space and time. We address in [40] an appealing new challenge for this domain: find tight space-time sequences, i.e., find within the same process: i) frequent sequences constrained in space and time that may not be frequent in the entire dataset and ii) the time interval and space range where these sequences are frequent. The discovery of such patterns along with their constraints may lead to extract valuable knowledge that can remain hidden using traditional methods since their support is extremely low over the entire dataset. Our contribution is a new Spatio-Temporal Sequence Miner (STSM) algorithm to discover tight space-time sequences.

7.4. Machine Learning for High-dimensional Data

7.4.1. Uncertainty in Fine-grained Classification

Participants: Titouan Lorieul, Alexis Joly.

Uncertainty is critical when considering classification problems that involve thousands of domain specific labels. A picture of a plant, for instance, contains only a partial information that is usually not sufficient to determine its scientific name with certainty. We first work on the modelling of such uncertainty in the context of crowdsourcing systems involving experts as well as non expert annotators. We rely on Bayesian inference to learn the annotators' confusion and to optimally assign them new items to be validated. In particular, we work on a non-parametric version of this model allowing to combine annotators' suggestions even when the number of possible labels is undetermined and might change over time [33]. In mirror to this research, we also work on the uncertainty of automatic classifiers, in particular deep convolutional neural networks trained on massive amounts of plant images. We conduct an experimental study aimed at evaluating quantitatively the intrinsic data ambiguity of image-based plant observations [64], and we started working on new methods for estimating the uncertainty of ensembles of deep neural networks by fitting a Dirichlet distribution on the set of their predictions. Besides, we study the use of different taxonomic levels as a source of potential reduction in prediction uncertainties [66].

7.4.2. Species Distribution Modelling based on Citizen Science Data

Participants: Christophe Botella, Alexis Joly.

Species distribution models (SDM) are widely used for ecological research and conservation purposes. Given a set of species occurrence, the aim is to infer its spatial distribution over a given territory. Because of the limited number of occurrences of specimens, this is usually achieved through environmental niche modeling approaches, i.e. by predicting the distribution in the geographic space on the basis of a mathematical representation of their known distribution in environmental space (= realized ecological niche). The environment is in most cases represented by climate data (such as temperature, and precipitation), but other variables such as soil type or land cover can also be used. In [24], we study for the first time the relevance of a species distribution model computed from automatically identified plant observations made by citizens rather than from classical inventories made by experts. The results show that the resulting models have a great potential for the early detection of new invasions. In [65] and [60], we propose a deep learning approach to species distribution modelling in order to improve the predictive effectiveness in the context of massive amount of occurrence data. Non-linear prediction models have been of interest for SDM for more than a decade but our study is the first one bringing empirical evidence that deep, convolutional and multilabel models might participate to resolve the limitations of SDM.

7.4.3. Evaluation of Species Identification and Prediction Algorithms

Participants: Alexis Joly, Hervé Goëau, Christophe Botella, Jean-Christophe Lombardo.

We ran a new edition of the LifeCLEF evaluation campaign [45] with the involvement of 13 research teams worldwide. The main novelties and outcomes of the 2018-th edition are the following:

- **GeoLifeCLEF**: a new challenge [71] dedicated to the location-based prediction of species based on spatial occurrences and environmental data tensors. The evaluation concludes that deep environmental convolutional neural networks perform better than spatial models or ponctual environmental models.
- **Man vs. Machine plant identification**: To evaluate how far automated identification systems are from the best possible performance, we organize a challenge involving 19 deep-learning systems implemented by 4 different research teams and 9 of the best expert botanists of the French flora. The main outcome of this work is that the performance of state-of-the-art deep learning models is now very close to the most advanced human expertise.
- **Bird sounds identification**: the 2018-the edition of the BirdCLEF challenge reveals impressive identification performance when considering bird sounds recorded by the Xeno-Canto community. Identifying birds in raw, multi-directional soundscapes, however, remains a very challenging task.

7.4.4. Towards the Recognition of The World's Flora: When HPC Meets Deep Learning

Participants: Hervé Goëau, Jean-Christophe Lombardo, Alexis Joly.

Automated identification of plants and animals have improved considerably in the last few years, in particular thanks to the recent advances in deep learning. In 2017, a challenge on 10,000 plant species (PlantCLEF) resulted in impressive performances with accuracy values reaching 90%. One of the most popular plant identification application, Pl@ntNet, nowadays works on 18K plant species. It accounts for million of users all over the world and already has a strong societal impact in several domains including education, landscape management and agriculture. Now, the big challenge is to train such systems at the scale of the world's biodiversity. Therefore, we built a training set of about 12M images illustrating 300K species of plants. Training a convolutional neural network on such a large dataset can take up to several months on a single node equipped with four recent GPUs. Moreover, to select the best performing architecture and optimize the hyper-parameters, it is often necessary to train several of such networks. Overall, this becomes a highly intensive computational task that has to be distributed on large HPC infrastructures. Therefore, we experiment two french national supercomputers through an access offered by GENCI (Occigen@CINES, a 3.5 Pflop/s Tier-1 cluster based on Broadwell-14cores@2.6Ghz nodes and Joliot-Curie»@TGCC, a BULL-Sequana-X1000 cluster integrating 1656 nodes Intel Skylake8168-24cores@2.7GHz). To implement the synchronized stochastic gradient descent on the CPU cluster Joliot-Curie, we are using the deep learning framework Intel CAFFE coupled with Intel MLSL library (in the context of a collaboration with Intel).

7.4.5. Evaluation of Music Separation Techniques

Participants: Antoine Liutkus, Fabian-Robert Stöter.

After the groundbreaking advent of deep learning, we feel the music processing community needs to step back and think about what had been accomplished and what remains challenging in the problems of musical signal processing and filtering. Therefore, we give a complete overview of the state of the art in music demixing in [32] comprising more than 350 references, as well as two chapters in dedicated books [68], [67]. These references may be considered as complete overviews of the state of the art in music demixing. Furthermore, we introduce the topic to non-expert researchers and engineers in [26].

Apart from this effort in presenting the most recent advances in music processing to the community, we organize yearly a systematic evaluation of state of the art. We report the results of the 2018 Signal Separation Evaluation Campaign in [58], gathering a record number of participants. A perceptual evaluation of the results obtained through this campaign is presented in [59], in collaboration with researchers from the Surrey University.

7.4.6. Robust Probabilistic Models for Time-series

Participants: Antoine Liutkus, Fabian-Robert Stöter.

Processing large amounts of data for denoising or analysis comes with the need to devise models that are robust to outliers and that permit efficient inference. For this purpose, we advocate the use of non-Gaussian models for this purpose, which are less sensitive to data-uncertainty. Most of our effort on this topic is split in two subtasks.

First, we develop new filtering methods that go beyond least-squares estimation. In collaboration with researchers from RWTH, Aachen, Germany, we introduce a new model based on mixtures of Gaussians for filtering in [50]. It combines tractability with a better account of phase consistency for complex data. Along with researchers from IRISA, Rennes and Telecom ParisTech, we also work on filtering α-stable processes [44], [46], [57], which enjoy important applications in robust signal processing.

Second, we work on large amounts of musical archives. This includes an original way to scale up interference reduction in live musical recordings in collaboration with the managers of the Montreux Jazz Festival data at EPFL (Switzerland).

8. Bilateral Contracts and Grants with Industry

8.1. SAFRAN (2018)

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).

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. Labex NUMEV, Montpellier

URL: http://www.lirmm.fr/numev

We participate in the Laboratory of Excellence (labex) NUMEV (Digital and Hardware Solutions, Modelling for the Environment and Life Sciences) headed by University of Montpellier in partnership with CNRS, and Inria. NUMEV seeks to harmonize the approaches of hard sciences and life and environmental sciences in order to pave the way for an emerging interdisciplinary group with an international profile. The project is decomposed in four complementary research themes: Modeling, Algorithms and computation, Scientific data (processing, integration, security), Model-Systems and measurements.

9.1.2. Institute of Computational Biology (IBC), Montpellier

URL: http://www.ibc-montpellier.fr

IBC is a 6 year project (2012-2018) with a funding of 2Meuros by the MENRT (PIA program) to develop innovative methods and software to integrate and analyze biological data at large scale in health, agronomy and environment. Patrick Valduriez heads the workpackage on integration of biological data and knowledge.

9.2. National Initiatives

9.2.1. Institut de Convergence Agriculture numérique #DigitAg, (2017-2023), 275Keuro.

Participants: 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.

9.2.2. PIA (Projets Investissements d'Avenir) Floris'Tic (2015-2018), 430Keuro.

Participants: Antoine Affouard, Jean-Christophe Lombardo, Hervé Goëau, Alexis Joly.

Floris'tic aims at promoting the scientific and technical culture of plant sciences through innovative pedagogic methods, including participatory initiatives and the use of IT tools such as the one built within the Pl@ntNet project. A. Joly heads the work package on the development of the IT tools. This is a joint project with the AMAP laboratory, the TelaBotanica social network and the Agropolis foundation.

9.2.3. ANR WeedElec (2018-2021), 106 Keuro.

Participants: Jean-Christophe Lombardo, 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.

9.2.4. Others

9.2.4.1. INRA/Inria PhD program, 100Keuros

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).

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. 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
Partner: Europe: 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. The cloud database appliance features: (i) a scalable operational database able to process high update workloads such as the ones processed by banks or telcos, combined with a fast analytical engine able to answer analytical queries in an online manner; (ii) an operational Hadoop data lake that integrates an operational database with Hadoop, so operational data is stored in Hadoop that will cover the needs from companies on big data; (iii) a cloud hardware appliance leveraging the next generation of hardware to be produced by Bull, the main European hardware provider. This hardware is a scale-up hardware similar to the one of mainframes but with a more modern architecture. Both the operational database and the in-memory analytics engine will be optimized to fully exploit this hardware and deliver predictable performance. Additionally, CloudDBAppliance will tolerate catastrophic cloud data centres failures (e.g. a fire or natural disaster) providing data redundancy across cloud data centres. In this project, Zenith is in charge of designing and implementing the components for analytics and parallel query processing.

9.4. International Initiatives

9.4.1. Inria Associate Teams Not Involved in an Inria International Labs

9.4.1.1. 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.

9.4.2. Inria International Partners

9.4.2.1. 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), Vikram Salatore (Manager of Artificial Intelligence Products Group at Intel Corporation).
- Asia: National Univ. of Singapore (Beng Chin Ooi, Stéphane Bressan), Wonkwang University, Korea (Kwangjin Park), Kyoto University (Japan)
- 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)
- 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)

9.4.3. Participation in Other International Programs

BD-FARM

Title: Big Data Management and Analytics for Agriculture and Farming

International Partner (Institution - Laboratory - Researcher):

Chubu University - International Digital Earth Applied Science Research Center (IDEAS), Kiyoshi Honda

Duration: 2016 - 2018

Start year: 2016

See also: https://team.inria.fr/zenith/bdfarm-2016-2018-stic-asia/

World population is still growing and people are living longer and older. World demand for food rises sharply and current growth rates in agriculture are clearly not sufficient. But extreme flood, drought, typhoon etc, caused by climate change, give severe damages on traditional agriculture. Today, an urgent and deep redesign of agriculture is crucial in order to increase production and to reduce environmental impact. In this context, collecting, managing and analyzing dedicated, large, complex, and various datasets (Big Data) will allow improving the understanding of complex mechanisms behind adaptive, yield and crop improvement. Moreover, sustainability will require detailed studies such as the relationships between genotype, phenotype and environment. In other words, data science and ICT for agriculture must help improving production. Moreover, it has to be done while getting properly adapted to soil, climatic and agronomic constraints as well as taking into account the genetic specificities of plants.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

Several international scientists visited the team and gave seminars

- Vitor Silva (COPPE/UFRJ,Brazil): “A methodology for capturing and analyzing dataflow paths in computational simulations” on January 31.
- Dennis Shasha (NYU): “Reducing Errors by Refusing to Guess (Occasionally)” on June 1.
- Daniel de Oliveira (UFF, Brazil): “Parameter and Data Recommendation in Scientific Workflows based on Provenance” on June 5.
- Eduardo Ogasawara, (CEFET-RJ, Brazil): “Comparing Motif Discovery Techniques with Sequence Mining in the Context of Space-Time Series” on November 26.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

- P. Valduriez: general chair of the VLDB Latin America Data Science Workshop (LaDAS@VLDB 2018)
- P. Valduriez: scientific chair, First Data Science School, IMSP, Django, Bénin

10.1.1.2. Member of the Organizing Committees

- A. Joly: organizing committee of the international conference CLEF 2018 and the chair of the LifeCLEF track, Avignon, sept. 2018 (http://clef2018.clef-initiative.eu/)

- A. Joly: organizing committee of the Floris'tic national workshop held in Montpellier, nov. 2018 (http://floristic.org/journeefloristic/)
- A. Liutkus: organizer of the 2018 Signal Separation Evaluation Campaign (https://sisec18.unmix.app/)
- F. Masseglia: finance chair of IEEE ICDE 2018 (https://icde2018.org)
- F. Masseglia: organization commitee of the Inria Science Days 2018 (https://www.inria.fr/en/news/news-from-inria/inria-science-days-2018)
- P. Valduriez: sponsor co-chair of IEEE ICDE 2018 (https://icde2018.org)
- P. Valduriez: sponsor co-chair of VLDB 2018 (https://vldb2018.lncc.br)

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

- A. Joly: area chair of ACM Multimedia 2018 (http://www.acmmm.org/2018)
- E. Pacitti: PC chair of the VLDB workshop on Big Social Data and Urban Computing (BiDU@VLDB 2018)

10.1.2.2. Member of the Conference Program Committees

- ACM/SIGAPP Symposium On Applied Computing (ACM SAC) Data Mining track, 2018: F. Masseglia
- IEEE International Conference on Data Mining (IEEE ICDM), 2018: F. Masseglia
- International Joint Conference on Artificial Intelligence (IJCAI), "Sister Conference Best Paper Track", 2018: F. Masseglia
- International Symposium on Methodologies for Intelligent Systems (ISMIS), 2018: F. Masseglia
- Pacific-Asia Conference on Advances in Knowledge Discovery and Data Mining (PAKDD), 2018: F. Masseglia
- European Conference on Machine Learning and Principles and Practice of Knowledge Discovery in Databases (PKDD), 2018: F. Masseglia
- IEEE Artificial Intelligence and Knowledge Engineering (IEEE AIKE), 2018: F. Masseglia
- International Conference on Information Management and Big Data (SIMBig), 2018: F. Masseglia
- International Conference on Data Science, Technology and Applications (DATA), 2018: F. Masseglia
- International Conference on Very Large Data Bases (VLDB), 2018: R. Akbarinia
- International Workshop on Big Data Management in Cloud Systems, 2018: R. Akbarinia
- Int. Conf. on Extending DataBase Technologies (EDBT), 2019: E. Pacitti
- Int. Conf. on Multimedia Retrieval (ICMR), 2018: A. Joly
- Int. Conf. on Acoustics, Speech, and Signal Processing (ICASSP), 2018: A. Joly
- Int. Conf. on Computer Vision (CVPR), 2018: A. Joly
- Int. Conf. and Labs of the Evaluation Forum (CLEF), 2018: A. Joly
- European. Conf. on Information Retrieval (ECIR), 2019: A. Joly
- Conférence sur la Gestion de Données – Principes, Technologies et Applications (BDA 2018): F. Masseglia, E. Pacitti

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- VLDB Journal: P. Valduriez.
- Journal of Transactions on Large Scale Data and Knowledge Centered Systems: R. Akbarinia.

- Distributed and Parallel Databases, Kluwer Academic Publishers: E. Pacitti, P. Valduriez.
- Book series “Data Centric Systems and Applications” (Springer): P. Valduriez.
- Multimedia Tools and Applications: A. Joly.
- Plant Methods: C. Pradal.

10.1.3.2. Reviewer - Reviewing Activities

Reviewing in international journals :

- Distributed and Parallel Databases (DAPD): R. Akbarinia, E. Pacitti, P. Valduriez
- IEEE Transactions on Knowledge and Data Engineering (TKDE): R. Akbarinia, F. Masseglia
- VLDB Journal: R. Akbarinia
- ACM Transactions on Database Systems (TODS): A. Joly
- IEEE Transactions on Pattern Analysis and Machine Intelligence (PAMI): A. Joly
- Information Sciences: A. Joly
- Ecological Informatics: A. Joly
- Multimedia Tools and Applications Journal (MTAP): A. Joly
- Multimedia Systems: A. Joly
- Transactions on Information Forensics & Security: A. Joly
- International Journal of Computer Vision: 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
- Frontiers in Plant Science: C. Pradal

10.1.4. Invited Talks

- A. Joly: keynote talk on "Towards The Recognition of the World’s Flora: When HPC Meets Deep Learning" at Digital Infrastructures 2018 on Oct. 10
- A. Joly: keynote talk on "The Recognition of the World’s Flora" at Terratec 2018
- A. Liutkus: tutorial on music source separation at the International Symposium on Music Information Retrieval (ISMIR 2018).
- F. Masseglia: talk on "Massively Distributed Data Analytics", IRISA (Lacodam team), April 2018
- F. Masseglia: talk on "Massively Distributed Time Series Indexing and Querying", LIMOS, December 2018
- P. Valduriez: keynote talk on "Blockchain 2.0: opportunities and risks" on 29 may at Africatek 2018, Cotonou, Bénin, on 25 october at BDA 2018, Bucharest, Romania, and on 19 december at Colloquim COPPE/UFRJ, Rio de Janeiro
- C. Pradal: keynote talk on "OpenAlea : an open source project for plant modelling at different scales", August 2018, Crops in Silico Symposium, NCSA, Univ. Illinois, USA.
- C. Pradal: keynote talk on "OpenAlea : a modular platform for multiscale plant modelling", April 2018, EGU 2018, Vienna, Austria.

10.1.5. Leadership within the Scientific Community

- A. Joly: scientific manager of the LifeCLEF and Pl@ntNet research platforms

- A. Liutkus: elected member of the IEEE Technical Committee on Audio and Acoustic Signal Processing
- 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)
- P. Valduriez: President of the Steering Committee of the BDA conference

10.1.6. Scientific Expertise

- R. Akbarinia, F. Masseglia: reviewer for international programs (STIC AmSud, ECOS SUD).
- R. Akbarinia: expert for the French National Research Agency (ANR).
- A: Joly: reviewer for STIC AmSud international program
- F. Masseglia: scientific referent for Inria on the frame agreement with SAFRAN about "System Monitoring and Data Analytics"
- E. Pacitti: reviewer for STIC AmSud international program
- P. Valduriez: reviewer for STIC AmSud international program
- P. Valduriez: reviewer for NSERC (Canada)
- C. Pradal: reviewer for STIC AmSud international program
- C. Pradal: member of CSS EGBIP (Commissions Scientifiques Spécialisées) INRA

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, UM2

IG4: Object-relational databases, 32h, level M1, Polytech’ Montpellier, UM2

IG5: Distributed systems, virtualization, 27h, level M2, Polytech’ Montpellier, UM2

Industry internship committee, 50h, level M2, Polytech’ Montpellier

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

10.2.2. Supervision

PhD & HdR:

PhD : Vitor Silva, Analysis of raw data from multiple data sources during the execution of computational simulations, started 2014, UFRJ, Brazil, June 2018. Advisors: Marta Mattoso (UFRJ), Daniel Oliveira (UFF), Patrick Valduriez

PhD : Sakina Mahboubi, Privacy Preserving Top-k Query Processing over Outsourced Data, Univ. Montpellier, Nov. 21, 2018. Advisors: Reza Akbarinia, Patrick Valduriez.

PhD : Djamel-Edine Yagoubi, Massive distribution for indexing and mining time series, Univ. Montpellier, March 12, 2018. Advisors: Reza Akbarinia, Florent Masseglia, Themis Palpanas (Univ Paris Descartes).

PhD : Mehdi Zitouni, Parallel Itemsets Mining in Massively Distributed Environments, Univ. Tunis, Dec. 5, 2018. Advisors: Reza Akbarinia, Florent Masseglia, Sadok Ben Yahia (Univ Tunis).

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: Christophe Botella, Large-scale Species Distribution Modelling based on crowd-srouced image streams, started Oct 2016, Univ. Montpellier. Advisors: Alexis Joly, François Munoz (IRD), Pascal Monestiez (INRA).

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: Renan Souza, Massively Distributed Clustering, started 2015, UFRJ, Brazil. Advisors: Marta Mattoso (UFRJ), Daniel Oliveira (UFF), Patrick Valduriez.

PhD in progress: Mathieu Fontaine, Alpha-stable models for signal processing, started 2016, IAEM, Nancy, France. Advisors: Roland Badeau (Telecom ParisTech), Antoine Liutkus.

10.2.3. Juries

Members of the team participated to the following PhD or HDR committees:

- R. Akbarinia: Sakina Mahboubi (Univ. Montpellier, advisor), Djamel-Edine Yagoubi (Univ. Montpellier, advisor)
- A. Joly: Lee Sue Han (Univ. of Malaya)
- F. Masseglia: Yann Dauxais (Univ. Rennes), Steeve Vanel-Siyou (Univ. Clermont-Ferrand, reviewer), Marc Plantevit (HDR, Univ. Lyon, reviewer), Djamel-Edine Yagoubi (Univ. Montpellier, advisor)
- E. Pacitti: Abdoul Macine (Univ. Nice, reviewer)
- P. Valduriez: Louis Jachiet (Univ. Grenoble), Ovidiu-Cristian Marcu (Univ. Rennes 1, reviewer), Vitor Silva (UFRJ, Rio de Janeiro, advisor), Sakina Mahboubi (Univ. Montpellier, advisor), Yania Molina Souto (LNCC, Rio de Janeiro, reviewer)

Members of the team participated to the following hiring committees:

- A. Joly: associate professor position, Univ. Toulon
- F. Masseglia: Inria ARP/SRP; full professor position, INSA, Lyon

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 (https://www.inria.fr/recherches/mediation-scientifique/actions-de-mediation-scientifique/presentation)

10.3.2. Articles and contents

Alexis Joly participated to the realization of a report on "Deep Learning and Agriculture" edited by the AgroTIC chair (https://www.agrotic.org/). He co-authored on article on data collection in citizen science projects [37].

10.3.3. Education

Teaching code is now officially in the school programs in France. Class'Code is a PIA project that aims at training the needed 300,000 teachers and professionals of education France. The project is a hybrid MOOC (both online courses and physical meetings). Florent Masseglia is co-author of the first course and scientific referent of the other courses.

Along with Class'Code, the association “La main à la pâte” has coordinated the writing of a school book on the teaching of computer science teaching, with Inria (Gilles Dowek, Pierre-Yves Oudeyer, Florent Masseglia and Didier Roy), France-IOI and the University of Lorraine. The book has been requested by and distributed to 15,000 readers in less than one month. The extension of this book for the French "Collège" has been released in 2017 with new activities and new scientific content.

F. Masseglia is giving a doctoral training at different doctoral schools in Montpellier, in order to train facilitators for helping teachers and people of the education world to better understand the "computational thinking". So far, 14 people have been trained.

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 December 11.

F. Masseglia is member of the pedagogic committee of "Edu'up", a project from France-IOI on learning code and computational thinking.

F. Masseglia gave a one day training session to school teachers in Créteil, on October 3.

Alexis Joly gave about 15 hours of professional training in the use of digital tools for environmental education (Pl@ntNet, ThePlantGame and Smart'Flore).

10.3.4. Interventions

Zenith participated to the following events:

- F. Masseglia co-organized the regional Code-Week events with the local network of media-library ("réseau des médiathèques de Montpellier Méditerranée Métropole").
- F. Masseglia is member of the project selection committee for “La fête de la science” in Montpellier.
- F. Masseglia animated a stand at the "semaine de la mémoire" event organized by Genopolys (September 20&21).
- F. Masseglia participated in a class visit, at Saussan, with Charles Torossian (co-author of the "Vallani-Torossian" report) and the rectrice, about code teaching.

10.3.5. Internal action

F. Masseglia organized, and participated to, a 2 days training session on the Poppy Ergo Jr robot (June 25&26).

10.3.6. 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, to be announced officially in January 2019, provides support for education to computer science from the history point of view.

11. Bibliography

Major publications by the team in recent years

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