Activity Report Sophia Antipolis - Méditerranée 2016

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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

Keywords:

Computer Science and Digital Science:

2.5. - Software engineering
3.3.2. - Data mining
3.4.1. - Supervised learning
3.4.2. - Unsupervised learning
6.1.4. - Multiscale modeling
6.2.4. - Statistical methods
6.2.8. - Computational geometry and meshes
7.2. - Discrete mathematics, combinatorics
7.5. - Geometry, Topology
7.9. - Graph theory
8.2. - Machine learning

Other Research Topics and Application Domains:

1.1.1. - Structural biology
1.1.7. - Immunology
1.1.9. - Bioinformatics

1. Members

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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 [48]. 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.

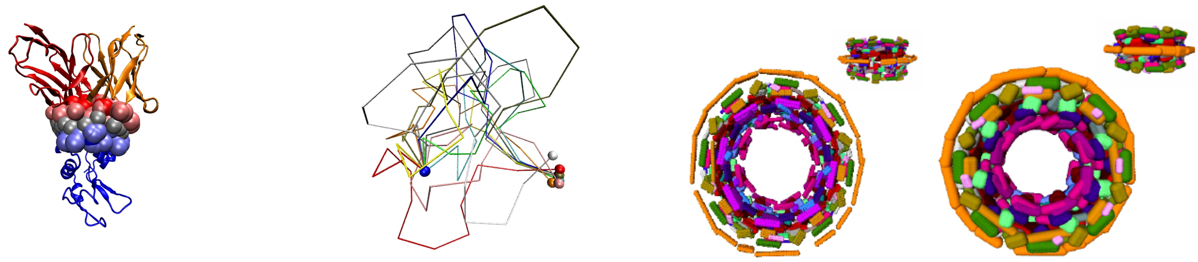
Modeling in Computational Structural Biology. Acquiring structural data is not always possible: NMR is restricted to relatively small molecules; membrane proteins do not crystallize, etc. As a matter of fact, the order of magnitude of the number of genomes sequenced is of the order of one thousand, which 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 [46], [35] and later Connolly [31], 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) [37], 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 [6]. 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 [48]. Yet, in spite of almost three decades of investigations, the basic principles guiding the formation of interfaces and accounting for its stability are unknown [51]. Current investigations follow two routes. From the experimental perspective [34], directed mutagenesis enables one to quantify the energetic importance of residues, important residues being termed *hot* residues. Such studies recently evidenced the *modular* architecture of interfaces

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

[45]. From the modeling perspective, the main issue consists of guessing the hot residues from sequence and/or structural informations [40].

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 [29], 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 [49], [36]. 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 [41]. 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 [30]. At the atomic level and in spite of recent observations on the local structure of the neighborhood of a given atom [50], 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 [33].

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 [44]. More generally, any significant observation raised in the static setting deserves investigations in the dynamic setting, so as to assess its stability. Such questions are also related to the problem of correlated motions, which we discuss next.

3.3. Modeling macro-molecular assemblies

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

3.3.1. Reconstruction by Data Integration

Large protein assemblies such as the Nuclear Pore Complex (NPC), chaperonin cavities, the proteasome or ATP synthases, to name a few, are key to numerous biological functions. To improve our understanding of these functions, one would ideally like to build and animate atomic models of these molecular machines. However, this task is especially tough, due to their size and their plasticity, but also due to the flexibility of the proteins involved. In a sense, the modeling challenges arising in this context are different from those faced for binary docking, and also from those encountered for intermediate size complexes which are often amenable to a processing mixing (cryo-EM) image analysis and classical docking. To face these new challenges, an emerging paradigm is that of reconstruction by data integration [28]. 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 [27], the largest assembly known to date in the eukaryotic cell, and consisting of 456 protein *instances* of 30 *types*.

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

3.3.2. Modeling with Uncertainties and Model Assessment

Reconstruction by data integration requires three ingredients. First, a parametrized model must be adopted, typically a collection of balls to model a protein with pseudo-atoms. Second, as in NMR, a functional measuring the agreement between a model and the data must be chosen. In [26], 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 [26]. Interestingly, averaging the positions of all balls of a particular protein type across these models resulted in 30 so-called *probability density maps*, each such map encoding the probability of presence of a particular protein type at a particular location in the NPC. Second, the assessment of all models (individual and averaged) is non trivial. In particular, the lack of straightforward statistical analysis of the individual models and the absence of assessment for the averaged models are detrimental to the mechanistic exploitation of the reconstruction results. At this stage, such models therefore remain qualitative.

3.4. Modeling the flexibility of macro-molecules

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

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

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

At the side-chain level, the question of improving rotamer libraries is still of interest [32]. 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) [47]. 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 [43], to Morse theory [38] and to analysis of meta-stable states of time series [39] have been proposed.

3.5. Algorithmic foundations

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

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

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

3.5.1. Modeling Interfaces and Contacts

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

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

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

3.5.2. Modeling Macro-molecular Assemblies

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

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

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

3.5.3. Modeling the Flexibility of Macro-molecules

Given a sampling on an energy landscape, a number of fundamental issues actually arise: how does the point cloud describe the topography of the energy landscape (a question reminiscent from Morse theory)? Can one infer the effective number of degrees of freedom of the system over the simulation, and is this number varying? Answers to these questions would be of major interest to refine our understanding of folding and docking, with applications to the prediction of structural properties. It should be noted in passing that such questions are probably related to modeling phase transitions in statistical physics where geometric and topological methods are being used [42].

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 [7]. 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. Highlights of the Year

4.1. Highlights of the Year

In 2016, several achievements are worth noticing in three realms, namely in computer science, computational structural biology, and software.

4.1.1. Computer Science

► **Optimal transportation problems with connectivity constraints**
Reference: [21]

In a nutshell: Optimal transportation theory provides a rich framework to compare *measures*, both in the continuous and discrete settings. In this work, we study generalization of discrete transportation problems, when the supply and demand nodes are endowed with a graph structure; due to these constraints, our study focuses on transport plans respecting selected connectivity constrains. Our contributions encompass a formalization of these problems, as well as hardness results and heuristic algorithms.

Assessment: To the best of our knowledge, this work is the first one focusing on transport plans with connectivity constraints. One of the key applications targeted is the comparison of potential energy landscapes (PEL) in biophysics. Our algorithms provide a novel way to compare PEL, a topic overlooked so far.

► **Clustering stability revealed by matchings between clusters of clusters**
Reference: [22]

In a nutshell: Clustering is a fundamental problem in data science, yet, the variety of clustering methods and their sensitivity to parameters make clustering hard. This work provides a new tier of methods to compare two clusterings, by computing meta-clusters within each clustering– a meta-cluster is a group of clusters, together with a matching between these.

Assessment: Our methods will help assess the coherence between two clusterings, in two respects: by stressing the (lack of) stability of clustering while varying the parameters of a given algorithm, and by allowing a detailed comparisons of various algorithms.

4.1.2. Computational Structural Biology

► **Novel structural parameters of Ig-Ag complexes yield a quantitative description of interaction specificity and binding affinity**
Reference: [23]

In a nutshell: Understanding the specificity of antibodies for the targeted antigens, and predicting the affinity an antibody - antigen complexes is a central question in structural immunology. Using novel parameters acting as proxys for important biophysical quantities, we obtained affinity predictions of unprecedented accuracy, and were able to provide a quantitative explanation for the specific role of so-called *complementarity determining regions* – in particular CDR3 of heavy chains. See details in section 6.1.2.

Assessment: Our affinity predictions are the most accurate known to date, and show that for certain classes of IG - Ag complexes, the affinity prediction problem may be solved from databases of high resolution crystal structures.

► **Energy landscapes and persistent minima**
Reference: [15]

In a nutshell: Potential energy landscapes (PEL) of molecular systems are complex high-dimensional height functions. In this work, we introduced several tools from graph theory, optimization, and computational topology, so as to identify prominent features of PEL – prosaically distinguishing the signal from the noise. See details in section 6.3.1.

Assessment: Our work calls for important developments in two directions. The first one is concerned with the *calibration / learning* of features of PEL. The second one is the systematic comparison of force fields used in biophysics, as from current knowledge, deciding which force field is best for a given task or system is an open issue.

► **Hybridizing rapidly growing random trees and basin hopping yields an improved exploration of energy landscapes**
Reference: [18]

In a nutshell: We developed a novel exploration algorithm for high-dimensional non convex (potential) energy functions used in biophysics. Our algorithm exploits the ability of *basin hopping* to locate low-lying local minima, and that of *rapidly exploring random tree* to foster the exploration of yet unexplored regions. See details in section 6.3.2.

Assessment: Our exploration algorithm outperform the two classical algorithms it is derived from. To strike a major impact, though, our exploration strategy needs to be complemented by enhanced thermodynamic sampling algorithms, able to bridge the gap between structures on the one hand, and thermodynamics / dynamics on the other hand.

4.1.3. Software

► **The Structural Bioinformatics Library**
Reference: [20]

In a nutshell: The SBL was released in 2015. In 2016, two important milestones were achieved, with the addition of several important packages, notably geared towards the generation and the analysis of conformational ensembles, and the publication of [20]–to appear in Bioinformatics.

Assessment: As outlined by the reviewers of [20], the SBL is to the best of our knowledge the first library proposing a coherent framework, in terms of algorithms, data structures and biophysical models, to tackle the most important problems in structural bioinformatics. Our paper presenting the SBL being in press as of December 2016, statistics on users and downloads will be reported in the 2017 activity report.

5. New Software and Platforms

5.1. The Structural Bioinformatics Library

5.1.1. The SBL : overview

The `SBL` (http://sbl.inria.fr) is a generic C++/python library providing algorithms and applications to solve complex problems in computational structural biology (CSB). [20].

For Biologists, the key advantages are:

- comprehensive in silico environment providing software applications,
- answering complex bio-physical problems (modeling interfaces and contacts, modeling the flexibility of proteins, and modeling macro-molecular assemblies),
- in a robust, fast and reproducible way.

For Developers, the striking facts are:

- broad C++/python toolbox,
- with modular design and careful specifications,
- fostering the development of complex applications.

5.1.2. The SBL : rationale and design

Software development generally faces a dichotomy, with on the one hand generic libraries providing methods of ubiquitous interest, and on the other hand application driven libraries targeting specific application areas. Libraries in the former category typically provide state-of-the art low level algorithms carefully specified, at the detriment of high level applications. Libraries in the latter category are generally high level and user-friendly, but the lack of formalism often makes it difficult to couple them to low level algorithms with formal specifications. The `SBL` ambitions to reconcile both software development philosophies, based on an advanced design suited for all classes of users and developers.

In terms of high-level operations, the `SBL` provides various applications revolving around the problem of understanding the relationship between the structure and the function of macro-molecules and their complexes (see below). In terms of low-level operations, the design of the `SBL` is meant to accommodate both the variety of models coding the physical and chemical properties of macro-molecular systems (models based on unions of balls such as van der Walls models or solvent accessible models, or models based on conformations and conformational ensembles), as well as the variety of operations (geometric, topological, and combinatorial) undertaken on these models.

More precisely, the `SBL` consists of the following software components, detailed below:

- `SBL-APPLICATIONS`**:** high level applications solving specific applied problems.
- `SBL-CORE`**:** low-level generic C++ classes templated by traits classes specifying C++ concepts [0].
- `SBL-MODELS`**:** C++ *models* matching the C++ concepts required to instantiate classes from `SBL-CORE`.
- `SBL-MODULES`**:** C++ classes instantiating classes from the `SBL-CORE` with specific biophysical models from `SBL-MODELS`. A module may be seen as a black box transforming an input into an output. With modules, an application workflow consists of interconnected modules.

5.1.3. The SBL for end-users: SBL-APPLICATIONS

End users will find in the `SBL` portable applications running on all platforms (Linux, MacOS, Windows). These applications split into the following categories:

- **Space Filling Models:** applications dealing with molecular models defined by unions of balls.
- **Conformational Analysis:** applications dealing with molecular flexibility.
- **Large assemblies:** applications dealing with macro-molecular assemblies involving from tens to hundreds of macro-molecules.
- **Data Analysis:** applications providing novel data analysis - statistical analysis tools.
- **Data Management:** applications to handle input data and results, using standard tools revolving around the XML file format (in particular the XPath query language). These tools allow automating data storage, parsing and retrieval, so that upon running calculations with applications, statistical analysis and plots are a handful of python lines away.

5.1.4. The SBL for developers: SBL-CORE, SBL-MODELS and SBL-MODULES

The `SBL` makes it easy to develop novel high-level applications, by providing high level ready to use C++ classes instantiating various biophysical models.

In particular, modules allow the development of applications without the burden of instantiating low level classes. In fact, once modules are available, designing an application merely consists of connecting modules.

[0] The design has been guided by that used in the Computational Geometry Algorithm Library (CGAL), see http://www.cgal.org

5.1.5. The SBL for low-level developers and contributors: SBL-CORE, and SBL-MODELS

Low level developments may use classes from / contribute classes to `SBL-CORE` and `SBL-MODELS`. In fact, such developments are equivalent to those based upon C++ libraries such as CGAL (http://www.cgal.org/) or boost C++ libraries (http://www.boost.org/). It should be noticed that the `SBL` heavily relies on these libraries. The `SBL-CORE` is organized into four sub-sections:

- CADS : Combinatorial Algorithms and Data Structures.
- GT : Computational geometry and computational topology.
- CSB : Computational Structural Biology.
- IO : Input / Output.

It should also be stressed that these packages implement algorithms not available elsewhere, or available in a non-generic guise. Due to the modular structure of the library, should valuable implementations be made available outside the `SBL` (e.g. in CGAL or boost), a substitution may occur.

5.1.6. Interoperability

The `SBL` is interoperable with existing molecular modeling systems, at several levels:

- At the library level, our state-of-the-art algorithms (e.g. the computation of molecular surfaces and volumes) can be integrated within existing software by instantiating the required classes from `SBL-CORE`, or using the adequate modules.
- At the application level, our applications can easily be integrated within processing pipelines, since the format used for input and output are standard ones. (For input, the PDB format can always be used. For output, our applications generate XML files.)
- Finally, for visualization purposes, our applications generate outputs for the two reference molecular modeling environments, namely Visual Molecular Dynamics (http://www.ks.uiuc.edu/Research/vmd/) and Pymol (http://www.pymol.org/).

5.1.7. Releases, distribution, and license

The `SBL` is released under a proprietary open source license, see http://sbl.inria.fr/license/.

The source code is distributed from http://sbl.inria.fr, using tarballs and a git repository. Bugzilla is used to handle user's feedback and bug tracking.

6. New Results

6.1. Modeling interfaces and contacts

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

6.1.1. Predicting binding poses and affinities for protein - ligand complexes in the 2015 D3R Grand Challenge using a physical model with a statistical parameter estimation

Participants: Frédéric Cazals, Simon Marillet.

In collaboration with Sergei Grudinin, Maria Kadukova and Andreas Eisenbarth (Univ. Grenoble Alpes / CNRS / Inria, France).

The 2015 D3R Grand Challenge provided an opportunity to test our new model for the binding free energy of small molecules [17], as well as to assess our protocol to predict binding poses for protein-ligand complexes. Our pose predictions were ranked 3-9 for the HSP90 dataset, depending on the assessment metric. For the MAP4K dataset the ranks are very dispersed and equal to 2-35, depending on the assessment metric, which does not provide any insight into the accuracy of the method. The main success of our pose prediction protocol was the re-scoring stage using the recently developed Convex-PL potential. We make a thorough analysis of our docking predictions and discuss the effect of the choice of rigid receptor templates, the number of flexible residues in the binding pocket, the binding pocket size, and the subsequent re-scoring.

However, the main challenge was to predict experimentally determined binding affinities for two blind test sets. Our affinity prediction model consisted of two terms, a pairwise-additive enthalpy, and a non pairwise-additive entropy. We trained the free parameters of the model with a regularized regression using affinity and structural data from the PDBBind database. Our model performed very well on the training set, however, failed on the two test sets. We explain the drawback and pitfalls of our model, in particular in terms of relative coverage of the test set by the training set and missed dynamical properties from crystal structures, and discuss different routes to improve it.

6.1.2. Novel structural parameters of Ig-Ag complexes yield a quantitative description of interaction specificity and binding affinity

Participants: Frédéric Cazals, Simon Marillet.

In collaboration with Pierre Boudinot (INRA Jouy-en-Josas) and M-P. Lefranc (University of Montpellier 2).

Antibody-antigen complexes challenge our understanding, as analyses to date failed to unveil the key determinants of binding affinity and interaction specificity. In this work [23], we partially fill this gap based on novel quantitative analyses using two standardized databases, the IMGT/3Dstructure-DB and the structure affinity benchmark.

First, we introduce a statistical analysis of interfaces which enables the classification of ligand types (protein, peptide, chemical; cross-validated classification error of 9.6%), and yield binding affinity predictions of unprecedented accuracy (median absolute error of 0.878 kcal/mol). Second, we exploit the contributions made by CDRs in terms of position at the interface and atomic packing properties to show that in general, VH CDR3 and VL CDR3 make dominant contributions to the binding affinity, a fact also shown to be consistent with the enthalpy - entropy compensation associated with pre-configuration of CDR3. Our work suggests that the affinity prediction problem could be solved from databases of high resolution crystal structures of complexes with known affinity.

6.2. Modeling macro-molecular assemblies

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

No new result on this topic in 2016.

6.3. Modeling the flexibility of macro-molecules

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

6.3.1. Energy landscapes and persistent minima

Participants: Frédéric Cazals, Dorian Mazauric.

In collaboration with David Wales and Joanne Carr, from Cambridge University (UK).

In this work [15], we consider a coarse-graining of high-dimensional potential energy landscapes based upon persistences—which correspond to lowest barrier heights to lower-energy minima. Persistences can be calculated efficiently for local minima in kinetic transition networks that are based on stationary points of the prevailing energy landscape. The networks studied here represent peptides, proteins, nucleic acids, an atomic cluster, and a glassy system. Minima with high persistence values are likely to represent some form of alternative structural morphology, which, if appreciably populated at the prevailing temperature, could compete with the global minimum (defined as in- finitely persistent). Threshold values on persistences (and in some cases equilibrium occupation probabilities) have therefore been used in this work to select subsets of minima, which were then analysed to see how well they can represent features of the full network. Simplified disconnectivity graphs showing only the selected minima can convey the funnelling (including any multiple-funnel) characteristics of the corresponding full graphs. The effect of the choice of persistence threshold on the reduced disconnectivity graphs was considered for a system with a hierarchical, glassy landscape. Sets of persistent minima were also found to be useful in comparing networks for the same system sampled under different conditions, using minimum oriented spanning forests.

6.3.2. Hybridizing rapidly growing random trees and basin hopping yields an improved exploration of energy landscapes

Participants: Frédéric Cazals, Tom Dreyfus, Andrea Roth.

In collaboration with Charles Robert (IBPC / CNRS, Paris, France).

The number of local minima of the potential energy landscape (PEL) of molecular systems generally grows exponentially with the number of degrees of freedom, so that a crucial property of PEL exploration algorithms is their ability to identify local minima which are low lying and diverse. In this work [18], we present a new exploration algorithm, retaining the ability of basin hopping (BH) to identify local minima, and that of transition based rapidly exploring random trees (T-RRT) to foster the exploration of yet unexplored regions. This ability is obtained by interleaving calls to the extension procedures of BH and T-RRT, and we show tuning the balance between these two types of calls allows the algorithm to focus on low lying regions. Computational efficiency is obtained using state-of-the art data structures, in particular for searching approximate nearest neighbors in metric spaces. We present results for the BLN69, a protein model whose conformational space has dimension 207 and whose PEL has been studied exhaustively. On this system, we show that the propensity of our algorithm to explore low lying regions of the landscape significantly outperforms those of BH and T-RRT.

6.4. Algorithmic foundations

Keywords: computational geometry, Computational topology, Voronoi diagrams, α-shapes, Morse theory, graph algorithm, combinatorial optimization, statistical learning.

6.4.1. The Structural Bioinformatics Library: modeling in biomolecular science and beyond

Participants: Frédéric Cazals, Tom Dreyfus.

Software in structural bioinformatics has mainly been application driven. To favor practitioners seeking off-the-shelf applications, but also developers seeking advanced building blocks to develop novel applications, we undertook the design of the Structural Bioinformatics Library (SBL, http://sbl. inria.fr) [20], 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.

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 tools can also be combined to tackle integrated analysis problems. For developers, the SBL provides a broad C++ toolbox with modular design, involving (2) core 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.

The SBL is available from http://sbl.inria.fr.

6.4.2. Optimal transportation problems with connectivity constraints

Participants: Frédéric Cazals, Dorian Mazauric.

The earth mover distance (EMD) or the Mallows distance are example optimal transportation (OT) problems reducing to linear programs. In this work [21], we study a generalization of these problems when the supply and demand nodes are the vertices of two graphs called the supply and the demand graphs. The novel problems embed connectivity constraints in the transport plans computed, using a Lipschitz-like condition involving distances between certain subgraphs of the supply graph and certain subgraphs of the demand graph. More precisely, we make three contributions.

First, we formally introduce two optimal transportation problems generalizing EMD, namely Minimum-cost under flow, transport size, and connectivity constraints problem (problem EMD-FCC) and Maximum-flow under cost, transport size, and connectivity constraints problem (problem EMD-CCC). We prove that problems EMD-CCC and EMD-FCC are NP-complete, and that EMD-FCC is hard to approximate within any given constant. Second, we develop a greedy heuristic algorithm returning admissible solutions, of time complexity $O(n^3m^2)$ with n and m the numbers of vertices of the supply and demand graphs, respectively. Third, on the experimental side, we apply our novel OT algorithms for two applications, namely the comparison of clusterings, and the analysis of so-called potential energy landscapes in molecular science. These experiments show that optimizing the transport plan and respecting connectivity constraint can be competing objectives. Implementations of our algorithms are available in the Structural Bioinformatics Library at http://sbl.inria.fr.

6.4.3. Clustering stability revealed by matchings between clusters of clusters

Participants: Frédéric Cazals, Dorian Mazauric, Romain Tetley.

Clustering is a fundamental problem in data science, yet, the variety of clustering methods and their sensitivity to parameters make clustering hard. To analyze the stability of a given clustering algorithm while varying its parameters, and to compare clusters yielded by different algorithms, several comparison schemes based on matchings, information theory and various indices (Rand, Jaccard) have been developed. In this work [22], 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. Altogether, these pieces of information help assessing the coherence between two clusterings.

More specifically, 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 (k,D) and D-family-matching problems on intersection graphs, with k the number of meta-clusters and D the upper-bound on the diameter of the graph induced by the clusters of any meta-cluster. First we prove hardness and inapproximability results. Second, we design exact polynomial time dynamic programming algorithms for some classes of graphs (in particular trees). Then, we prove efficient (exact, approximation, and heuristic) algorithms, based on spanning trees, for general graphs. Practically, we present extensive experiments in two directions. First, we illustrate the ability of our algorithms to identify relevant meta-clusters between a given clustering and an edited version of it. Second, we show how our methods can be used to identify notorious instabilities of the k-means algorithm.

6.4.4. Experimental evaluation of a branch and bound algorithm for computing pathwidth

Participant: Dorian Mazauric.

In collaboration with David Coudert and Nicolas Nisse (COATI project-team, Université Côte D'Azur, Inria, I3S / CNRS).

Path-decompositions of graphs are an important ingredient of dynamic programming algorithms for solving efficiently many NP-hard problems. Therefore, computing the pathwidth and associated path-decomposition of graphs has both a theoretical and practical interest. In [16], we design a Branch and Bound algorithm that computes the exact pathwidth of graphs and a corresponding path-decomposition. Our main contribution consists of several non-trivial techniques to reduce the size of the input graph (pre-processing) and to cut the exploration space during the search phase of the algorithm. We evaluate experimentally our algorithm by comparing it to existing algorithms of the literature. It appears from the simulations that our algorithm offers a significant gain with respect to previous work. In particular, it is able to compute the exact pathwidth of any graph with less than 60 nodes in a reasonable running-time (≤ 10 minutes on a standard laptop). Moreover, our algorithm achieves good performance when used as a heuristic (i.e., when returning best result found within bounded time-limit). Our algorithm is not restricted to undirected graphs since it actually computes the directed pathwidth which generalizes the notion of pathwidth to digraphs.

6.4.5. *Extracting the core structural connectivity network: guaranteeing network connectedness through a graph-theoretical approach*

Participant: Dorian Mazauric.

In collaboration with Demian Wassermann, Guillermo Gallardo-Diez and Rachid Deriche (ATHENA project-team, Université Côte d'Azur, Inria).

In this work [19], we present a graph-theoretical algorithm to extract the connected core structural connectivity network of a subject population. Extracting this core common network across subjects is a main problem in current neuroscience. Such network facilitates cognitive and clinical analyses by reducing the number of connections that need to be explored. Furthermore, insights into the human brain structure can be gained by comparing core networks of different populations. We show that our novel algorithm has theoretical and practical advantages. First, contrary to the current approach our algorithm guarantees that the extracted core subnetwork is connected agreeing with current evidence that the core structural network is tightly connected. Second, our algorithm shows enhanced performance when used as feature selection approach for connectivity analysis on populations.

6.4.6. *On the complexity of the representation of simplicial complexes by trees*

Participant: Dorian Mazauric.

In collaboration with Jean-Daniel Boissonnat (DataShape team, Université Côte d'Azur, Inria).

In this paper [14], we investigate the problem of the representation of simplicial complexes by trees. We introduce and analyze local and global tree representations. We prove that the global tree representation is more efficient in terms of time complexity for searching a given simplex and we show that the local tree representation is more efficient in terms of size of the structure. The simplicial complexes are modeled by hypergraphs. We then prove that the associated combinatorial optimization problems are very difficult to solve and to approximate even if the set of maximal simplices induces a planar graph of maximum degree at most three or a bounded degree hypergraph. However, we prove polynomial time algorithms that compute constant factor approximations and optimal solutions for some classes of instances.

6.4.7. *Well balanced designs for data placement*

Participant: Dorian Mazauric.

In collaboration with Jean-Claude Bermond (COATI project-team, Université Côte D'Azur, Inria, I3S / CNRS), Alain Jean-Marie (MAESTRO project-team, Université Côte D'Azur, Inria) and Joseph Yu (Department of Mathematics, UFV, Abbotsford, BC, Canada).

The problem we consider in [13] is motivated by data placement, in particular data replication in distributed storage and retrieval systems. We are given a set V of v servers along with b files (data, documents). Each file is replicated on exactly k servers. A placement consists in finding a family of b subsets of V (representing the files) called blocks, each of size k. Each server has some probability to fail and we want to find a placement that minimizes the variance of the number of available files. It was conjectured that there always exists an optimal placement (with variance better than any other placement for any value of the probability of failure). We show that the conjecture is true, if there exists a well-balanced design, that is a family of blocks, each of size k, such that each j-element subset of V, $1 \leq j \leq k$, belongs to the same or almost the same number of blocks (difference at most one). The existence of well-balanced designs is a difficult problem as it contains, as a subproblem, the existence of Steiner systems. We completely solve the case math formula and give bounds and constructions for math formula and some values of v and b.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral contracts with industry

In this section, we describe the collaboration between ABS and MS Vision (http://msvision.eu/), and company based in the Netherlands. MSVision was created in 2004 and currently involves 20 employees; it is a worldwide leader in delivering tailored hardware solutions to the mass spectrometry community. As detailed below, the collaboration aims at strengthening the offer of the company on the algorithmic and software sides.

This collaboration is funded by the Instituts Carnots (http://www.instituts-carnot.eu/en).

7.1.1. Context

Protein complexes underlie most biological functions, so that studying such complexes in native conditions (intact molecular species taken in solution) is of paramount importance in biology and medicine. Unfortunately, the two leading experimental techniques to date, X ray crystallography and cryo electron microscopy, involve aggressive sample reparation (sample crystallization and sample freezing in amorphous ice, respectively) which may damage the structures and/or create artifacts. These experimental constraints legitimate the use of mass spectrometry (MS) to study biomolecules and their complexes under native conditions, using electrospray ionization (ESI), a soft ionization technique developed by John Fenn (Nobel prize in chemistry, 2002). MS actually delivers information on the masses of the molecular species studied, from which further information on the stoichiometry, topology and contacts between subunits can be inferred. Thanks to ESI, MS is expected to play a pivotal role in biology to unravel the structure of macromolecular complexes underlying all major biological processes, in medicine and biotechnology to understand the complex patterns of molecules involved in pathways, and also in biotechnologies for quality checks.

7.1.2. Specific goals

A mass spectrometer delivers a mass spectrum, i.e. an histogram representing the relative abundance of the ions (ionized proteins or protein complexes in our case), as a function of their mass-to-charge (m/z) ratio. Deconvoluting a mass spectrum means transforming it into a human readable mass histogram. Due to the nature of the ESI process (i.e. the inclusion of solvent and various other molecules) and the intrinsic variability of the studied biomolecules in native conditions, the interpretation of such spectra is delicate. Methods currently used are of heuristic nature, failing to satisfactorily handle the aforementioned difficulties. The goal of this collaboration is to develop optimal algorithms and the associated software to fill the critical gap of mass spectra deconvolution. The benefits for the analyst will be twofold, namely time savings, and the identification of previously undetected components. Upon making progress on the deconvolution problem, the collaboration will be expanded on the geometric and topological modeling of large macro-molecular assemblies, a topic to which ABS recently made significant contributions [2], [3].

8. Dissemination

8.1. Promoting scientific activities

8.1.1. Scientific Events Organisation

8.1.1.1. General Chair, Scientific Chair

Frédéric Cazals, together with C. Robert (IBPC, CNRS Paris) and J. Cortés (LAAS, CNRS Toulouse) organized the *energy landscapes* workshop, an international gathering devoted to all topics revolving around energy landscapes, as encountered in physics, chemistry, biochemistry, biology, applied mathematics, and computer science. See details at https://eland2016.inria.fr/.

8.1.2. Scientific Events Selection

8.1.2.1. Member of the Conference Program Committees

– Frédéric Cazals was member of the following program committees:

- Symposium On Geometry Processing
- Shape Modeling International: 2016
- Symposium on Solid and Physical Modeling
- Intelligent Systems for Molecular Biology (ISMB), PC member of Protein Interactions & Molecular Networks
- International Conference on Pattern Recognition in Bioinformatics

8.1.3. Journal

8.1.3.1. Reviewer - Reviewing Activities

– Frédéric Cazals reviewed papers for the following journals:

- The International Journal of Computational Geometry and Applications
- Bioinformatics
- The Journal of Immunology

8.1.4. Invited Talks and Presentations

– Frédéric Cazals gave the following invited talks:

- *Energy landscapes: sampling, analysis*, Congrès de la Société Française de Biophysique – Structural biology meets biophysics, Obernai. December 2016.
- *Modeling energy landscapes of biomolecular systems*, Ecole Normale Supérieure de Cachan. September 2016.
- *Novel structural parameters of Ig-Ag complexes yield a quantitative description of interaction specificity and binding affinity*, Structural Aspects of Infectious Disease, Cambridge, UK, August 2016.
- *Energy landscapes: sampling, analysis, and comparison*, Energy Landscapes Workshop, Porquerolles. July 2016.
- *Improved understanding of protein dynamics via energy landscape sampling, analysis, and comparison*, TSRC on protein dynamics. Les Houches, March 2016.

– Romain Tetley gave the following invited talk:

- *A bootstrap method for detecting structurally conserved motifs*, Energy Landscapes Workshop, Porquerolles. July 2016.

– Poster presentations:

- Dorian Mazauric presented the following poster:
  Unveiling Contacts within Macro-molecular Assemblies by solving Minimum Weight Connectivity Inference Problems, Congrès de la Société Française de Biophysique – Structural biology meets biophysics, Obernai. December 2016.
- Augustin Chevallier presented the following poster:
  Towards free energy calculations for biomolecules: generic Wang-Landau algorithm with automatic parameters selection, Congrès de la Société Française de Biophysique – Structural biology meets biophysics, Obernai. December 2016.
- Dorian Mazauric presented the following poster:
  Mass Transportation Problems with Connectivity Constraints and Energy Landscape Comparison, Energy Landscapes Workshop, Porquerolles. July 2016.

8.1.5. Leadership within the Scientific Community

– FrédéricCazals:

- 2010-.... Member of the steering committee of the *GDR Bioinformatique Moleculaire*, for the *Structure and macro-molecular interactions* theme.

8.1.6. Scientific Expertise

– Frédéric Cazals acted as expert for the *Italian Research and University Evaluation Agency (ANVUR)*.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Master: Frédéric Cazals (Inria ABS) and S. Oudot (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: Frédéric Cazals and Dorian Mazauric (Inria ABS), *Algorithmic problems in computational structural biology*, 24h, Master of Science in Computational Biology from the University of Nice Sophia Antipolis, France, see http://cbb.unice.fr.

8.2.2. Supervision

PhD thesis, defended, December 2016. Simon Marillet, *Modeling the antibody response: from the structure of immunoglobulins - antigen complexes to the clonal complexity of heavy chain repertoires*, University of Nice Sophia Antipolis. The thesis is co-advised by Frédéric Cazals and Pierre Boudinot (INRA Jouy-en-Josas).

PhD thesis, ongoing. Romain Tetley, *Structural alignments: beyond the rigid case*, University of Nice Sophia Antipolis. Under the supervision of Frédéric Cazals.

PhD thesis, ongoing. Augustin Chevallier, *Sampling biomolecular systems*, University of Nice Sophia Antipolis. Under the supervision of Frédéric Cazals.

Postdoctoral research of Rémi Watrigant, 2016 - 2018. Projet de Recherche Exploratoire (Inria). *Improving inference algorithms for macromolecular structure determination*. Under the supervision of Dorian Mazauric and Frédéric Havet (Inria COATI project-team).

8.2.3. Juries

– Frédéric Cazals:

- Huaxiong Ding, University of Lyon, December 2016. Committee member. *Combining 2D facial Texture and 3D face morphology for estimating people soft biometrics: gender, facial expression.* Advisors: Liming Chen and Jean-Marie Morvan.

8.3. Popularization

8.3.1. Dissemination of scientific culture

Participant: Dorian Mazauric, member of the group of Médiation et Animation des MAthématiques, des Sciences et Techniques Informatiques et des Communications (MASTIC), Inria Sophia Antipolis - Méditerranée.

8.3.1.1. Publications and ressources.

- 2016. *Graphes et Algorithmes – Jeux grandeur nature*. Dorian Mazauric, en collaboration avec Laurent Giauffret, Direction des Services Départementaux de l'Éducation Nationale (DSDEN) des Alpes-Maritimes. [https://hal.inria.fr/hal-01366804]
- 2016. *Graphes et Algorithmes - Diffusion de l'information scientifique.* Dorian Mazauric. [https://hal.inria.fr/hal-01383665]
- 2016. *Information et communication : la Théorie des Graphes*. Jean-Claude Bermond et Dorian Mazauric. Fondation la main à la pâte. To appear.

8.3.1.2. Fête de la Science en PACA.

- 22-23/10/2016. Village des sciences et de l'innovation au Palais des Congrès d'Antibes Juan-les-Pins. Fête de la Science 2016. *a) La magie des graphes et du binaire. b) Algorithmes grandeur nature. c) Pas besoin de réfléchir, les ordinateurs calculent tellement vite ? Théorie des graphes et algorithmique pour les réseaux.* [https://www.inria.fr/centre/sophia/agenda/fete-de-la-science-2016]
- 10-12/10/2016. Fête de la Science au collège Yves Montand, Vinon-sur-Verdon. Institut Esope 21. *a) La magie des graphes et du binaire. b) Algorithmes grandeur nature. c) Pas besoin de réfléchir, les ordinateurs calculent tellement vite ? Théorie des graphes et algorithmique pour les réseaux.* [https://www.inria.fr/centre/sophia/agenda/fete-de-la-science-2016]

8.3.1.3. Stage MathC2+ à Inria Sophia Antipolis - Méditerranée.

- 15-16/06/2016. Activité pour une quarantaine de lycéens des Alpes-Maritimes (accueillis à Inria Sophia Antipolis - Méditerranée durant 4 jours). *Algorithmes grandeur nature pour le calcul d'un arbre couvrant de poids minimum (application pour la conception d'un réseau électrique).* Présentation aux lycéens du stage. *Pas besoin de réfléchir, les ordinateurs calculent tellement vite ? Théorie des graphes et algorithmique pour les réseaux.* [http://www.inria.fr/centre/sophia/actualites/mathc2-40-lyceens-des-alpes-maritimes-en-immersion-au-coeur-d-un-centre-de-recherche] [https://youtu.be/rLj5I1Gu1uI]

8.3.1.4. Interventions à l'ÉSPÉ de l'Académie de Nice.

- 8-15/03/2016. Organisation d'un atelier à l'École Supérieure du Professorat et de l'Éducation (ÉSPÉ) de l'Académie de Nice (site de Stéphen Liégeard) en collaboration avec l'Inspection Académique (avec Laurent Giauffret). Animation, avec des étudiants de l'ÉSPÉ, pour 360 élèves de CM1 et de CM2. *La magie des graphes et du binaire, algorithmes et jeux (réseaux de tri).* [http://www.inria.fr/actualite/agenda/semaine-des-mathematiques-au-mois-de-mars?utm_content=buffer4b539&utm_medium=social&utm_source=twitter.com&utm_campaign=buffer] [http://www2.ac-nice.fr/DSDEN06/cid101665/des-chercheurs-de-retour-a-l-ecole.html]

8.3.1.5. Formations pour les enseignants en collaboration avec la DSDEN des Alpes-Maritimes.

- 15-19/09/2016. Préparation avec Laurent Giauffret d'une formation pour 17 enseignants de cycle 3 (cours moyen d'enseignement élémentaire). *a) Présentation d'Inria et du dispositif ASTEP.b) Graphes et Algorithmes : théorie et mise en pratique avec des jeux.c) Présentation de Thymio et mise en avant des possibilités offertes.d) Présentation du logiciel Scratch par le Maître Assistant Informatique de circonscription.*

8.3.1.6. Conférences dans des lycées dans le cadre du dispositif régional "Science Culture".

- 26/01/2016. Conférence au lycée Amiral de Grasse (classes de seconde). *a) Pas besoin de réfléchir, les ordinateurs calculent tellement vite ? Théorie des graphes et algorithmique pour les réseaux. b) La magie des graphes et du binaire.*
- 21/01/2016. Conférence au lycée Amiral de Grasse (classes de terminale). *a) Pas besoin de réfléchir, les ordinateurs calculent tellement vite ? Théorie des graphes et algorithmique pour les réseaux. b) La magie des graphes et du binaire.*

8.3.1.7. Conférences dans des collèges des Alpes-Maritimes.

- 05/12/2016. Conférence au collège Jules Verne de Cagnes-sur-Mer (deux classe de sixième) (avec Rémi Watrigant). *La magie des graphes et du binaire*.

8.3.1.8. Conférences dans des écoles primaires des Alpes-Maritimes dans le cadre d'ASTEP.

- 22/03/2016. Conférence à l'école élémentaire de La Tournière, Antibes (classe de CE2). *La magie des graphes et du binaire, algorithmes et jeux (algorithmes grandeur nature pour trier, jeux combinatoires...)*.
- 18/03/2016. Conférence à l'école élémentaire Langevin 2, Vallauris (classe de CP). *La magie des graphes et du binaire, algorithmes et jeux (algorithmes grandeur nature pour trier, jeux combinatoires...)*.

8.3.1.9. Autres présentations.

- 05/01/2016. Présentation à des lycéens d'Australie et de Nouvelle-Zélande (classes de secondes) à Inria Sophia Antipolis - Méditerranée. *La magie des graphes et du binaire*.

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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

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6.2.1. - Numerical analysis of PDE and ODE
6.2.6. - Optimization
6.3.1. - Inverse problems
6.3.5. - Uncertainty Quantification

Other Research Topics and Application Domains:

1.1.10. - Mathematical biology
5.2.1. - Road vehicles
5.3. - Nanotechnology
7.1.1. - Pedestrian traffic and crowds
7.1.2. - Road traffic
8.1.1. - Energy for smart buildings

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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 [95], or to the dynamics of turbulent flows for which large scale / small scale vortical structures interfere [123].

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 [64] for an existence result and [49], [63] 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 [55], [84] for some applications in traffic flow modelling, and [74], [79], [81] 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 [49], [63].

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 [56], [66] for the derivation of Lighthill-Whitham-Richards [107], [122] traffic flow model from Follow-the-Leader and [75] for results on crowd motion models (see also [97]). 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 [67], and extensively used since then to prove convergence of approximate solutions and deduce existence results, see for example [76] 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 [38], [78]. We refer, for example, to the notion of solution for non-hyperbolic systems [86], 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 [78].

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 [60]), and proved to be successful for studying emerging self-organised flow patterns [59]. The theoretical measure framework proves to be also relevant in addressing micro-macro limiting procedures of mean field type [87], 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* [130], [131]. Indeed, as observed in [114], 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 [106]). 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 [45], [46], [68], [105], 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 [118], 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 [62] 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, [36]) 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

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

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 [33], sedimentation [40], supply chains [89], conveyor belts [90], biological applications like structured populations dynamics [113], or more general problems like gradient constrained equations [34]. Also, non-local in time terms arise in conservation laws with memory, starting from [61]. 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 [3], [6] [48], [52], [126]. 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 [3], [6] 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 [35] for scalar equations in one space dimension ($N = d = 1$), in [53] for scalar equations in several space dimensions ($N = 1$, $d \geq 1$) and in [29], [54], [58] for multi-dimensional systems of conservation laws. Besides, specific finite volume numerical methods have been developed recently in [29], [6] and [104].

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 [47]. In aerodynamics, inflow conditions like velocity modulus and direction, are subject to fluctuations [93], [112]. For some engineering problems, the geometry of the boundary can also be uncertain, due to structural deformation, mechanical wear or disregard of some details [70]. 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 [124], [129], 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 [125], [128], 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 [111]. 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 [93], [102], [108], [133] or an entropy closure method [65], or by discretizing the probability space and extending the numerical schemes to the stochastic components [28]. 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 [119], [129], [132].

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 [39]. Besides, we plan to extend previous works on sensitivity analysis [70], [109] 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 [41] (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 [129]. 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 [121] 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 [37], [88] for the backward time integration of the adjoint variables. The sensitivity equation method (SEM) offers a promising alternative [69], [98], 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 [70].
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) [123] , Detached-Eddy Simulation (DES) [127] or Organized-Eddy Simulation (OES) [43], 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 [100] 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 [71] [72]. 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 [73] 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 [116] 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 [135].

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 [80]. 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 [30] 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 CO_2 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 [134]. 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 [85]. 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 [94]. Further improvements require more advanced models, keeping into better account interactions at the microscopic scale, and adapted control techniques, see [44] 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 [57], [83], 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 [99].
- *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 [96] 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 [50], [51]), 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 [64], [84] or via the Hamilton-Jacobi approach [50], [51] could allow to optimize the flow by controlling some specific vehicles corresponding to internal conditions.

4.3. Concurrent design for building systems

Building industry has to face more and more stringent requirements, including energy performance, structural safety and environmental impact. To this end, new materials and new technologies have emerged [103] to help the construction firms meet these requirements. At the same time, many different teams or firms interact, most of the interaction being of non-cooperative nature. The teams involved in construction have different goals, depending on which stage they operate. Indeed, the lifetime of a building goes through three stages: construction, use and destruction. To each of these phases correspond quality criteria related in particular to:

- Safety: structural, fire, evacuation, chemical spread, etc.
- Well-being of its occupants: thermal and acoustic comfort.
- Functionality of its intended use.
- Environmental impact.

These stages and criteria form a complex system, the so-called building system, whose overall quality (in an intuitive sense) is directly impacted by many heterogeneous factors, such as the geographical location or the shape or material composition of some of its components (windows, frames, thermal convectors positions, etc.) It is obvious that the optimization process of these settings must be performed at the "zero" stage of the project design. Moreover, the optimization process has to follow a global approach, taking into account all the concurrent criteria that intervene in the design of building systems.

The application of up-to-date concurrent optimization machinery (games, Pareto Fronts) for multiphysics systems involved in the building is an original approach. With our industrial partner, who wishes routine use of new high performance components in the construction of buildings, we expect that our approach will yield breakthrough performances (with respect to the above criteria) compared to the current standards.

The research project relies on the ADT BuildingSmart (see software development section) for the implementation of industrial standard software demonstrators.

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 [91], dorsal closure [32], actin organization [31]). 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 [77] it is shown that Madin-Darby Canine Kidney (MDCK) cells extend cryptic lamellipodia to drive the migration, several rows behind the wound edge. In [117] 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 [74], [79], [81].

- **Modeling cardio-stents.**

  Atherosclerosis or arterial calcification is a major vascular disease, caused by fatty deposits on the inner walls of arteries. Angioplasty techniques propose several solutions to remedy this pathology. We are interested in those which consist in introducing a metallic stent, to crush the lipid plaques, and ensure permanent enlargement of the damaged arterial wall. The implementation of such an element is accompanied by an immune reaction of the arterial walls, which is manifested by an accelerated proliferation of cells within the so called media, which highlights two major risks: restenosis, and thrombosis . One promising technique is to introduce a "Drug Eluting Stent", which is a metallic stent coated with a polymer layer containing an antiproliferative drug to slow the proliferation process, in order to improve the functioning of the stent. Our major objective in this part is to setup and develop the mathematical modeling and computational tools that lead to the effective estimation of the Fractional Flow Reserve [115], which is a promising new technique to help the cardiologists take decisions on stent implantation.

- **Game strategies for thermoelastography.** Thermoelastography is an innovative non-invasive control technology, which has numerous advantages over other techniques, notably in medical imaging [110]. 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 [92], [101], we have demonstrated that Nash game approaches are efficient to tackle ill-posedness. We intend to extend the results obtained for Laplace equations in [92], 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. [120], 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

- P. Goatin got the *Trophée des Femmes en Or* for the “Smart City” category.

6. New Software and Platforms

6.1. BuildingSmart

BuildingSmart interactive visualization
KEYWORDS: Physical simulation - 3D rendering - 3D interaction

- Contact: Abderrahmane Habbal

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). The software is to be integrated in an immersive space (https://www.youtube.com/watch?v=wAm7faixBak) The project is hosted by the ACUMES project-team in collaboration with the SED service (Service d'Expérimentation et de Développement) and Experts from ArcelorMittal Construction. The project is financed by an Inria ADT which recruited an experienced engineer (starting in december 2015), whose main task is to study and develop solutions dedicated to interactive visualisation of building performances (heat, structural) in relation to the Building Information Modeling BIM framework.

7. New Results

7.1. Macroscopic traffic flow models on networks

Participants: Guillaume Costeseque, Paola Goatin, Bhargava Rama Chilukuri [Georgia Tech, USA], Maria Laura Delle Monache [U Rutgers - Camden], Aurélien Duret [IFSTTAR, France], Simone Göttlich [U Mannheim, Germany], Oliver Kolb [U Mannheim, Germany], Jorge A. Laval [Georgia Tech, USA], Benedetto Piccoli [U Rutgers - Camden], Armin Seyfried [Forschungszentrum Jülich, Germany], Antoine Tordeux [Forschungszentrum Jülich, Germany].

In collaboration with M.L. Delle Monache and B. Piccoli, and in the framework of the Associated Team ORESTE, we have introduced a new Riemann solver for traffic flow on networks. The Priority Riemann solver (PRS) provides a solution at junctions by taking into consideration priorities for the incoming roads and maximization of through flux. We prove existence of solutions for the solver for junctions with up to two incoming and two outgoing roads and show numerically the comparison with previous Riemann solvers. Additionally, we introduce a second version of the solver that considers the priorities as softer constraints and illustrate numerically the differences between the two solvers. See [24].

Still in collaboration with M.L. Delle Monache, we studied well-posedness of scalar conservation laws with moving flux constraints arising in the modeling of moving bottlenecks in traffic flow. In particular, we showed the Lipschitz continuous dependence of BV solutions with respect to the initial data and the constraint trajectory [23].

In collaboration with S. Göttlich and O. Kolb, we have investigated how second order traffic flow models, in our case the Aw-Rascle equations, can be used to reproduce empirical observations such as the capacity drop at merges and solve related optimal control problems. To this aim, we have proposed a model for on-ramp junctions and derive suitable coupling conditions. These are associated to the first order Godunov scheme to numerically study the well-known capacity drop effect, where the outflow of the system is significantly below the expected maximum. Control issues such as speed and ramp meter control have also been addressed in a first discretize-then optimize framework [25].

Together with J. A. Laval and B. R. Chilukuri, we have investigated the implications of source terms in the Hamilton-Jacobi formulation of macroscopic first order traffic flow models. Hamilton-Jacobi equations (without source terms) have been demonstrated to be very useful in traffic flow engineering since they provide explicit formula for initial and boundary-values problems. However, for sake of realism, additional source terms should be incorporated to account for continuous inflows or outflows on freeways for instance. We showed that explicit Lax-Hopf formula can still be obtained when the source term is exogenous, say the lateral inflow or outflow does not depend on the density on the main road. We also provide numerical methods based on Bellman's dynamic programming principle to deal with non-exogenous source terms in discrete time [7].

With A. Duret, we have designed a new traffic flow model for taking into account the multiclass and multilane features of real traffic. This model is based on a system of coupled Hamilton-Jacobi PDEs for an appropriate choice of framework that mixes spatial and Lagrangian coordinates. The coupling conditions emerge from the moving bottleneck theory that has been developed in the traffic flow literature several years ago but for which a real mathematical sound basis lacked. Very recently, there were some new results dealing with the existence of a solution under suitable assumptions [64]. However, these results were set for the hyperbolic conservation law in Eulerian coordinates and they are not straightforward to be extended to Hamilton-Jacobi equations in different coordinates. Despite that the well-posedness of the problem is still an open problem, a numerical method is developed by taking advantage of the classical representation formula available for HJ PDEs. This numerical scheme has been proved to provide good qualitative results [14].

In collaboration with A. Tordeux, M. Herty and A. Seyfried, we studied the derivation of convection-diffusion macroscopic traffic flow models from a first order microscopic follow-the-leader model that takes into account a non-trivial time delay. The derivation is based on a change of variables from Lagrangian to Eulerian coordinates and makes use of Taylor expansions with respect to the time delay. The macroscopic diffusion term is due to the microscopic reaction time parameter and allows to reproduce the scatter of empirical flow-density data. Different numerical methods are proposed for computing the numerical flux and the linear stability of the homogeneous solutions obtained for each method is investigated. Interestingly, we recover some stability results for infinite systems of delayed ODEs [27].

7.2. Initial-boundary value problems for non-local scalar conservation laws

Participants: Cristiana de Filippis, Paola Goatin.

As a first step in this direction, we have proved global well-posedness results for weak entropy solutions of bounded variation (BV) of scalar conservation laws with non-local flux on bounded domains in one space dimension, under suitable regularity assumptions on the flux function. In particular, existence is obtained by proving the convergence of an adapted Lax-Friedrichs algorithm. Lipschitz continuos dependence from initial and boundary data is derived applying Kružhkov 's doubling of variable technique [22].

7.3. High order schemes for non-local conservation laws

Participants: Paola Goatin, Christophe Chalons [UVST], Luis Miguel Villada Osorio [U Bio-Bio].

We have designed Discontinuous Galerkin (DG) schemes and Finite Volume WENO (FV-WENO) schemes to obtain high-order approximations of the solutions of a class of non-local conservation laws in one space dimension. The DG schemes give the best numerical results but their CFL condition is very restrictive. On the contrary, FV-WENO schemes can be used with larger time steps. The evaluation of the convolution terms necessitates the use of quadratic polynomials reconstructions in each cell in order to obtain the high-order accuracy with the FV-WENO approach. See [21].

7.4. Isogeometric analysis for hyperbolic systems

Participants: Régis Duvigneau, Asma Azaouzi [ENIT], Maher Moakher [ENIT].

The use of high-order numerical schemes is necessary to reduce numerical diffusion/dispersion in simulations, maintain a reasonable computational time for 3D problems, estimate accurately uncertainties or sensitivities, etc. Moreover, the capability to handle exactly CAD data in physical solvers is desirable to foster design optimization or multidisciplinary couplings.

Consequently, we develop high-order isogeometric schemes for the applications targeted by the team, in particular for convection-dominated problems. Specifically, we investigate a Discontinuous Galerkin method for compressible Euler equations, based on an isogeometric formulation: 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), while the same rational approximation space is adopted for the solution. This topic is partially studied in A. Azaouzi's PhD work.

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 example the one-dimensional barotropic Euler equations. Different approaches are tested to integrate the additional source term: a Roe solver, a Godunov method and a moving cells approach. This study is achieved in collaboration with C. Chalons from University of Versailles, in the context of C. FIorini's PhD work.

7.6. Characterization of model uncertainty for turbulent flows

Participants: Régis Duvigneau, Jérémie Labroquère [THALES], Emmanuel Guilmineau [CNRS-ECN], Marianna Braza [CNRS-IMFT], Mathieu Szubert [CNRS-IMFT].

The uncertainty related to turbulence modeling is still a bottleneck in realistic flows simulation. Therefore, some studies have been conducted to quantify this uncertainty for two problems in which turbulence plays a critical role. Firstly, the impact of the model choice has been estimated in the case of a massively detached flow over a 2D backward facing step including an oscillatory active control device, whose parameters are optimized [5]. Secondly, the influence of the transition point location has been investigated, in the case of the 3D flow around a bluff-body, using models ranging from RANS to DES models [9], in collaboration with M. Braza from Institut de Mécanique des Fluides de Toulouse, in the context of the M. Szubert's PhD work.

7.7. Optimization accounting for experimental and numerical uncertainties

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

Optimization of real-life applications requires to account for the uncertainties arising during the performance evaluation procedure, that could be either experimental or numerical. A Gaussian-Process based optimization algorithm has been proposed to efficiently determine the global optimum in presence of noise, whose amplitude can be user-defined or inferred from observations. The method has been applied to two very different problems related to performance optimization in sport.

The first case corresponds to the optimization of the shape of a racing kayak, in the framework of SOKA project, in preparation to 2016 Olympic Games. The performance is estimated by coupling Newton's law with incompressible Navier-Stokes equations to compute the kayak velocity from the effort of the athlete, considered as input. The proposed method has been used here to filter the noise arising from the numerical simulation [18], [11]. This work is conducted in collaboration with Ecole Centrale de Nantes and National Kayak Federation.

The second case corresponds to the optimization of a sail trimming, whose performance can be estimated either experimentally in a wind tunnel, or numerically by solving a fluid-structure interaction problem. In the former case, uncertainty has been estimated according to measurements accuracy, while in the latter case the numerical noise has be inferred from a set of observations collected during the optimization[12]. This work is part of M. Sacher's PhD at Ecole Navale.

7.8. Modeling activated/inhibited cell-sheet wound dynamics

Participants: Abderrahmane Habbal, Hélène Barelli [Univ. Nice Sophia Antipolis, CNRS, IPMC], Grégoire Malandain [Inria, EPI Morpheme], Boutheina Yahyaoui [PhD, LAMSIN, Univ. Tunis Al Manar], Mekki Ayadi [LAMSIN, Univ. Tunis Al Manar].

In a previous paper [91], we have shown that the well-known Fisher-KPP equations are able to model the natural wound closure of cell-sheets. This family of equations, with constant coefficients, exhibit progressive fronts with constant speed and we have proved by confronting to experiments that F-KPP is remarkabely able to predict the dynamics of experimental wounds. However, this is no more the case when the cell-sheet is either inhibited or activated exogeneously. In this case, we used a F-KKP equation with time-dependent coefficients, and proved again that with this modification we were able to capture the wound dynamics [13]. To take into account further biological features in the mathematical model, we implemented a coupling between the mechanical behavior of the cell tissue and the evolution of the density, using classical linear visco-elastic models from the literature. Our present effort is on assessing the ability of the mechano-biological coupled system to render some of the cell-sheet dynamics that are missing from the Fisher-KPP equation alone.

7.9. A Nash game for the coupled problem of conductivity identification and data completion

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

In this work, we are interested in solving the electrocardiography inverse problem which could be reduced to the data completion problem for the Poisson equation. The difficulty comes from the fact that the conductivity values of the torso organs like lungs, bones, liver,...etc, are not known and could be patient dependent. Our goal is to construct a methodology allowing to solve both data completion and conductivity optimization problems at the same time.

In [92], [101] a Nash game approach was developed to tackle the data completion problem. Our algorithm turned out to be efficient and robust with respect to noisy data. In a first attempt, presented in [17], we formulated the identification-completion problem as a Stackelberg game. Some numerical experiments were successful in this joint identification, but some were not. Which led us to develop new formulations, with direct impact on the technological modus operandi in the theoretical tomography process. In few words, the new formulations are based on the remark that not all the over-specified data are necessary to ensure the existence and uniqueness for the Cauchy problem, since by Holmgren theorem, only a piece of these data (over a subset of the boundary with non zero superficial measure) is necessary and sufficient. Presently, we are investigating the ability of these new formulations to ensure identifiability of the conductivity coefficients, for Poisson and linear elasticity equations.

7.10. Bayesian Optimization approaches to find Nash equilibria

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

Our aim here is to show that the Bayesian Optimization -BO- apparatus can be applied to the search of game equilibria, and in particular the classical Nash equilibrium (NE), known to be very costly the compute, notably when involved in the framework of large scale scientific computing areas.

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.

We have proposed in [26] a novel approach to solve Nash games with drastically limited budgets of evaluations based on GP regression, taking the form of a Bayesian optimization algorithm. Experiments on challenging benchmark problems demonstrate the potential of this approach compared to classical, derivative-based algorithms.

On the test problems, two acquisition functions performed similarly well. The first one, Stepwise Uncertainty Reduction -SUR- has recently emerged in the machine learning community. We introduced a new one, the Probability of Equilibrium P_E, which has the benefit of not relying on conditional simulation paths, which makes it simpler to implement and less computationally intensive in most cases. Still, the SUR approach has several decisive advantages; in particular, it does not actually require the new observations to belong to the grid (sampling of the , such that it could be optimized continuously. Moreover, it lays the groundwork for many extensions that may be pursued in future work.

First, SUR strategies are well-suited to allow selecting batches of points instead of only one, a key feature in distributed computer experiments. Second, other games and equilibria may be considered: the versatility of the SUR approach may allow its transposition to other frameworks, such as mixed-strategies or Bayesian games. In particular, our framework transposes directly to the case of noisy evaluations, as it can be directly modeled by the GPs without affecting the acquisition functions.

7.11. Crowd motion modeled by Fokker-Planck constrained Nash games

Participants: Alfio Borzí [Univ. Würzburg], Paola Goatin, Abderrahmane Habbal, Souvik Roy [Indian Statistical Institute, Kolkata].

Fokker-Planck-Kolmogorov (FPK) equations are PDEs which govern the dynamics of the probability density function (PDF) of continuous-time stochastic processes (e.g. Ito processes). In [36] a FPK-constrained control framework, where the drift was considered as control variable is developed and applied to crowd motion.

We consider in [42] the extension of the latter framework to the case where two crowds (or pedestrian teams) are competing through a Nash game. The players strategies are the drifts, which yield two uncoupled FPK equations for the corresponding PDFs. The interaction is done through cost functions : each player would prefer to avoid overcrowding (w.r.t. the other one, hence the coupling) additionally to have her own preferred trajectory and obstacle avoidance. In this particular setting, we prove the existence and uniqueness of the Nash equilibrium (NE). The NE is computed by means of a fixed point algorithm and adjoint-state method is used to compute the pseudo-gradients. We finally present some numerical experiments to illustrate which dynamics may arise from such equilibria.

7.12. Concurrent Aerodynamic Optimization of Rotor Blades Using a Nash Game Method

Participants: Enric Roca León [ONERA DAAP Meudon, doctoral student], Arnaud Le Pape [ONERA DAAP Meudon, research engineer], Michel Costes [ONERA DAAP Meudon, research engineer], Jean-Antoine Désidéri, David Alfano [Airbus Helicopters].

A multiobjective strategy adapted to the aerodynamic concurrent optimization of helicopter rotor blades is developed. The present strategy is based on Nash games from game theory, where the objective functions are minimized by virtual players involved in a noncooperative concurrent game. A method is presented to split the design vector into two subspaces, defined to be the strategies of the players in charge of the minimization of the primary and the secondary objective functions, respectively. This split of territory allows the optimization of the secondary function while causing the least possible degradation of the first one. This methodology is applied to the model rotor ERATO, seeking to maximize the figure of merit in hover while minimizing the required rotor power in forward flight, assuming frozen structural properties. An initial constrained optimization in hover is conducted using a previously developed adjoint-based technique using the three-dimensional Navier–Stokes solver elsA along with the gradient-based CONMIN algorithm. The chord, twist, and sweep distributions of the baseline blade are parameterized using Bézier and cubic splines for a total of 16 design variables. The obtained optimized rotor is then used as a starting point to launch constrained and unconstrained Nash games. The comprehensive rotor code Eurocopter's Helicopter Overall Simulation Tool (HOST) is used to evaluate forward flight performance, and a surrogate model is built to obtain the hover performance at low computational cost. Twist and sweep distribution laws are optimized independently at first, and then a final joint optimization involving twist, sweep, and chord is performed. The results demonstrate the potential of this technique to obtain helicopter rotor designs realizing interesting trade-offs between strongly antagonistic objectives [8].

7.13. Parametric optimization of pulsating jets in unsteady flow by Multiple-Gradient Descent Algorithm (MGDA)

Participants: Jean-Antoine Désidéri, Régis Duvigneau.

Two numerical methodologies are combined to optimize six design characteristics of a system of pulsating jets acting on a laminar boundary layer governed by the compressible Navier-Stokes equations in a time-periodic regime. The flow is simulated by second-order in time and space finite-volumes, and the simulation provides the drag as a function of time. Simultaneously, the sensitivity equations, obtained by differentiating the governing equations w.r.t. the six parameters are also marched in time, and this provides the six-component parametric gradient of drag. When the periodic regime is reached numerically, one thus disposes of an objective-function, drag, to be minimized, and its parametric gradient, at all times of a period. Second, the parametric optimization is conducted as a multi-point problem by the Multiple-Gradient Descent Algorithm (MGDA) which permits to reduce the objective-function at all times simultaneously, and not simply in the sense of a weighted average [19].

7.14. Stochastic Multiple Gradient Descent Algorithm

Participants: Jean-Antoine Désidéri, Quentin Mercier [ONERA DADS Châtillon, doctoral student], Fabrice Poirion [ONERA DADS Châtillon, research engineer].

We have proposed a new method for multiobjective optimization problems in which the objective functions are expressed as expectations of random functions. This method is based on an extension of the classical stochastic gradient algorithm and a deterministic multiobjective 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 multiobjective 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 two academic examples and its performance is compared to the deterministic MGDA algorithm coupled with a Monte-Carlo expectation estimator. A third example is treated, considering the optimization of a sandwich material under constitutive material uncertainties.

7.15. Finite-volume goal-oriented mesh adaptation for aerodynamics using functional derivative with respect to nodal coordinates

Participants: Giovanni Todarello [ONERA DMFN Châtillon, intern], Floris Vonck [ONERA DMFN Châtillon, intern], Sébastien Bourasseau [ONERA, doctoral student], Jacques Peter [ONERA DMFN Châtillon, research engineer], Jean-Antoine Désidéri.

A new goal-oriented mesh adaptation method for finite volume/finite difference schemes is extended from the structured mesh framework to a more suitable setting for adaptation of unstructured meshes. The method is based on the total derivative of the goal with respect to volume mesh nodes that is computable after the solution of the goal discrete adjoint equation. The asymptotic behaviour of this derivative is assessed on regularly refined unstructured meshes. A local refinement criterion is derived from the requirement of limiting the first order change in the goal that an admissible node displacement may cause. Mesh adaptations are then carried out for classical test cases of 2D Euler flows. Efficiency and local density of the adapted meshes are presented. They are compared with those obtained with a more classical mesh adaptation method in the framework of finite volume/finite difference schemes [46]. Results are very close although the present method only makes usage of the current grid [10].

7.16. Quasi-Riemannian approach to constrained optimization

Participants: Didier Bailly [Research Engineer, ONERA Department of Applied Aerodynamics, Meudon], Jean-Antoine Désidéri.

In differentiable optimization, the Broyden-Fletcher-Goldfarb-Shanno (BFGS) method is one of the most efficient methods for unconstrained problems. Besides function values, it only requires the specification of the gradient. An approximate Hessian is calculated by successive approximations as part of the iteration, using rank-1 correction matrices. As a result, the iteration has superlinear convergence : when minimizing a quadratic function in n variables, if the one-dimensional minimizations in the calculated directions of search are done exactly, the Hessian matrix approximation is exact after n iterations, and from this, the iteration identifies to Newton's iteration, and produces the exact local optimum in only one additional iteration ($n + 1$ in total).

However the BFGS method does extend to constrained problems very simply. Following Gabay [82] and other authors, Chunhong Qi *et al* [120] have proposed a "Riemannian" variant, RBFGS that indeed incorporates equality constraints in the formulation and actually demonstrates superior convergence rates for problems with a large number of variables. However these Riemannian formulations are non trivial to implement since they require procedures implementing non-trivial differential-geometry operators ('retraction' and 'metric transport') to be developed. In their paper, they assume a formal expression of the constraint to be known. But, in PDE-constrained optimization, many constraints are functional, and it is not clear how can the metric transport operator in particular can be defined.

We are investigating how can a quasi-Riemannian method can be defined based on the sole definition of evaluation procedures for the gradients. By condensing all the equality constraints in one, a purely-explicit approximate retraction operator has been defined that yields a point whose distance to the contraint surface is fourth-order at least. The associated transport operator is currently being examined formally. These techniques will be experimented in the context of constrained optimum-shape design in aerodynamics [20]

7.17. Multifidelity surrogate modeling based on Radial Basis Functions

Participants: Jean-Antoine Désidéri, Cédric Durantin [CEA LETI Grenoble, doctoral student], Alain Glière [CEA LETI Grenoble, research engineer], Justin Rouxel [CEA LETI Grenoble, doctoral student].

Multiple models of a physical phenomenon are sometimes available with different levels of approximation. The high fidelity model is more computation-ally demanding than the coarse approximation. In this context, including information from the lower fidelity model to build a surrogate model is desirable. Here, the study focuses on the design of a miniaturized photoacoustic gas sensor which involves two numerical mod- els. First, a multifidelity metamodeling method based on Radial Basis Function, the co-RBF, is proposed. This surrogate model is compared with the classical co-kriging method on two analytical benchmarks and on the photoacoustic gas sensor. Then an extension to the multifidelity framework of an already existing RBF- based optimization algorithm is applied to optimize the sensor efficiency. The co-RBF method brings promising results on a problem in larger dimension and can be considered as an alternative to co-kriging for multifidelity metamodeling.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. Project BOUM

G. Costeseque holds a BOUM (SMAI) project on *"Mathematical homogenization techniques for traffic flow models"* with W. Salazar and M. Zaydan (LMI, INSA Rouen) and J.A. Firozaly (CERMICS, Ecole des Ponts ParisTech and LAMA, Université Paris-Est Créteil).

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. TraM3

Type: FP7

Defi: NC

Instrument: ERC Starting Grant

Objectif: NC

Duration: October 2010 - March 2016

Coordinator: Inria

Inria contact: Paola Goatin

Abstract: The project intends to investigate traffic phenomena from the macroscopic point of view, using models derived from fluid-dynamics consisting in hyperbolic conservation laws. The scope is to develop a rigorous analytical framework and fast and efficient numerical tools for solving optimization and control problems, such as queues lengths control or buildings exits design. See also: http://www-sop.inria.fr/members/Paola.Goatin/tram3.html

8.3. International Initiatives

8.3.1. Inria International Labs

Inria@SiliconValley

Associate Team involved in the International Lab:

8.3.1.1. 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

Start year: 2015

See also: http://www-sop.inria.fr/members/Paola.Goatin/ORESTE/index.html

This project focuses on traffic flow modeling and optimal management on road networks. Based on the results obtained during the first three years, we aim at further develop a unified macroscopic approach for traffic monitoring, prediction and control. In particular, we aim at investigating user equilibrium inference and Lagrangian controls actuations using macroscopic models consisting of conservation laws or Hamilton-Jacobi equations.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

- L.M. Villada-Osorio (February-July 2016, University of Bio-Bio, Chile): high order Discontinuous Galerkin and WENO finite volume schemes for non-local scalar conservation laws in one space-dimension.
- A. Borzí (June and October 2016, University of Wuerzburg): Stochastic differential games and Fokker-Planck equations.
- A. Keimer (November 2016, UC Berkeley): modeling and well-posedness study for Dynamic Traffic Assignement.

8.4.1.1. Internships

- C. De Filippis (April-August 2016, University of Milan - Bicohcca): well-posedness of initial-boundary value problems for non-local scalar conservation laws in one space-dimension.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

- P. Goatin was member of the scientific committee of *"PED2016 - Conference on Pedestrian and Evacuation Dynamics"*, Hefei (China), October 2016.
- P. Goatin is member of the the scientific committee of the annual seminar CEA-GAMNI *"Numerical fluid-mechanics"*.
- A. Habbal was member of the scientific committee of the *CARI 2016 Colloque Africain sur la Recherche en Informatique et Mathematiques Appliquees*, Tunis (Tunisia) 10-14 October 2016.

9.1.1.2. Member of the Organizing Committees

- P. Goatin organized the Workshop *"TRAM3 Terminus"*, Sophia Antipolis (France), January 2016.
- R. Duvigneau was co-organizer of the mini-symposium "Surrogate Models for Efficient Robust Optimization and Data Assimilation in Computational Mechanics", part of SIAM Conference on Uncertainty Quantification, Lausanne, April 2016.

9.1.2. Journal

9.1.2.1. Reviewer - Reviewing Activities

- J.-A. Désidéri has made reviews for the *International Journal of Information Technology & Decision Making*, and *Comptes Rendus de l'Académie des Sciences*,
- 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 is reviewers for the following international journals: Acta Applicandæ Mathematicæ ; African Journal of Mathematics and Computer Science Research; Algorithms; Annales de l'Institut Henri Poincaré (C) Analyse Non Linéaire; Applied Mathematics and Computation; Computer-aided Civil and Infrastructure Engineering; Discrete and Continuous Dynamical Systems; European Journal of Operational Research; IEEE Transactions on Automatic Control; IEEE Transactions on Intelligent Transportation Systems; International Journal of Dynamical Systems and Differential Equations; Journal of Computational Physics; Journal of Flow, Turbulence and Combustion; Mathematical Models and Methods in Applied Sciences; Mathematics of Computation; Networks and Heterogeneous Media; New Journal of Physics; Nonlinear Analysis Ser. B: Real World Applications; SIAM Journal of Mathematical Analysis; SIAM Journal of Applied Mathematics; SIAM Journal of Numerical Analysis; SIAM Journal on Scientific Computing.
- A. Habbal is reviewer for the following international journals: Applied Mathematics (AM), Scientific Research Publishing ; Journal of Structural and Multidisciplinary Optimization ; Journal of Math. Model. Nat. Phenom. ; International Journal of Mechanical Sciences ; Modern Applied Science ; Asian Journal of Control ; Applied Mathematics and Computation ; Computer Methods in Applied Mechanics and Engineering ; Bulletin of Mathematical Biology ; Journal of Pure and Applied Functional Analysis ; AMS reviews.

9.1.3. Invited Talks

- J.-A. Désidéri: ONERA Palaison, April 2016.
  Invited talk: *"Multiple Gradient Descent Algorithm for Multiobjective Optimization"*,
- R. Duvigneau: Ecole Navale, Brest, January 2016.
  Invited talk: *"The Sensitivity Equation Method for optimization, fast estimation of neighboring solutions and uncertainty propagation"*.
- R. Duvigneau: Ecole des Mines Paris-Tech, Sophia-Antipolis, June 2016.
  Invited talk: *"Optimization of complex fluid systems using a statistical learning strategy"*.
- P. Goatin: EU-US Frontiers of Engineering Symposium, Helsinki (Finland), October 2016.
  Session: "The road to future urban mobility".
  Invited talk: *"Traffic management by macroscopic models"*.

- P. Goatin: SIMAI 2016 - XIII Congress of the Italian Society of Industrial and Applied Mathematics, Milano (Italy), September 2016.
  Mini-symposium: “Analysis and numerics for the modeling through conservation laws”.
  Invited talk: *“A Riemann Solver at junctions preserving priorities”*.
  Mini-symposium: “Mean-field models in pedestrian dynamics”.
  Invited talk: *“Non-local macroscopic models of traffic flow”*.
- P. Goatin: 11th Meeting on Nonlinear Hyperbolic PDEs and Applications, Trieste (Italy), June 2016.
  Invited talk: *“Conservation laws with local constraints arising in traffic modeling”*.
- P. Goatin: SIAM Conference on Uncertainty Quantification, Lausanne (Switzerland), April 2016.
  Mini-symposium: “Data-driven methods for uncertainty quantification”.
  Invited talk: *“Parametric uncertainty in macroscopic traffic flow models calibration from GPS data”*.
- P. Goatin: Workshop “Analysis and control on networks: trends and perspectives”, Padova (Italy), March 2016.
  Invited talk: *“Optimization based control of networks of discretized PDEs: Application to road traffic management”*.
- P. Goatin: ANR HJNet 5th Meeting, Tours (France), January 2016.
  Invited talk: *“Conservation laws with local and unilateral flux constraints”*.
- A. Habbal: IX NPU-UTC Sino-French Seminar on Virtual Prototyping for Design and Fabrication, 11-15 April 2016.
  Invited talk: *“Pareto optimality and game equilibria, two approaches to solve multiobjective optimization”*.
- A. Habbal: Lorentz Center workshop SAMCO: Surrogate-Assisted Multi-Criteria Optimization, February 29 - March 4, 2016.
  Invited senior participant: *"Many objectives and selection algorithms"*.

9.1.4. Scientific Expertise

J.-A. Désidéri has been a consultant for ONERA (since 2007) at DMFN-Châtillon (Dept. of Numerical Fluid Mechanics) and DAAP-Meudon (Dept. of Applied Aerodynamics), and also directs a thesis at DADS-Châtillon (Dept. of Aeroelasticity and Structural Dynamics).

9.1.5. Research Administration

- P. Goatin is member of BCP (“Bureau du Comité des Projets”) 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, R. Duvigneau).

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: Concurrent design in building structures, M2 Students Project, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (A. Habbal).

9.2.2. Supervision

PhD in progress : Cédric Durantin, *Meta-modelling for the optimization of nanophotonic devices*, October 2014. Supervisors : J.-A. Désidéri and A. Glière (CEA LETI).

PhD in progress : Quentin Mercier, *Multicriterion optimization under uncertainties : the stochastic multiple gradient approach. Application to aerelasticity*, October 2015. Supervisors : J.-A. Désidéri and F. Poirion.

PhD in progress : Maroua Mokni, *Development, analysis and numerical evaluation of MGDA*, October 2013. Supervisors : J.-A. Désidéri and M. Ayadi (LAMSIN-ENIT, Tunisia).

PhD in progress : 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 in progress: Boutheina Yahyaoui, *Validation of mecano-chemo-biological models for cell sheet wound closure*, Jan 2013, Supervisors: A. Habbal, Mekki Ayadi (LAMSIN, ENIT, Tunis)

PhD in progress: Rabeb Chamekh, *Game strategies for thermo-elasticity*, Jan 2015, 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 in progress: A. Azaouzi, *isogeometric analysis methods for hyperbolic systems*, ENIT (Tunisia) / University of Nice - Sophia Antipolis, Oct. 2013, supervisors: R. Duvigneau and M. Moakher (ENIT).

PhD in progress: 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 in progress: C. Fiorini, *Sensitivity equation method for hyperbolic systems*, Univ. Versailles, Oct. 2014, supervisors: R. Duvigneau, C. Chalons (Univ. Versailles).

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

PhD in progress : Emanuele Marrone (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

- P. Goatin was member of the committee of C. Perrin's PhD thesis *"Modèles hétérogènes en mécanique des fluides : phénomènes de congestion, écoulements granulaires et mouvement collectif"*, Université de Grenoble, July 8th, 2016.
- P. Goatin was referee of R. Sainct's PhD thesis *"Etude des instabilités dans les modèles de trafic"*, Université Paris-Est, September 22th, 2016.
- P. Goatin was member of the committee of M. Campanella's PhD thesis *"Microscopic modelling of walking behaviour"*, Delft University of Technology, November 21st, 2016.
- R. Duvigneau was member of the committee of Kevin Kasper's PhD thesis *"Apprentissage d'estimateurs sans modèle avec peu de mesures - Application à la mécanique des fluides"*, ENS Cachan, October 12th, 2016.

10. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journal

[1] A. AGGARWAL, P. GOATIN. *Crowd Dynamics through Non-Local Conservation Laws*, in "Boletim da Sociedade Brasileira de Matemática / Bulletin of the Brazilian Mathematical Society", 2016, vol. 47, p. 37 - 50 [*DOI :* 10.1007/S00574-016-0120-7], https://hal.inria.fr/hal-01402613.

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Project-Team AOSTE

Models and methods of analysis and optimization for systems with real-time and embedding constraints

IN COLLABORATION WITH: Laboratoire informatique, signaux systèmes de Sophia Antipolis (I3S)

IN PARTNERSHIP WITH:
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THEME
Embedded and Real-time Systems

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Project-Team AOSTE

Creation of the Project-Team: 2004 July 01, end of the Project-Team: 2016 December 31

Keywords:

Computer Science and Digital Science:

1.1.1. - Multicore
1.1.2. - Hardware accelerators (GPGPU, FPGA, etc.)
1.1.12. - Non-conventional architectures
1.2.3. - Routing
1.2.5. - Internet of things
1.2.7. - Cyber-physical systems
1.5.1. - Systems of systems
1.5.2. - Communicating systems
2.1.1. - Semantics of programming languages
2.1.6. - Concurrent programming
2.1.8. - Synchronous languages
2.1.10. - Domain-specific languages
2.2.4. - Parallel architectures
2.2.5. - GPGPU, FPGA, etc.
2.3. - Embedded and cyber-physical systems
2.4.1. - Analysis
2.4.2. - Model-checking
4.5. - Formal methods for security
6.1.5. - Multiphysics modeling
6.2.7. - High performance computing
7.2. - Discrete mathematics, combinatorics
7.11. - Performance evaluation

Other Research Topics and Application Domains:

5.1. - Factory of the future
5.4. - Microelectronics
6.1.1. - Software engineering
6.4. - Internet of things
6.6. - Embedded systems
8.1. - Smart building/home

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2. Overall Objectives

2.1. Embedded System Design

Typical embedded software *applications* display a mix of multimedia signal/data processing with modal interfaces, resulting in heterogenous concurrent data-flow streaming models, and often stringent real-time constraints. Similarly, embedded *architectural platforms* are becoming increasingly parallel, with dedicated hardware accelators and manycore processors. The optimized compilation of such kinds of applications onto such execution platforms involves complex mapping issues, both in terms of spatial distribution and in terms of temporal scheduling. Currently, it is far from being a fully automatic compilation process as in the case of commodity PC applications. Models are thus needed, both as formal mathematical objects from theoretical computer science to provide foundations for embedded system design, and also as engineering models to support an effective design flow.

Our general approach is directly inspired from the theories of synchronous languages, process networks, and of real-time distributed scheduling. We insist on the introduction of *logical time* as functional design ingredient to be explicitly considered as first-class modeling element of systems. Logical time is based on logical clocks, where such a clock can be defined as any meaningful sequence of event occurrences, usually meant as activation/triggering conditions for actions and operations in the systems. So logical time can be multiform, a global partial order built from local total orders of clocks. In the course of the design flow *time refinement* takes place, as decison are made towards placement and timing of various tasks and operations. This solves in part the constraints between clocks, committing to schedule and placement decisions. The final version should be totally ordered, and then subjet to physical timing verification as to physical constraints.

The general (logical) *Time Model* has been standardized as part of the OMG profile for Modeling and Analysis of Real-Time Embedded systems (MARTE).

Work on polychronous formalisms (descending from ESTEREL), on a Clock Constraint Specification Language (CCSL) handling logical time, on Application-Architecture Adequation approach and real-time scheduling results has been progressed over the years, resulting in sofware environments such as SYNDEX or TimeSquare.

3. Research Program

3.1. Models of Computation and Communication (MoCCs)

Participants: Julien Deantoni, Robert de Simone, Frédéric Mallet, Dumitru Potop Butucaru.

Esterel, SyncCharts, synchronous formalisms, Process Networks, Marked Graphs, Kahn networks, compilation, synthesis, formal verification, optimization, allocation, refinement, scheduling

Formal Models of Computation form the basis of our approach to Embedded System Design. Because of the growing importance of communication handling, it is now associated with the name, MoCC in short. The appeal of MoCCs comes from the fact that they combine features of mathematical models (formal analysis, transformation, and verification) with these of executable specifications (close to code level, simulation, and implementation). Examples of MoCCs in our case are mainly synchronous reactive formalisms and dataflow process networks. Various extensions or specific restrictions enforce respectively greater expressivity or more focused decidable analysis results.

DataFlow Process Networks and Synchronous Reactive Languages such as ESTEREL/SYNCCHARTS and SIGNAL/POLYCHRONY [54], [55], [49], [15], [4], [13] share one main characteristics: they are specified in a self-timed or loosely timed fashion, in the asynchronous data-flow style. But formal criteria in their semantics ensure that, under good correctness conditions, a sound synchronous interpretation can be provided, in which all treatments (computations, signaling communications) are precisely temporally mapped. This is refered to as clock calculus in synchronous reactive systems, and leads to a large body of theoretical studies and deep results in the case of DataFlow Process Networks [50], [48] (consider SDF balance equations for instance [56]).

As a result, explicit schedules become an important ingredient of design, which ultimately can be considered and handled by the designer him/herself. In practice such schedules are sought to optimize other parts of the design, mainly buffering queues: production and consumption of data can be regulated in their relative speeds. This was specially taken into account in the recent theories of Latency-Insensitive Design [51], or N-synchronous processes [52], with some of our contributions [6].

Explicit schedule patterns should be pictured in the framework of low-power distributed mapping of embedded applications onto manycore architectures, where they could play an important role as theoretical formal models on which to compute and optimize allocations and performances. We describe below two lines of research in this direction. Striking in these techniques is the fact that they include time and timing as integral parts of early functional design. But this original time is logical, multiform, and only partially ordering the various functional computations and communications. This approach was radically generalized in our team to a methodology for logical time based design, described next (see 3.2).

3.1.1. K-periodic static scheduling and routing in Process Networks

In the recent years we focused on the algorithm treatments of ultimately k-periodic schedule regimes, which are the class of schedules obtained by many of the theories described above. An important breakthrough occurred when realizing that the type of ultimatelly periodic binary words that were used for reporting *static scheduling* results could also be employed to record a completely distinct notion of ultimately k-periodic route switching patterns, and furthermore that commonalities of representation could ease combine them together. A new model, by the name of K-periodical Routed marked Graphs (KRG) was introduced, and extensively studied for algebraic and algorithmic properties [5].

The computations of optimized static schedules and other optimal buffering configurations in the context of latency-insensitive design led to the K-Passa software tool development (now terminated)

3.1.2. Endochrony and GALS implementation of conflict-free polychronous programs

The possibility of exploring various schedulings for a given application comes from the fact that some behaviors are truly concurrent, and mutually *conflict-free* (so they can be executed independently, with any choice of ordering). Discovering potential asynchronous inside synchronous reactive specifications then becomes something highly desirable. It can benefit to potential distributed implementation, where signal communications are restricted to a minimum, as they usually incur loss in performance and higher power consumption. This general line of research has come to be known as Endochrony, with some of our contributions [11].

3.2. Logical Time in Model-Driven Embedded System Design

Participants: Julien Deantoni, Frédéric Mallet, Marie Agnes Peraldi Frati, Robert de Simone.

Starting from specific needs and opportunities for formal design of embedded systems as learned from our work on MoCCs (see 3.1), we developed a Logical Time Model as part of the official OMG UML profile MARTE for Modeling and Analysis of Real-Time Embedded systems. With this model is associated a Clock Constraint Specification Language (CCSL), which allows to provide loose or strict logical time constraints between design ingredients, be them computations, communications, or any kind of events whose repetitions can be conceived as generating a logical conceptual clock (or activation condition). The definition of CCSL is provided in [1].

Our vision is that many (if not all) of the timing constraints generally expressed as physical prescriptions in real-time embedded design (such as periodicity, sporadicity) could be expressed in a logical setting, while actually many physical timing values are still unknown or unspecified at this stage. On the other hand, our logical view may express much more, such as loosely stated timing relations based on partial orderings or partial constraints.

So far we have used CCSL to express important phenonema as present in several formalisms: AADL (used in avionics domain), EAST-ADL2 (proposed for the AutoSar automotive electronic design approach), IP-Xact (for System-on-Chip (*SoC*) design). The difference here comes from the fact that these formalisms were formerly describing such issues in informal terms, while CCSL provides a dedicated formal mathematical notation. Close connections with synchronous and polychronous languages, especially Signal, were also established; so was the ability of CCSL to model dataflow process network static scheduling.

In principle the MARTE profile and its Logical Time Model can be used with any UML editor supporting profiles. It has also evolved to become a Domain-Specific Language, independent of UML. It is connected to the CAPELLA environment, and the PAPYRUS open-source editor. We developed under Eclipse the TIMESQUARE solver and emulator for CCSL constraints (see 5.6), with its own graphical interface, as a stand-alone software module, again now coupled with MARTE and Papyrus, but also as part of the GeMoC studio environment developed in the GeMoC ANR project.

The MARTE profile and its Logical Time Model can be used with any UML editor supporting profiles but evolved to become a DSL independant of UML. We developed as a set of eclipse plugins the TIMESQUARE tool to edit and simulate CCSL specifications. TimeSquare has been coupled with various tools like Papyrus or Capella and is now part of the concurent solver integrated in the GEMOC studio.

While CCSL constraints may be introduced as part of the intended functionality, some may also be extracted from requirements imposed either from real-time user demands, or from the resource limitations and features from the intended execution platform. Sophisticated detailed descriptions of platform architectures are allowed using MARTE, as well as formal allocations of application operations (computations and communications) onto platform resources (processors and interconnects). This is of course of great value at a time where embedded architectures are becoming more and more heterogeneous and parallel or distributed, so that application mapping in terms of spatial allocation and temporal scheduling becomes harder and harder. This approach is extensively supported by the MARTE profile and its various models. As such it originates from the Application-Architecture-Adequation (AAA) methodology, first proposed by Yves Sorel, member of Aoste. AAA aims at specific distributed real-time algorithmic methods, described next in 3.3.

Of course, while logical time in design is promoted here, and our works show how many current notions used in real-time and embedded systems synthesis can naturally be phrased in this model, there will be in the end a phase of validation of the logical time assumptions (as is the case in synchronous circuits and SoC design with timing closure issues). This validation is usually conducted from Worst-Case Execution Time (WCET) analysis on individual components, which are then used in further analysis techniques to establish the validity of logical time assumptions (as partial constraints) asserted during the design.

3.3. The AAA (Algorithm-Architecture Adequation) methodology and Real-Time Scheduling

Participants: Liliana Cucu, Laurent George, Dumitru Potop Butucaru, Yves Sorel.

Note: The AAA methodology and the SynDEx environment are fully described at http://www.syndex.org/, together with relevant publications.

3.3.1. Algorithm-Architecture Adequation

The AAA methodology relies on distributed real-time scheduling and relevant optimization to connect an Algorithm/Application model to an Architectural one. We now describe its premises and benefits.

The Algorithm model is an extension of the well known data-flow model from Dennis [53]. It is a directed acyclic hyper-graph (DAG) that we call “conditioned factorized data dependence graph”, whose vertices are “operations” and hyper-edges are directed “data or control dependences” between operations. The data dependences define a partial order on the operations execution. The basic data-flow model was extended in three directions: first infinite (resp. finite) repetition of a sub-graph pattern in order to specify the reactive aspect of real-time systems (resp. in order to specify the finite repetition of a sub-graph consuming different data similar to a loop in imperative languages), second “state” when data dependences are necessary between different infinite repetitions of the sub-graph pattern introducing cycles which must be avoided by introducing specific vertices called “delays” (similar to z^{-n} in automatic control), third “conditioning” of an operation by a control dependence similar to conditional control structure in imperative languages, allowing the execution of alternative subgraphs. Delays combined with conditioning allow the programmer to specify automata necessary for describing “mode changes”.

The Architecture model is a directed graph, whose vertices are of two types: “processor” (one sequencer of operations and possibly several sequencers of communications) and “medium” (support of communications), and whose edges are directed connections.

The resulting implementation model [9] is obtained by an external compositional law, for which the architecture graph operates on the algorithm graph. Thus, the result of such compositional law is an algorithm graph, "architecture-aware", corresponding to refinements of the initial algorithm graph, by computing spatial (distribution) and timing (scheduling) allocations of the operations onto the architecture graph resources. In that context "Adequation" refers to some search amongst the solution space of resulting algorithm graphs, labelled by timing characteristics, for one algorithm graph which verifies timing constraints and optimizes some criteria, usually the total execution time and the number of computing resources (but other criteria may exist). The next section describes distributed real-time schedulability analysis and optimization techniques for that purpose.

3.3.2. Distributed Real-Time Scheduling and Optimization

We address two main issues: uniprocessor and multiprocessor real-time scheduling where constraints must mandatorily be met, otherwise dramatic consequences may occur (hard real-time) and where resources must be minimized because of embedded features.

In the case of uniprocessor real-time scheduling, besides the classical deadline constraint, often equal to a period, we take into consideration dependences beetween tasks and several, latencies. The latter are complex related “end-to-end” constraints. Dealing with multiple real-time constraints raises the complexity of the scheduling problems. Moreover, because the preemption leads, at least, to a waste of resources due to its approximation in the WCET (Worst Execution Time) of every task, as proposed by Liu and Leyland [57], we first studied non-preemtive real-time scheduling with dependences, periodicities, and latencies constraints. Although a bad approximation of the preemption cost, may have dramatic consequences on real-time scheduling, there are only few researches on this topic. We have been investigating preemptive real-time scheduling since few years, and we focus on the exact cost of the preemption. We have integrated this cost in the schedulability conditions that we propose, and in the corresponding scheduling algorithms. More generally, we are interested in integrating in the schedulability analyses the cost of the RTOS (Real-Time Operating System), for which the cost of preemption is the most difficult part because it varies according to the instance (job) of each task.

In the case of multiprocessor real-time scheduling, we chose at the beginning the partitioned approach, rather than the global approach, since the latter allows task migrations whose cost is prohibitive for current commercial processors. The partitioned approach enables us to reuse the results obtained in the uniprocessor case in order to derive solutions for the multiprocessor case. We consider also the semi-partitioned approach which allows only some migrations in order to minimize the overhead they involve. In addition to satisfy the multiple real-time constraints mentioned in the uniprocessor case, we have to minimize the total execution time (makespan) since we deal with automatic control applications involving feedback loops. Furthermore, the domain of embedded systems leads to solving minimization resources problems. Since these optimization problems are NP-hard we develop exact algorithms (B & B, B & C) which are optimal for simple problems, and heuristics which are sub-optimal for realistic problems corresponding to industrial needs. Long time ago we proposed a very fast “greedy” heuristics [8] whose results were regularly improved, and extended with local neighborhood heuristics, or used as initial solutions for metaheuristics.

In addition to the spatial dimension (distributed) of the real-time scheduling problem, other important dimensions are the type of communication mechanisms (shared memory vs. message passing), or the source of control and synchronization (event-driven vs. time-triggered). We explore real-time scheduling on architectures corresponding to all combinations of the above dimensions. This is of particular impact in application domains such as automotive and avionics (see 4.3).

The arrival of complex hardware responding to the increasing demand for computing power in next generation systems exacerbates the limitations of the current worst-case real-time reasoning. Our solution to overcome these limitations is based on the fact that worst-case situations may have a extremely low probability of appearance within one hour of functioning (10^{-45}), compared to the certification requirements for instance (10^{-9} for the highest level of certification in avionics). Thus we model and analyze the real-time systems using probabilistic models and we propose results that are fundamental for the probabilistic worst-case reasoning over a given time window.

4. Application Domains

4.1. System Engineering Environments

Participants: Robert de Simone, Julien Deantoni, Frédéric Mallet, Marie Agnes Peraldi Frati.

In the case of Embedded and Cyber-Physical Systems, the cyber/digital design of discrete controlers is only a part of a larger design process, we other aspects of the physical environment need to be condidered as well, involving constraints and requirements on the global system (people even talk of *Systems of Systems*. Dedicated environments are now being defined, also considering system life-cycle and component reuse in this larger setting, under the name of *Atelier Génie Système* (in French). Such efforts usually involve large industrial end-users, together with software houses of tool vendors, and academic partners altogether. An instance of such environment is the Cappella (open-source, Eclipse) environment, promoted by the Clarity project and its associated consortium 8.1.2.2.

4.2. Many-Core Embedded Architectures

Participants: Robert de Simone, Dumitru Potop Butucaru, Liliana Cucu, Yves Sorel.

The AAA approach (fitting embedded applications onto embedded architectures) requires a sufficiently precise description of (a model of) the architecture (description platform). Such platforms become increasingly heterogeneous, and we had to consider a number of emerging ones with that goal in mind, such as Kalray MPPA (in the CAPACITES project 8.1.2.3, IntelCore dual CPU/GPU structure in a collaboration with Kontron, ARM big.LITTLE architecture in the course of the HOPE ANR project 8.1.1.1, or a dedicated supercomputer based on Network-on-Board interconnect in the Clistine project 8.1.1.3.

4.3. Transportation and the avionic domain

Participants: Robert de Simone, Julien Deantoni, Frédéric Mallet, Marie Agnès Peraldi Frati, Dumitru Potop Butucaru, Liliana Cucu, Yves Sorel.

A large number of our generic activities, both on modeling and design, and on analysis and implementation of real-time embedded systems, found specific applications in the avionic field (with partners such as Airbus, Thales, Safran,...), while other targets remained less attainable (car industry for instance).

5. New Software and Platforms

5.1. EVT Kopernic

Extreme Value Theory for Keeping Worst Reasoning Appropriate for Different Criticalities

FUNCTIONAL DESCRIPTION This software provides a probabilistic bound on the worst case execution time of a program. Its third version, released in March 2016, covers the case of statistically dependent execution times. Currently integrated in Rapitime (Rapita tool chain), a lighter version is under preparation for integration in FUI Waruna framework as well as in the preparation of hybrid versions to be released in 2017 as output of Capacites project.

- Participants: Liliana Cucu and Adriana Gogonel
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- URL: https://who.rocq.inria.fr/Liliana.Cucu/Software.html

5.2. KPASSA

K-Periodic Asap Static Schedule Analyser

FUNCTIONAL DESCRIPTION This software is dedicated to the simulation, analysis, and static scheduling of Event/Marked Graphs, SDF and KRG extensions. A graphical interface allows to edit the Process Networks and their time annotations (latency, ...). Symbolic simulation and graph-theoretic analysis methods allow to compute and optimize static schedules, with best throughputs and minimal buffer sizes. In the case of KRG the (ultimately k-periodic) routing patterns can also be provided and transformed for optimal combination of switching and scheduling when channels are shared. KPASSA also allows for import/export of specific description formats such as UML-MARTE, to and from our other TimeSquare tool.

- Participants: Jean Vivien Millo and Robert De Simone
- Contact: Robert de Simone
- URL: http://www-sop.inria.fr/members/Jean-Vivien.Millo/kpassa/index.php

5.3. Lopht

Logical to Physical Time Compiler

SCIENTIFIC DESCRIPTION Lopht is a system-level compiler for embedded systems. Its input is formed of three objects:

- A functional specification in a high-level synchronous language.
- A description of the implementation platform, defining the topology of the parallel execution platform, and the capacity of its elements.
- A set of non-functional requirements, provided under the form of annotations on both functional specification and platform description.

The algorithmic core of Lopht is formed of allocation and scheduling heuristics which rely on two fundamental choices: the use of table-based static scheduling and the use of low-complexity heuristics based on list scheduling. The output of Lopht is formed of all the C code and configuration information needed to allow real deployment on the physical target platform.

FUNCTIONAL DESCRIPTION Accepted input languages for functional specifications include Heptagon and Scade v4. Lopht uses as f ront-end a modified version of the Heptagon compiler developed at Inria. The use of this front-end also allows the use of legacy/business C code satisfying the Heptagon calling convention.
Regarding scheduling, the originality of Lopht resides in a strong focus on classical compiler optimizations e.g. software pipelining), on novel architectural targets (many-core chips and time-triggered embedded systems), and the possibility to handle multiple, complex non-functional requirements covering real-time (release dates a nd deadlines possibly larger than the period, end-to-end flow constraints), ARINC 653 partitioning, the possibility to preempt or not each task, and allocation.
The output of Lopht is formed of all the C code and configuration information needed to allow compilation, linking/loading, and real-time execution on the target platform. Lopht fully automates the creation of tasks, partition, the full synthesis of C code compliant with the target API (e.g. C/APEX for ARINC 653 platforms), including communication code, and OS configuration for each computer), as well as the synthesis of communication schedules for the system

Two Lopht back-ends provide distinct input languages for platform description:

- One for distributed time-triggered architectures using ARINC 653-based processing nodes (SBCs) and Time-Triggered Ethernet networks
- One for many-core processors with support with timing predictability.

An ongoing research effort aims at providing a unified, formal platform description language allowing the unification of these back-ends.

- Participants: Dumitru Potop Butucaru, Raul Gorcitz, and Keryan Didier
- Contact: Dumitru Potop Butucaru

5.4. SAS

Simulation and Analysis of Scheduling
SCIENTIFIC DESCRIPTION The SAS (Simulation and Analysis of Scheduling) software allows the user to perform the schedulability analysis of periodic task systems in the monoprocessor case.

The main contribution of SAS, when compared to other commercial and academic softwares of the same kind, is that it takes into account the exact preemption cost between tasks during the schedulability analysis. Beside usual real-time constraints (precedence, strict periodicity, latency, etc.) and fixed-priority scheduling policies (Rate Monotonic, Deadline Monotonic, Audsley++, User priorities), SAS additionaly allows to select dynamic scheduling policy algorithms such as Earliest Deadline First (EDF). The resulting schedule is displayed as a typical Gantt chart with a transient and a permanent phase, or as a disk shape called "dameid", which clearly highlights the idle slots of the processor in the permanent phase.
FUNCTIONAL DESCRIPTION The SAS software allows the user to perform the schedulability analysis of periodic task systems in the monoprocessor case.

- Participants: Daniel De Rauglaudre and Yves Sorel
- Contact: Yves Sorel
- URL: http://pauillac.inria.fr/~ddr/sas-dameid/

5.5. SynDEx

KEYWORDS: Embedded systems - Real time - Optimization - Distributed - Scheduling analyses
SCIENTIFIC DESCRIPTION SynDEx is a system level CAD software implementing the AAA methodology for rapid prototyping and for optimizing distributed real-time embedded applications. It is developed in OCaML.

Architectures are represented as graphical block diagrams composed of programmable (processors) and non-programmable (ASIC, FPGA) computing components, interconnected by communication media (shared memories, links and busses for message passing). In order to deal with heterogeneous architectures it may feature several components of the same kind but with different characteristics.

Two types of non-functional properties can be specified for each task of the algorithm graph. First, a period that does not depend on the hardware architecture. Second, real-time features that depend on the different types of hardware components, ranging amongst execution and data transfer time, memory, etc.. Requirements are generally constraints on deadline equal to period, latency between any pair of tasks in the algorithm graph, dependence between tasks, etc.

Exploration of alternative allocations of the algorithm onto the architecture may be performed manually and/or automatically. The latter is achieved by performing real-time multiprocessor schedulability analyses and optimization heuristics based on the minimization of temporal or resource criteria. For example while satisfying deadline and latency constraints they can minimize the total execution time (makespan) of the application onto the given architecture, as well as the amount of memory. The results of each exploration is visualized as timing diagrams simulating the distributed real-time implementation.

Finally, real-time distributed embedded code can be automatically generated for dedicated distributed real-time executives, possibly calling services of resident real-time operating systems such as Linux/RTAI or Osek for instance. These executives are deadlock-free, based on off-line scheduling policies. Dedicated executives induce minimal overhead, and are built from processor-dependent executive kernels. To this date, executives kernels are provided for: TMS320C40, PIC18F2680, i80386, MC68332, MPC555, i80C196 and Unix/Linux workstations. Executive kernels for other processors can be achieved at reasonable cost following these examples as patterns.
FUNCTIONAL DESCRIPTION Software for optimising the implementation of embedded distributed real-time applications and generating efficient and correct by construction code

- Participants: Yves Sorel and Meriem Zidouni
- URL: http://www.syndex.org

5.6. TimeSquare

KEYWORDS: Profil MARTE - Embedded systems - UML - IDM
SCIENTIFIC DESCRIPTION TimeSquare offers six main functionalities:

- graphical and/or textual interactive specification of logical clocks and relative constraints between them,
- definition and handling of user-defined clock constraint libraries,
- automated simulation of concurrent behavior traces respecting such constraints, using a Boolean solver for consistent trace extraction,
- call-back mechanisms for the traceability of results (animation of models, display and interaction with waveform representations, generation of sequence diagrams...).
- compilation to pure java code to enable embedding in non eclipse applications or to be integrated as a time and concurrency solver within an existing tool.
- a generation of the whole state space of a specification (if finite of course) in order to enable model checking of temporal properties on it

FUNCTIONAL DESCRIPTION TimeSquare is a software environment for the modeling and analysis of timing constraints in embedded systems. It relies specifically on the Time Model of the Marte UML profile, and more accurately on the associated Clock Constraint Specification Language (CCSL) for the expression of timing constraints.

- Participants: Frederic Mallet, and Julien Deantoni
- Contact: Frederic Mallet
- URL: http://timesquare.inria.fr

5.7. Vercors

KEYWORD:

- Participants: Eric Madelaine, Oleksandra Kulankhina, Jimmy Awk, Xudong Qin
- Contact: Eric Madelaine
- URL: http://www-sop.inria.fr/oasis/Vercors

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.

We have achieved this year a major version of the platform frontend, named VCE-v4, that is now distributed on our website, and used by some of our partners. This version features a full chain of tools from the design of systems in the graphical component editors (VCE), the checking of static semantics correcteness, the generation of a semantic model suitable for model-checking, and finally the generation of executable code for the Proactive/GCM platform. These new features, and the tool architecture, have been described in [29] and [18].

6. New Results

6.1. CCSL as a Logical Clock Calculus Algebra: expressiveness and analysis techniques

Participants: Robert de Simone, Julien Deantoni, Frédéric Mallet, Dongdong An.

CCSL is a simple, half-declarative and half-imperative language describing relations and constraints between sequences of events considered as Logical Clocks. The usage of CCSL for specification of embedded systems is powerful in that it defers the precise setting of physical timing until later implementation design phases (which may vary according to circumstances), see 3.2.

Early this year we established the universal recursive expressivity of CCSL, by encoding the dynamics of Petri Nets with inhibitor arcs in our framework (still unpublished). Those results were presented by Robert de Simone in a keynote talk at Memocode 2016. This result prompts the use of non-automatic methods for establishing actual schedules as solutions of CCSL specifications seen as schedulability constraints. Steps in that direction were made in [37].

We also considered the extension of CCSL towards stochastic modeling of potential input clocks as my emerge from the Cyber-Physical world (mixing probabilistic modeling of external events with discrete transformations by discrete cyber digital controlers). This work was initiated in [28], and should be further extended in the ongoing PhD thesis of Dongdong An.

Finally, we have also investigated to decide on specific schedules (e.g. periodic schedules) valid for a subset of CCSL. We have established a sufficient static condition for the existence of such a periodic schedule as well as a practical implementation to build such a solution [39] based on a SMT solver.

6.2. Industrial design flow for Embedded System Engineering

Participants: Julien Deantoni, Frédéric Mallet, Marie Agnes Peraldi Frati, Robert de Simone, Hui Zhao, Ales Mishchenko.

As part of the PIA LEOC Clarity collaborative project we considered the inytroduction of formal methods into a high-level model-based design environment for embedded systems, named CAPELLA (https://polarsys.org/capella/). CAPELLA is part of the Polarsys Eclipse project. It originates from Thales, and is currently being deployed in real operational divisions in a number of companies.

Our activities consisted in demonstrating how the theoretical models of Logical Time and derives Models of Computation could be used to give precise semantics and provide simulation benefits, when applied to the modeling paradigms used in CAPELLA and advanced in Clarity. In particular we focused on the connection between timing/performance properties and other kinds of non-functional properties, including model variability.

This year we focused on two mains tasks:

First, we clarified and extended the notion of Modes and States in the Capella system engineering language. Specifically, a specific diagram has been introduced to deal with the system modes. The notion of mode is then used to specify different configurations of the system, mainly in terms of the active functions, their data dependencies, their deployment on the logical and physical architecture as well as the scenario to be verified in this specific mode. In consequence, the behavioural semantics of the mode diagram strongly interacts with the behavioral semantics of the other diagrams. The execution semantics was given by promoting our contributions in GEMOC and BCOoL (see 6.3).

Second, Capella proposes a consistent multi-view approach accross different engineering domains. At some step in the refinement process, these different views are extracted to a domain specific tool (like Simulink for instance). It is then required 1) to verify that the manipulation done in the domaine specific tool respect the original semantics expected by the architect, and 2) to understand the impact of the decisions made in domain specific tools on the interaction with the other views. To do so we provided a generic aproach to confront the race to the behavioral semantics we formally defined in Capella. We are curretly working on a theoretical approach to improve the overal performance of such approach.

While BCOoL and Gemoc only considers discrete models, the PhD thesis of Hui Zhao, which started in March 2016, explores a possible extension that specifically targets Cyber-Physical Systems where we different timed models combined, including both discrete and dense timed models. In this thesis, we also explore the impact of such an heterogeneous modeling framework to guarantee security and safety properties of the combined models. This is done in collaboration with Ludovic Apvrille (who is co-advisor of the thesis) from Telecom ParisTech.

6.3. Coordination of heterogeneous Models of Computation as Domain-Specific Languages

Participants: Matias Vara Larsen, Julien Deantoni, Frédéric Mallet.

Our work this on coordination of heterogeneous languages produced two major results. The first one is the development of BCOoL (Behavioral Coordination Operator Language. BCOoL is a language dedicated to the specification of coordination patterns between heterogeneous languages. It comes with a tool chain allowing the generation of the coordination given a BCOoL operator and specific models. Our second result is the development of an heterogeneous execution engine, integrated to Gemoc studio, to run conjointly different models. Both works re extensively reported in Matias Vara Larsen PhD thesis [19].

6.4. SoC multiview (meta)modeling for performance, power, and thermal aspects

Participants: Amani Khecharem, Robert de Simone, Emilien Kofman, Julien Deantoni.

In the framework of the ANR HOPE project we progressed the definition of multiview metamodels for the design of Systems-on-Chip) (SoC systems integrating performance, power and thermal aspects. The main concern was to stress regularity and commonalitbetween those views, each developed on "domains" defined as partitions of the original block diagram (clock domains, voltage domains, floorplans,...), and with finite state machine controlers setting the levels of these domains; links between distinct views are originally provided by laws of physics, but then usually identified with discrete allowed values(such as OPP, Operating Performance Points, providing the available frequency-voltage levels for processor clocks).

The corresponding methodology, named MuArch, was reported as Ameni Khacharem PhD document [16].

6.5. MoCs and novel architectures

Participants: Amine Oueslati, Robert de Simone, Albert Savary, Emilien Kofman.

In the context of the FUI Clistine project we considered the links betwen formal Models of Computation and parallel programming models (MPI mainly). The objective is to figure to what level an abstraction of MPI processes as concuurent communicating processes can help for the AAA design process being applied to theselection of adequate MPI communications. This topic reflects the ongoing PhD thesis of Amine Oueslati, and the engineering work of Albert Savary in the first semester.

6.6. Solving AAA constraints analytically

Participants: Emilien Kofman, Dumitru Potop Butucaru, Robert de Simone, Amine Oueslati.

We experimented on the use of SMT solvers to compute efficient mappings (bothe schedules and placement allocations) for concurrent embedded applications onto specific embedded architectures of big.LITTLE features (where alocation and migration of tasks can follow concern for low-power consumption). In fact, the work consisted greatly in a study of how the various models could be encoded to scale up, allowing the solvesr to provide results in reasonalble time. The results have been presented [41], [31], and will soon appear as E. Kofman PhD thesis.

6.7. Coupling SystemC and FMI for co-simulation of Cyber-Physical Systems

Participants: Stefano Centomo, Julien Deantoni, Robert de Simone.

In collaboration with Professor Davide Quaglia, from the University of Verona, we are studying the proper joint modeling of interactions between different domains involved in a cyber-physical system (CPS), and specifically between the cyber and physical parts. In our first work, realized in the context of Stefano Centomo master internship, we investigated how an event based hardware description language can be used in an emerging industry standard for co-simulation (FMI/FMU developed orginally in a Modelica framework). Preliminary results were published [26], and we hope to start a PhD as follow-up of these results.

6.8. Behavioural Semantics if Open pNets

Participants: Eric Madelaine, Ludovic Henrio, Siqi Li, Min Zhang.

We have extended our preliminary work on Parameterised Networks of Automata (pNets), by looking at the behavioural semantics and at bisimulation equivalences for open pNet systems. These can be used to encode operators of various process algebras, construct of distributed or reactive system programming languages, or even parallel algorithmic skeletons, and generic distributed algorithms. As a first step, we studied the properties of a strong bisimulation equivalence based on logical hypotheses about the behaviour of process variables in the open systems. This has been published in [22], [33] and an extended version as an Inria research report [43]. We are now implementing algorithms for computing the symbolic behavioural semantics of open pNets, and checking strong bisimulation, using a SAT engine for reasoning on the hypotheses.

In order to understand better this behavioural semantics, we also have defined another version with a denotational flavour, namely using a “Universal Theory of Processes (UTP)” style. There we express the communication actions of pNets using traces of interaction events, and we were able to prove axiomatic properties of some simple (open) pNets. This was published in [32]. In the long term, it could be interesting to study the relations between the FH-bisimulation and the UTP semantics, relating both behavioural, denotational and algebraic semantics of pNets.

6.9. Behavioural semantics for GCM components

Participants: Ludovic Henrio, Oleksandra Kulankhina, Eric Madelaine.

With Ludovic Henrio (Comred/I3S) and Rabea Ameur-Boulifa (Labsoc/Telecom-Paristech), we have pursued our research on the Behavioural semantics, in terms of pNets, of the core concepts of Grid Component Model (GCM). The results are currently submitted for publication as a journal paper, under revision.

6.10. Performance analysis and optimisation of an HPC scientific application

Participants: Luis Agustin Nieto, Sid Touati.

In the context of the internatinal Internship of Luis Agustin Nieto we conducted a large-scale experiment of source code optimization for HPC application. This work is meant to identify potential approaches that may be automatized in the future. The current use case was an application named CONVIV. CONVIV is a computer code implementing the VMFCI Method to solve the stationary Schrödinger equation for a set of distinguishable degrees of freedom (https://svn.oca.eu/trac/conviv). It is used in Chemistry for computing the energy levels of molecules.

This application is very computer-intensive (many hours of computation on a high performance grid computer). We have been given its source code (fortran with OpenMP), and we have been asked to analyse its performance and to optimise its execution time.

We did an extensive set of experiments for this application on many computers, and mainly on the `cicada.unice.fr` shared grid computer used for scientific parallel computing at UNS). We varied many parameters in our experiments:

- The number of threads was 2, 4, 6, 8, 16 threads. We also analysed the sequential code version.
- The thread affinity strategies for scheduling were: none (linux scheduler), scatter, compact.
- We repeated each experience 35 times to analyse performance stability.
- We used 2 compilers (gfortran, ifort) with -O3.
- We did a precise performance profiling using the Intel Vtune tool.

During our experiments we observed that, even with all the parameters above kept fixed, repeating the executions 35 times shows grat variability between best and worst execution times (more than double in some cases). The critical-path functions remained the same for each configuration choice, including in particular specific matrix computation functions.

After investigation and experiments, we succeed in getting a spectacular performance improvement by applying the following optimisations:

- Replace one of the matrix computation function by an MKL one (highly optimised and tuned function done by Intel).
- Use the compact thread scheduling strategy (OpenMP parameter).
- By using gfortran compiler with -O3, we reduced the execution time from 18400 seconds to 820 seconds (speedup=22).
- By using the ifort compiler with -03, we reduced the execution time from 21000 seconds to 620 seconds (speedup=33).

6.11. Formal translation validation of multi-processor real-time schedules

Participants: Keryan Didier, Dumitru Potop-Butucaru.

This research direction is mainly represented by the PhD thesis of Keryan Didier, and takes place in the framework of the ITEA3 ASSUME project. The technical focus of the ASSUME project is on formal compiler verification and on correct real-time implementation for parallel applications. The objective of this PhD thesis is to formally prove the correctness of (part of) the automatic code generation technology of Lopht, considering the respect of non-functional requirements, and in particular real-time requirements such as release dates, deadlines and periods.

During this first year of work we have:

1. Simplified the allocation and scheduling algorithms of Lopht to facilitate proof while still being able to handle the industrial use case. The resulting algorithms consider all the aspects pertaining to functional specification and non-functional requirements, but make simplifying assumptions on the execution platform (by not taking into account memory access interferences during parallel execution).
2. Developed a formally proved translation validation tool to determine the correctness of schedules produced by the algorithms at point (1). The tool is developed and proved in Coq. Coq code extraction is used to produce OCaML code that integrates in the allocation and scheduling flow.
3. Evaluated the tool on a large-scale industrial use case from Airbus (6000 Scade nodes). We demonstrated the tool to our project partners and during the ASSUME project evaluation. This evaluation showed that our scheduling and formally proved validation tools scale up to the size of large applications.

The main limitation of the current work is that it does not take into account the interferences due to concurrent memory accesses. This gives the main research direction for the next year.

We are currently writing a paper on this subject.

6.12. Lopht back-end for TTEthernet-based distributed systems

Participants: Raul Gorcitz, Dumitru Potop-Butucaru.

The global objective of this activity is a large-scale, ongoing effort to assess the possibility of automatically synthesizing full real-time implementations, including the so-called "bus frame" (the network configuration) on complex industrial platforms and for complex functional and non-functional specifications. We worked this year in the context of the post-doctoral position of Raul Gorcitz, funded by the ITEA3 ASSUME project, but also in the framework of our collaboration with CNES and Airbus DS.

The chosen platform was an industry-level evaluation platform using several Single-Board Computers (SBCs) running the VxWorks 653 OS, and connected through a Time-Triggered Ethernet (TTE) network. This platform was provided by CNES, as typical target for embedded applications. TTE is a standardized commmercial communication network, on top of a switched Ethernet basis, ommmercialized by TTTech. TTE adds support for realtime and fault tolerant communications, allows multiple communications of mixed criticalities to share a single physical medium. This is ensured by means of dedicated hardware using a set of configuration files describing the system architecture and behavior. These configurations are synthesized by the proprietary TTEplan tool starting from a global network description file.

The main scientific difficulty was the formal modeling of the behavior of the TTE network, followed by the extension of scheduling algorithms to consider such a network. While preliminary results were obtained and published last year, we completed and demonstrated this work to our industrial partners, and we are currently writing a second paper on the subject.

6.13. Uniprocessor Real-Time Scheduling

Participants: Mehdi Mezouak, Yves Sorel, Walid Talaboulma.

In the context of the master internship of Mehdi Mezouak, we thoroughly tested the offline time triggered scheduler implemented on an ARM Cortex M4 last year. We remind that this scheduler, intended for safety critical applications, uses a scheduling table containing the instants when the scheduler will be called through interruptions triggered by a timer. This table is generated by a uniprocessor offline schedulability analysis which accounts accurately for the scheduler cost itself, and for the cost of all preemptions the data dependent tasks are subjected to. This approach allows accounting for preemptions induced by the cost of other preemptions. We implemented a time measurement system on a LPC4080 microcontroller board of NXP which includes the ARM Cortex M4 and several timers, to determine on the one hand the actual cost of the scheduler and the cost of one preemption, and on the other hand start, resume and completion times of every task of the task sets. For the ARM Cortex M4 with a 120Mhz clock we obtained 142 cycles (2.3 μs) for the scheduler cost and 54 cycles (0.9 μs) for the cost of one preemption. We used these values for schedulability analyses we applied to various task sets. We improved the graphical tools proposed last year to draw the timing diagrams obtained during the schedulability analysis and during the real-time execution of the task set in order to compare them. For example, thanks to these measurement system and tools, we showed that this scheduler, based on a non periodic timer rather than the usual periodic one, allows the periodic execution of tasks without any jitter.

6.14. Multiprocessor Real-Time Scheduling

Participants: Mehdi Mezouak, Salah Eddine Saidi, Yves Sorel.

Always in the context of the master internship of Mehdi Mezouak, we studied the extension to multiprocessor of our offline time triggered scheduler. Since we chose the partitioned multiprocessor scheduling approach rather than the global one which is not suited to safety critical applications due to the prohibitive cost of task

migrations, the uniprocessor schedulability analysis is easily extended. Indeed, the main modification consists, for every processor, in accounting for the cost of inter-processor communications and synchronizations due to data dependences when a producer task is allocated to a processor which is different from the one the corresponding consumer task is allocated to. Therefore, new scheduler calls are added to the scheduling table corresponding to instants when awaited data are available, i.e. produced and then transfered. Of course, there are as many scheduling tables, and thus schedulers, as there are processors, and these scheduling tables are supposed to share a unique global time. The implementation of this global time raises a complex problem since it is not possible to dispatch a unique physical clock to all the processors. Among various solutions, we chose to use a physical clock rather than a logical one like in the Lamport's timestamp approach since we are interested in safety critical real-time. In addition, we chose the Berkeley's algorithm based on a master-slave approach where the clock server is maintained by one of the processor of the multiprocessor. This algorithm is more robust to failures than other algorithms based on an external clock server. Finally, using the measurement system mentioned previously, we measured accurately the cost of inter-processor communications according to the number of transfered data, in the case of an ethernet network that we experimented last year to connect several LPC4080 microcontroller boards.
During the second year of the PhD thesis of Salah Eddine Saidi, we continued to study the parallelization on multi-core of FMI-based co-simulation of numerical models, that is increasingly used for the design of Cyber-Physical Systems. Such model developed according to the FMI standard is defined by a number of C functions, called "operations", for computing its variables (inputs, outputs, state) and data dependences between these variables. Each model has an associated integration step and exchanges data with the other models according to its communication step which can be larger or equal to its integration step. These models are represented by a dataflow graph of operations [35] that is compliant with the conditioned repetitive dataflow model of our AAA methodology for functional specification. Our work mainly focused on two aspects. First, we proposed a graph transformation algorithm in order to allow handling multi-rate co-simulation, i.e. where connected models have different communication steps. This algorithm is based on the concept of graph unfolding similarly to the unrolling algorithm of our AAA methodology. The new graph is represented over the hyper-step which is equal to the least common multiple of the communication steps of all the models. Each operation is repeated in the graph according to the ratio between the hyper-step and its communication step. Then, rather than adding edges connecting all the repetitions of dependent operations, specific rules are used to define the repetitions that have to be connected by edges. These rules ensure correct data exchange between the operations as requested in the context of simulation. Second, some FMI functions called to compute model variables may not be "thread-safe", i.e. they cannot be executed in parallel as they may share some resource (e.g. variables). Consequently, if two or more operations belonging to the same model are executed on different cores, a mechanism that ensures these operations are executed in strictly disjoint time intervals must be set up. We proposed an acyclic orientation heuristic to solve this problem. This heuristic adds non directed edges between the operations that belong to the same model, and then assigns directions to these edges with the aim of minimizing the critical path of the resulting graph and subject to the constraint that no cycle is generated in the graph.

6.15. Probabilistic Solutions for Hard Real-Time Systems

Participants: Adriana Gogonel, Dorin Maxim, Antoine Bertout, Tomasz Kloda, Irina Asavoae, Mihail Asavoae, Cristian Maxim, Walid Talaboulma, Slim Ben-Amor, Robert Davis, Liliana Cucu.

The probabilistic solutions for hard real-time systems are built under the hypothesis that worst case values and worst case execution scenarios have extremely low probability of appearance. While continuing the estimation of bounds for the worst case execution times of a program [34], [25], we have proposed the first utilisation of probabilistic description for mixed-criticality systems [42]. Our result is exploiting the heavy tails of the execution times of a program to propose efficient scheduling solutions. Moreover since the feasibility intervals [21] for a probabilistic real-time system is not formally identified, we have formulated the first feasibility reasoning for such systems [47] under fixed-priority assignment policies [20]. Another important problem for probabilistic real-time systems concerns the feasibility in presence of precedence constraints, often used by our industry partners. The introduction of precedence constraints requires the comparison of probabilistic arrivals and we showed that existing measures are not correct in this context and we proposed and proved correct new measures [24].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

Airbus CIFRE grant This contract, started on March 2014, provides full support for the PhD thesis of Cristian Maxim. The thesis concerns the statistical timing analysis while different variability factors are taken into account. The proposed methods are built on top of existing statistical approaches while proving appropriate programs for training these methods and thus learning from the history of the execution.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

8.1.1.1. HOPE

Participants: Carlos Gomez Cardenas, Ameni Khecharem, Emilien Kofman, Robert de Simone.

The ANR HOPE project focused on hierarchical aspects for the high-level modeling and early estimation of power management techniques, with potential synthesis in the end if feasible. Partners were Intel, Synopsys, Magillem, UNS UMR LEAT, and ourselves.
We defined a multi-view, Model-Based design environment named MuVarch, accounting for power-level and performance of embedded hardware architectures, together with representation of abstract applications defining typical use cases fro these platforms.
Started in November 2013, the project reached its completion in February 2016, while Ameni Khecharem PhD defense took place in April 2016 [16].

8.1.1.2. GeMoC

Participants: Matias Vara Larsen, Julien Deantoni, Frédéric Mallet.

This project was admistratively handled by CNRS for our joint team, on the UMR I3S side. It ended September 2016. Partners were Inria (DiverSE EPC), ENSTA-Bretagne, IRIT, Obeo, Thales TRT and Supelec. The project focused on the executable modeling of heterogeneous systems using Models of Computation and Communication described using meta-languages. Specifically, the operational semantics of languages were equipped with precise timely constraints specified in CCSL. There were many outputs from the project but, from AOSTE perspective, we essentially developped MoCCML, an extension of CCSL with constraint automata (already integrated to TimeSquare) and BCool, a language dedicated to coordination apttern specification, which is described as part of Matias Vara-Larsen PhD thesis[19]. All the development realized in this project will end up as the first official eclipse research consortium.

8.1.1.3. FUI CLISTINE

Participants: Robert de Simone, Amin Oueslati, Emilien Kofman.

This project was started in Oct 2013, and provides PhD funding for Amine Oueslati. Partners are SynergieCAD (coordinator), Avantis, Optis, and the two EPIs Aoste and Nachos. The goal is to study the feasibility of building a low-cost, low-power "supercomputer", reusing ideas from SoC design, but this time with out-of-chip network "on-board", and out-of-the-shelf processor elements organized as an array. The network itself should be time predictable and highly parallel (far more than PCI-e for instance). We started a thorough classification of parallel program types (known as "Dwarfs" in the literature), to provide benchmarks and evaluate the platform design options.

8.1.1.4. FUI Waruna

Participants: Liliana Cucu, Adriana Gogonel, Walid Talaboulma, Dorin Maxim.

This recent project was started in September 2015. It targets the creation of a framework allowing to connect different existing methods while enriching the description with Waruna results. This framework allows timing analyses for different application domains like avionics, railways, medical, aerospace, automotive, etc.

8.1.2. Investissements d'Avenir

8.1.2.1. DEPARTS

Participants: Liliana Cucu-Grosjean, Adriana Gogonel, Walid Talaboulma.

This project is funded by the BGLE Call (*Briques Logicielles pour le Logiciel Embarqué*) of the national support programme *Investissements d'Avenir*. Formally started on October 1st, 2012 with the kick-off meeting held on April, 2013 for administrative reasons. Research will target solutions for probabilistic component-based models, and a Ph.D. thesis should start at latest on September 2015. The goal is to unify in a common framework probabilistic scheduling techniques with compositional assume/guarantee contracts that have different levels of criticality.

8.1.2.2. CLARITY

Participants: Frédéric Mallet, Julien Deantoni, Ales Mishchenko, Robert de Simone, Marie Agnès Peraldi-Frati.

This project is funded by the LEOC Call (*Logiciel Embarqué et Objets Connectés*) of the national support programme *Investissements d'Avenir*. It was started in September 2014 , and a kick-of meeting was held on October 9th. Partners are: 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.
Our technical contributions to the project achievement are described in subsection 6.2.

8.1.2.3. Capacites

Participants: Liliana Cucu-Grosjean, Dumitru Potop-Butucaru, Yves Sorel, Walid Talaboulma.

This project is funded by the LEOC Call (*Logiciel Embarqué et Objets Connectés*) of the national support programme *Investissements d'Avenir*. It has started on November 1st, 2014 with the kick-off meeting held on November, 12th 2014. The project cordinator is Kalray, and the objective of the project is to study the relevance of Kalray-style MPPA processor array for real-time computation in the avionic domain (with partners such as Airbus for instance). The post-doc of Mihail Asavoae and the PhD of Walid Talaboulma are funded on this contract.

8.2. European Initiatives

8.2.1. Collaborations in European Programs, Except FP7 & H2020

8.2.1.1. ASSUME

Participants: Dumitru Potop-Butucaru, Keryan Didier, Liliana Cucu.

This project is funded by the ITEA3 program. It has started on September 1st 2015. Project coordinator is Daimler. ASSUME has funded the (now completed) post-doc of Raul Gorcitz, and funds the PhD thesis of Keryan Didier.

Future mobility solutions will increasingly rely on smart components that continuously monitor the environment and assume more and more responsibility for a convenient, safe and reliable operation. Currently the single most important roadblock for this market is the ability to come up with an affordable, safe multi-core development methodology that allows industry to deliver trustworthy new functions at competitive prices. ASSUME will provide a seamless engineering methodology, which addresses this roadblock on the constructive and analytic side.

In this project, most our effort goes to work package "Synthesis of Predictable Concurrent Systems", which we lead. Main scientific results of our work in this project have beenn presented in sections 6.11 and 6.12. In addition, we closely interacted with our industrial partners to determine their needs, and developed importer tools for their internal formalisms, including Scade v4 and internal formalisms used at Airbus (all importers were developed jointly with EPI PARKAS). This work also resulted in proposals to Airbus on the specification of certain non-functional properties (e.g. the atomic groups of operations that cannot be split during allocation and scheduling). By applying our prototype tools, we have also determined that the use case has significant potential parallelism and will achieve significant speedups through execution on the chosen target architecture (the many-core Kalray MPPA256).

8.3. International Initiatives

8.3.1. FM4CPS

Title: Formal Models and tools for Cyber-Physical Systems

International Partner (Institution - Laboratory - Researcher):

ECNU (China) - Artificial Intelligence Lab - Jifeng He

Start year: 2015

See also: https://project.inria.fr/fm4cps/

Cyber-Physical Systems (CPS) and the connected Internet of Things (IoT) are inherently heterogeneous systems, with ("cyber") computer digital parts interacting with their physical sensible environment, under user requirements for functional and temporal correctness. Thus, design of such systems as a whole requires a diversity of models, and the behavior orchestration between such models must be carefully defined and analyzed.

FM4CPS will address several facets of Formal Model-Driven Engineering for Cyber-Physical Systems and Internet of Things. The design of such large heterogeneous systems calls for hybrid modeling, and the combination of classes of models, most previously well-established in their own restricted area: Formal Models of Computations drawn from Concurrency Theory for the “cyber” discrete processors, timed extension and continuous behaviors for physical environments, requirement models and user constraints extended to non-functional aspects, new challenges for designing and analyzing large and highly dynamic communicating software entities. Orchestration and comparison of models, with their expressive power vs. their decidable aspects, shall be considered with the point of view of hybrid/heterogeneous modeling here. Main aspects are the various timing or quantitative structure extensions relying for instance on a hybrid logical clock model for the orchestration of underlying components.

The associated team aims at various level of research, from formal models, semantics, or complexity, to experimental tools development. This will start for example on one side with building a formal orchestration model for CPSs, based on an hybrid clock model that combine discrete and physical time, synchronous and asynchronous computations or communications. Another goal will be the study of expressiveness and decidability for CPS, based on dedicated sub-families of well-structured push-down systems, addressing both unbounded communication and time-sensitive models.

Beyond their own expertise in this field, the partners will build on the results of previous cooperations in the context of the Liama projects Hades and Tempo, and the associated team DAESD. The current proposal widely broadens the domain of collaboration, and with the inclusion, for the first time, of Jiao Tong University. We expect this is the first step towards the extension of LIAMA in Shanghai with the strengthening of the involvement of E.C.N.U., and the contribution of new top notch universities such as Jiaotong.

8.3.2. Inria International Partners

8.3.2.1. Declared Inria International Partners

We have signed an agreement with the University of Verona, which covers joint activities (see section 6.7, together with the housing of interns.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

8.4.1.1. Internships

Nieto Luis Agustin

Date: Sep 2015 - Feb 2016

Institution: Universidad de Buenos Aires (Argentina)

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

Eric Madelaine is General Chair of the 11$^{\text{th}}$ International Symposium on Theoretical Aspects of Software Engineering (TASE'17), and Steering Committee Chair of the International Symposium on Formal Aspects of Components Systems (FACS 2017)

Liliana Cucu-Grosjen and Rob Davis are Steering Committee members of 3 conferences (RTSS, RTAS and RTNS) and 2 workshops (RTSOPS and WMC)

Julien Deantoni was chair of the 4th GEMOC workshop, held in conjunction with the 19th ACM/IEEE International Conference on Model Driven Engineering Languages and Systems

9.1.2. Scientific Events Selection

9.1.2.1. Chair of Conference Program Committees

Robert de Simone will be PC Chair for the forthcoming EMSoft 2017 conference edition.

Frédéric Mallet will be PC Chair for the forthcoming TASE 2017 conference edition.

9.1.2.2. Member of the Conference Program Committees

Robert de Simone: EmSoft 2016, FDL 2016.

Dumitru Potop-Butucaru: RTNS 2016, ACSD 2016

Yves Sorel: DASIP 2016, EMSOFT 2016

Julien Deantoni: MODELS 2016, CAL 2016, GEMOC 2016, EXE 2016 DSD 2016, MOMO 2016.

Liliana Cucu-Grosjean: RTAS2016, SIES 2016, RTNS2016

Fredéric Mallet: DATE 2016, DSD 2016, ERTS 2016, ICTERI 2016.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

Yves Sorel: DASIP 2016, EMSOFT 2016

9.1.4. Invited Talks

Robert de Simone was invited Keynote Speaker at the international conference MeMoCode 2016 in Kanpur (India)

9.1.5. Leadership within the Scientific Community

Eric Madelaine and Frédéric Mallet are Council Members of the International Joint Laboratory of Trustworthy Software, Ministery of Education, China.

9.1.6. Scientific Expertise

Yves Sorel: Steering Committees of System Design and Development Tools Group of Systematic Paris-Region Cluster, and of Technologies and Tools Program of SystemX Institute for Technological Research (IRT)

9.1.7. Research Administration

Robert de Simone is Scientific Correspondant for the Inria/Safran collaboration programme, and (starting 2017) Deputy Director of the EDSTIC Doctoral School of Université Côte d'Azur.
Liliana Cucu-Grosjean is elected member of Inria Evaluation Commission.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master: Robert de Simone, Models of Computation for Networks-on-Chips (MoCs for NoCs), 36h, M2 Internationbal, UNS.

Master: Robert de Simone, Functional and Temporal Correctness, 36h, M1 Internationbal, UNS.

Master: Yves Sorel, Optimization of distributed real-time embedded systems, 36H, M2, University of Paris Sud

Master: Yves Sorel, Correct by construction design of reactive systems, 18H, M2, ESIEE Engineering School, Noisy-Le-Grand

Master : Julien Deantoni, Systèmes embarqués et Ambient, 10h, M2, Polytech'Nice, France.

Master : Julien Deantoni, Langage C++, 88h, M1,Polytech'Nice, France.

Master : Julien Deantoni, Finite State Machines, 24h, M1,Polytech'Nice, France.

Master : Julien Deantoni, Internship Management, 20h, M2, Polytech'Nice, France.

Master: Dumitru Potop Butucaru, Une approche synchrone des systèmes embarqués temps réel,12h, M1, EPITA Paris

Master: Dumitru Potop Butucaru and Thomas Carle, L'approche synchrone de la construction des systèmes embarqués temps réel, 12h, M2, Polytech Paris UPMC.

Licence: Laurent George, Java and Shell programming 48h, L1, IUT RT UPEC, France

Master: Laurent George, Distributed Real-Time Systems, 24h, M2, UPEC, France

Licence : Marie-Agnes Peraldi-Frati, Algorithms and programming 60h,L1, UNS Institute of technology.

Licence : Marie-Agnes Peraldi-Frati, System and Networks administration 80h, L2, UNS Institute of technology .

Licence : Marie-Agnes Peraldi-Frati, Web Programming 50 h, L2, UNS Institute of technology.

Licence: Frédéric Mallet, Conception Orientée Objet, 45h, L3, UNS.

Licence: Frédéric Mallet, Programmation Orientée Objet, 45h, L3, UNS.

Master: Frédéric Mallet, Programmation Avancée et Design Patterns, 45h, M1, UNS.

Master: Frédéric Mallet, Vérification temporelle et fonctionnelle, 24h, M1, UNS.

Master: Frédéric Mallet, Model-Driven Engineering, 24h, M1, UNS.

Master: Liliana Cucu, Distributed Databases and Statistics in Computer Science, 64h, U. Dunarea de Jos, Romania (Invited Professor)

Master: Dumitru Potop Butucaru, Une approche synchrone des systèmes embarqués temps réel,12h, M1, EPITA Paris

9.2.2. Supervision

PhD: Matias Vara-Larsen, *Toward a formal and hierarchical timed model for concurrent heterogeneous model*, UNS, defended April 2016, supervised by Frédéric Mallet, co-supervised by Julien Deantoni.

PhD in progress: Ameni Khecharem, *High-Level modeling of hierarchical power management policies in SoCs*, UNS, defended May 2016, supervised by Robert de Simone.

PhD in progress: Emilien Kofman, *Conception Haut Niveau Low Power d'objets mobiles communicants*, UNS, started Oct 2013, supervised by Robert de Simone, co-supervised by François Verdier (UMR CNRS/UNS LEAT).

PhD in progress: Amin Oueslati, *Modélisation conjointe d'applications et d'architectures parallèles embarqués en pratique*, UNS, started Jan 2014, supervised by Robert de Simone

PhD in progress: Yuanrui Zhang, ECNU-SEI/China, started Sep 2015, co-supervised by Frederic Mallet (joint supervision with Pr. Chen Yixiang(ECNU).

PhD in prgress: Hui (Vincent) Zhao, UNS, started February 2016, supervised by Frédéric Mallet, co-supervised by Ludovic Apvrille (Telecom ParisTech)

PhD in progress: Dongdong An, ECNU-SEI/China, started November 2016, co-supervised by R. de Simone, supervised by Jing Liu (ECNU).

PhD in progress: Cristian Maxim, *End to end constraints using probabilistic approaches*, UPMC, started on March 2014, supervised by Liliana Cucu

PhD in progress: Walid Talaboulma, *Probabilistic timing analysis in presence of dependences*, UPMC, started on November 2015, co-supervised by Liliana Cucu and Adriana Gogonel

PhD in progress: Salah Edinne Saidi, *Distributed real-time scheduling for the co-simulation of several control models*, University of UMPC-Paris-Sorbonne, started December 2014, co-supervised by Nicolas Pernet (IFPEN) and Yves Sorel.

PhD in progress: Keryan Didier, *Formal certification of real-time implementations*, Université Pierre et Marie Curie/EDITE, started November 2015, supervised by Dumitru Potop Butucaru.

PhD: Oleksandra Kulankhina, *A framework for rigorous development of distributed components: formalisation and tools*, UNS, defended October 2016, supervised by Eric Madelaine, co-supervised by Ludovic Henrio (UMR CNRS/UNS I3S).

PhD in progress: Salah Edinne Saidi, *Distributed real-time scheduling for the co-simulation of several control models*, University of UMPC-Paris-Sorbonne, started December 2014, co-supervised by Nicolas Pernet (IFPEN) and Yves Sorel.

PhD in progress: Keryan Didier, *Formal certification of real-time implementations*, Université Pierre et Marie Curie/EDITE, started November 2015, supervised by Dumitru Potop Butucaru.

PhD: Oleksandra Kulankhina, *A framework for rigorous development of distributed components: formalisation and tools*, UNS, defended October 2016, supervised by Eric Madelaine, co-supervised by Ludovic Henrio (UMR CNRS/UNS I3S).

PhD: Vincent Kherbache, *Ordonnancement des migrations à chaud de machines virtuelles*, UNS, defended December 2016, supervised by Eric Madelaine, co-supervised by Fabien Hermenier (UMR CNRS/UNS I3S).

9.2.3. Juries

Robert de Simone: reviewer for the HDR of Xavier Thirioux (ENSIIEHT, Sept. 2016)

Dumitru Potop Butucaru: PhD reviewer for Pierre Guillou - Ecole des Mines de Paris. Nov. 2016

Julien Deantoni: PhD reviewer for Florent Latombe (ENSIIEHT)

Liliana Cucu-Grosjean: PhD reviewer for Guillaume Phavorin (ENSMA Poitiers, September 2016)

Liliana Cucu-Grosjean: PhD jury member for Abhilash Thekkilakattil (University of Ma¨lardalen, May 2016)

9.3. Popularization

Liliana Cucu-Grosjean has supervised the video production of a popularization video regarding the outcomes of the PROXIMA project. The video has been made available on Inria channels and all PROXIMA partners.

10. Bibliography

Major publications by the team in recent years

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Publications of the year

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[17] V. KHERBACHE.*Live-migrations scheduling of virtual machines*, Université Côte d'Azur, December 2016, https://hal.inria.fr/tel-01419310.

[18] O. KULANKHINA.*A framework for rigorous development of distributed components: formalisation and tools*, Universite Nice Sophia Antipolis, October 2016, https://hal.inria.fr/tel-01419298.

[19] M. VARA LARSEN.*BCOol : the Behavioral Coordination Operator Language*, Université Nice Sophia Antipolis, April 2016, https://tel.archives-ouvertes.fr/tel-01302875.

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[20] R. I. DAVIS, L. CUCU-GROSJEAN, M. BERTOGNA, A. BURNS.*A review of priority assignment in real-time systems*, in "Journal of Systems Architecture", April 2016, vol. 65, p. 64 - 82, https://hal.inria.fr/hal-01419694.

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[23] J. DEANTONI.*Modeling the Behavioral Semantics of Heterogeneous Languages and their Coordination*, in "Architecture Centric Virtual Integration (ACVI)", Venise, Italy, Julien Delange and Jerome Hugues and Peter Feiler, April 2016, https://hal.inria.fr/hal-01291299.

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Project-Team APICS

Analysis and Problems of Inverse type in Control and Signal processing

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Optimization and control of dynamic systems

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Project-Team APICS

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Keywords:

Computer Science and Digital Science:

6.1.1. - Continuous Modeling (PDE, ODE)
6.2. - Scientific Computing, Numerical Analysis & Optimization
6.2.1. - Numerical analysis of PDE and ODE
6.2.5. - Numerical Linear Algebra
6.2.6. - Optimization
6.3.1. - Inverse problems
6.3.3. - Data processing
6.3.4. - Model reduction
6.4. - Automatic control
6.4.4. - Stability and Stabilization
7.3. - Optimization
7.5. - Geometry, Topology
7.6. - Computer Algebra

Other Research Topics and Application Domains:

2.6. - Biological and medical imaging
2.6.1. - Brain imaging
3. - Environment and planet
3.3. - Geosciences
3.3.1. - Earth and subsoil
5.2. - Design and manufacturing
5.2.4. - Aerospace
5.4. - Microelectronics
6.2.2. - Radio technology
6.2.3. - Satellite technology

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2. Overall Objectives

2.1. Research Themes

The team develops constructive, function-theoretic approaches to inverse problems arising in modeling and design, in particular for electro-magnetic systems as well as in the analysis of certain classes of signals.

Data typically consist of measurements or desired behaviors. The general thread is to approximate them by families of solutions to the equations governing the underlying system. This leads us to consider various interpolation and approximation problems in classes of rational and meromorphic functions, harmonic gradients, or solutions to more general elliptic partial differential equations (PDE), in connection with inverse potential problems. A recurring difficulty is to control the singularities of the approximants.

The mathematical tools pertain to complex and harmonic analysis, approximation theory, potential theory, system theory, differential topology, optimization and computer algebra. Targeted applications include:

- identification and synthesis of analog microwave devices (filters, amplifiers),
- non-destructive control from field measurements in medical engineering (source recovery in magneto/electro-encephalography), and paleomagnetism (determining the magnetization of rock samples).

In each case, the endeavor is to develop algorithms resulting in dedicated software.

3. Research Program

3.1. Introduction

Within the extensive field of inverse problems, much of the research by Apics deals with reconstructing solutions of classical elliptic PDEs from their boundary behavior. Perhaps the simplest example lies with harmonic identification of a stable linear dynamical system: the transfer-function f can be evaluated at a point $i\omega$ of the imaginary axis from the response to a periodic input at frequency ω. Since f is holomorphic in the right half-plane, it satisfies there the Cauchy-Riemann equation $\overline{\partial} f = 0$, and recovering f amounts to solve a Dirichlet problem which can be done in principle using, *e.g.* the Cauchy formula.

Practice is not nearly as simple, for f is only measured pointwise in the pass-band of the system which makes the problem ill-posed [70]. Moreover, the transfer function is usually sought in specific form, displaying the necessary physical parameters for control and design. For instance if f is rational of degree n, then $\overline{\partial} f = \sum_1^n a_j \delta_{z_j}$ where the z_j are its poles and δ_{z_j} is a Dirac unit mass at z_j. Thus, to find the domain of holomorphy (*i.e.* to locate the z_j) amounts to solve a (degenerate) free-boundary inverse problem, this time on the left half-plane. To address such questions, the team has developed a two-step approach as follows.

Step 1: To determine a complete model, that is, one which is defined at every frequency, in a sufficiently versatile function class (*e.g.* Hardy spaces). This ill-posed issue requires regularization, for instance constraints on the behavior at non-measured frequencies.

Step 2: To compute a reduced order model. This typically consists of rational approximation of the complete model obtained in step 1, or phase-shift thereof to account for delays. We emphasize that deriving a complete model in step 1 is crucial to achieve stability of the reduced model in step 2.

Step 1 relates to extremal problems and analytic operator theory, see Section 3.3.1. Step 2 involves optimization, and some Schur analysis to parametrize transfer matrices of given Mc-Millan degree when dealing with systems having several inputs and outputs, see Section 3.3.2.2. It also makes contact with the topology of rational functions, in particular to count critical points and to derive bounds, see Section 3.3.2. Step 2 raises further issues in approximation theory regarding the rate of convergence and the extent to which singularities of the approximant (*i.e.* its poles) tend to singularities of the approximated function; this is where logarithmic potential theory becomes instrumental, see Section 3.3.3.

Applying a realization procedure to the result of step 2 yields an identification procedure from incomplete frequency data which was first demonstrated in [76] to tune resonant microwave filters. Harmonic identification of nonlinear systems around a stable equilibrium can also be envisaged by combining the previous steps with exact linearization techniques from [33].

A similar path can be taken to approach design problems in the frequency domain, replacing the measured behavior by some desired behavior. However, describing achievable responses in terms of the design parameters is often cumbersome, and most constructive techniques rely on specific criteria adapted to the physics of the problem. This is especially true of filters, the design of which traditionally appeals to polynomial extremal problems [72], [56]. 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, see Section 3.2.2.

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 [61] 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] [13], [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.

[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.

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* [69]. In the two steps approach previously described, we implicitly removed this indeterminacy by requiring in step 1 that the measure be supported on the boundary (because we seek a function holomorphic throughout the right half-space), and by requiring in step 2 that the measure be discrete in the left half-plane (in fact: a 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).

Along these lines, Apics 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], [5], [40]. 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 EEG/MEG and inverse magnetization problems in geosciences, see Section 4.3.

The approximation-theoretic tools developed by Apics 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.

3.2. Range of inverse problems

3.2.1. Elliptic partial differential equations (PDE)

Participants: Laurent Baratchart, Sylvain Chevillard, Juliette Leblond, Konstantinos Mavreas, Christos Papageorgakis, Dmitry Ponomarev.

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 [54], [57].

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 [60]. 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 now under study in the team..

The piece of work we just mentioned requires defining and studying Hardy spaces of the conjugate-Beltrami equation, which is an interesting topic by itself. For Sobolev-smooth coefficients of exponent greater than 2, they were investigated in [4], [34]. The case of the critical exponent 2 is treated in [12], 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. Exponent 2 seems also to be the key to a similar theory on general (rectifiable) domains in the plane, for exponent 2 is all one is left with in general after a conformal transformation of the domain.

Generalized Hardy classes as above are used in [13] 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 Apics: 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, Apics 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], [36], see Section 5.1. In this connection, we collaborate with two groups of partners: Athena Inria project-team, CHU La Timone, and BESA company 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 [6], [37], [51]. Initial schemes to locate cracks or sources *via* rational approximation on planar domains were obtained this way [40], [44], [54]. 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 [7], [41]. 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 Apics, and again applications are sought to medical imaging and geosciences, see Sections 4.3, 4.2 and 5.1.

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, Matthias Caenepeel, Sylvain Chevillard, 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 [9] 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 [28], [9].
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 [55], 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.

Apics 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 [27] [8]. Thanks to quasi-convexity, the latter can be solved efficiently using iterative methods relying on linear programming. These were implemented in the software easy-FF (see easy-FF). Currently, the team is engaged in the synthesis of more complex microwave devices like multiplexers and routers, which connect several filters through wave guides. Schur analysis plays an important role here, because scattering matrices of passive systems are of Schur type (*i.e.* contractive in the stability region). The theory originates with the work of I. Schur [75], who devised a recursive test to check for contractivity of a holomorphic function in the disk. The so-called Schur parameters of a function may be viewed as Taylor coefficients for the hyperbolic metric of the disk, and the fact that Schur functions are contractions for that metric lies at the root of Schur's test. Generalizations thereof turn out to be efficient to parametrize solutions to contractive interpolation problems [29]. Dwelling on this, Apics contributed differential parametrizations (atlases of charts) of lossless matrix functions [28], [71], [65] 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 5.2 and 7.2.1.

In recent years, our attention was driven by CNES and UPV (Bilbao) to questions about stability of high-frequency amplifiers, see Section 6.2. 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 5.4. 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, Dmitry Ponomarev, 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 $1 \leq p < \infty$ 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 $1 \leq p \leq \infty$, 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 $\|g - \psi\|_{L^p(T \setminus K)} \leq M$ 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 [39], [42], [48], the solution to this convex infinite-dimensional optimization problem can be obtained when $p \neq 1$ upon iterating with respect to a Lagrange parameter the solution to spectral equations for appropriate Hankel and Toeplitz operators. These spectral equations involve the solution to the special case $K = T$ of (P), which is a standard extremal problem [63]:

> (P_0) Let $1 \leq p \leq \infty$ 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 [43]. In this form, the problem comes close to (but still is different from) H^∞ frequency optimization used in control [66], [74]. One can also impose bounds on the real or imaginary part of $g - \psi$ on $T \setminus K$, which is useful when considering Dirichlet-Neumann problems, see [68].

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, 5.1.5). 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: $\overline{\partial} f = \nu \overline{\partial f}$ [67], which are studied for $1 < p < \infty$ in [4], [12], [34] and [58]. 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 [60].

Another instance of problem (P) in with $p = 2$ and additional pointwise interpolation constraints inside a simply connected domain (disk) D was studied and solved in [11], Part I, and [15]. Such pointwise interpolation constraints could be of practical interest for inverse Cauchy type problems in cases where interior information is also available or to model uncertainty on boundary data.

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 [39] 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 5.1), 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) [36].

Just like solving problem (P) appeals to the solution of problem (P_0), our ability to solve problem (P_1) will depend on the possibility to tackle the special case where $O = S$:

> (P_2) Let $1 \leq p \leq \infty$ and $V \in L^p(S)$ be a $\mathbb{R}^n$-valued vector field. Find a harmonic gradient $G \in H^p(B)$ such that $\|G - V\|_{L^p(S)}$ is minimum.

Problem (P_2) is simple when $p = 2$ by virtue of the Hardy Hodge decomposition together with orthogonality of $H^2(B)$ and $H^2(\mathbb{R}^n \setminus \overline{B})$, which is the reason why we were able to solve (P_1) in this case. Other values of p cannot be treated as easily and are still under investigation, especially the case $p = \infty$ which is of particular interest and presents itself as a 3-D analog to the Nehari problem [73].

Companion to problem (P_2) is problem (P_3) below.

> (P_3) Let $1 \leq p \leq \infty$ and $V \in L^p(S)$ be a $\mathbb{R}^n$-valued vector field. Find $G \in H^p(B)$ and $D \in D(S)$ such that $\|G + D - V\|_{L^p(S)}$ is minimum.

Note that (P_2) and (P_3) are identical in 2-D, since no non-constant tangential divergence-free vector field exists on T. It is no longer so in higher dimension, where both (P_2) and (P_3) arise in connection with inverse potential problems in divergence form, like source recovery in electro/magneto encephalography and paleomagnetism, see Sections 3.2.1 and 4.3.

3.3.2. Best meromorphic and rational approximation

The techniques set forth in this section are used to solve step 2 in Section 3.2 and they are instrumental to approach inverse boundary value problems for the Poisson equation $\Delta u = \mu$, where μ is some (unknown) measure.

3.3.2.1. Scalar meromorphic and rational approximation

We put R_N for the set of rational functions with at most N poles in D. By definition, meromorphic functions in $L^p(T)$ are (traces of) functions in $H^p + R_N$.

A natural generalization of problem (P_0) is:

> (P_N) Let $1 \leq p \leq \infty$, $N \geq 0$ an integer, and $f \in L^p(T)$; find a function $g_N \in H^p + R_N$ such that $g_N - f$ is of minimal norm in $L^p(T)$.

Only for $p = \infty$ and f continuous is it known how to solve (P_N) in semi-closed form. The unique solution is given by AAK theory (named after Adamjan, Arov and Krein), which connects the spectral decomposition of Hankel operators with best approximation [73].

The case where $p = 2$ is of special importance for it reduces to rational approximation. Indeed, if we write the Hardy decomposition $f = f^+ + f^-$ where $f^+ \in H^2$ and $f^- \in H^2(\mathbb{C} \setminus \overline{D})$, then $g_N = f^+ + r_N$ where r_N is a best approximant to f^- from R_N in $L^2(T)$. Moreover, r_N has no pole outside D, hence it is a *stable* rational approximant to f^-. However, in contrast to the case where $p = \infty$, this best approximant may *not* be unique.

The 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 [32]. 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 [45], [47]. 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) [49] and more generally Cauchy integrals over hyperbolic geodesic arcs [52]. 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 [30] in higher dimension is a worthy and timely endeavor today. Meanwhile, an analog to AAK theory was carried out for $2 \leq p < \infty$ in [48]. Although not as effective computationally, it was recently used to derive lower bounds [3]. When $1 \leq p < 2$, problem (P_N) is still quite open.

A common feature to the above-mentioned problems is that critical point equations yield non-Hermitian orthogonality relations for the denominator of the approximant. This stresses connections with interpolation, which is a standard way to build approximants, and in many respects best or near-best rational approximation may be regarded as a clever manner to pick interpolation points. This was exploited in [53], [50], 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 5.1).

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 [59].

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 [64], see Section 5.2. 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 [35], [38]. The subject is intimately connected to orthogonal polynomials on the unit circle, and this line of investigation has been pursued towards an asymptotic study of orthogonal polynomials on planar domains, which is today an active area in approximation theory with application to quantum particle systems, spectra of random matrices, and Hele-Shaw flows, see Section 5.6.

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 [32] and mentioned in Section 3.3.2.1 generalizes to the matrix-valued situation [62]. 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 ([28], [65], [71]). Some of these parametrizations are also interesting to compute realizations and achieve filter synthesis ([65], [71]). 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 [46]. Matrix-valued Markov functions are the only known example beyond this one [31].

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 Apics 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 [5]. 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 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 ([5], [6], [37]), 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 [40]. 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 5.1. 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, Apics 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
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- URL: http://www-sop.inria.fr/apics/Dedale/

3.4.2. FindSources3D

FindSources3D-bolis

KEYWORDS: Health - Neuroimaging - Visualization - Compilers - Medical - Image - Processing

FUNCTIONAL DESCRIPTION

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.

This version of FindSources3D 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).

- Participants: Juliette Leblond, Maureen Clerc Gallagher, Théodore Papadopoulo, Jean-Paul Marmorat and Nicolas Schnitzler
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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
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- 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
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- 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, Dmitry Ponomarev.

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 Section 7.2.2.

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:

$$\int_{\Omega} \frac{\operatorname{div} m(x')\, dx'}{|x-x'|}\,, \tag{2}$$

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 [36] and Section 5.1.1, 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 from the University of Vienna, Apics has 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 involves are variants, in a spherical context, from those developed within the IMPINGE associate team for paleomagnetism, see Section 5.1.4.

4.3. Inverse source problems in EEG

Participants: Laurent Baratchart, Juliette Leblond, Jean-Paul Marmorat, Christos Papageorgakis, Nicolas Schnitzler.

This work is conducted in collaboration with Maureen Clerc and Théo Papadopoulo from the Athena EPI.

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 [7]. 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 [6], [41]. 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 5.1), in collaboration with the Athena team at Inria Sophia Antipolis, neuroscience teams in partner-hospitals (la Timone, Marseille), and the BESA company (Munich).

4.4. Identification and design of microwave devices

Participants: Laurent Baratchart, Sylvain Chevillard, Jean-Paul Marmorat, Martine Olivi, Fabien Seyfert.

This is joint work with Stéphane Bila (XLIM, Limoges).

One of the best training grounds for function-theoretic applications by the team is the identification and design of physical systems whose performance is assessed frequency-wise. This is the case of electromagnetic resonant systems which are of common use in telecommunications.

In space telecommunications (satellite transmissions), constraints specific to on-board technology lead to the use of filters with resonant cavities in the microwave range. These filters serve multiplexing purposes (before or after amplification), and consist of a sequence of cylindrical hollow bodies, magnetically coupled by irises (orthogonal double slits). The electromagnetic wave that traverses the cavities satisfies the Maxwell equations, forcing the tangent electrical field along the body of the cavity to be zero. A deeper study of the Helmholtz equation states that an essentially discrete set of wave vectors is selected. In the considered range of frequency, the electrical field in each cavity can be decomposed along two orthogonal modes, perpendicular to the axis of the cavity (other modes are far off in the frequency domain, and their influence can be neglected).

Figure 1. Picture of a 6-cavities dual mode filter. Each cavity (except the last one) has 3 screws to couple the modes within the cavity, so that 16 quantities must be optimized. Quantities such as the diameter and length of the cavities, or the width of the 11 slits are fixed during the design phase.

Each cavity (see Figure 1) has three screws, horizontal, vertical and midway (horizontal and vertical are two arbitrary directions, the third direction makes an angle of 45 or 135 degrees, the easy case is when all cavities show the same orientation, and when the directions of the irises are the same, as well as the input and output slits). Since screws are conductors, they behave as capacitors; besides, the electrical field on the surface has to be zero, which modifies the boundary conditions of one of the two modes (for the other mode, the electrical field is zero hence it is not influenced by the screw), the third screw acts as a coupling between the two modes. The effect of an iris is opposite to that of a screw: no condition is imposed on a hole, which results in a coupling between two horizontal (or two vertical) modes of adjacent cavities (in fact the iris is the union of two rectangles, the important parameter being their width). The design of a filter consists in finding the size of each cavity, and the width of each iris. Subsequently, the filter can be constructed and tuned by adjusting the screws. Finally, the screws are glued once a satisfactory response has been obtained. In what follows, we shall consider a typical example, a filter designed by the CNES in Toulouse, with four cavities near 11 GHz.

Near the resonance frequency, a good approximation to the Helmholtz equations is given by a second order differential equation. Thus, one obtains an electrical model of the filter as a sequence of electrically-coupled resonant circuits, each circuit being modeled by two resonators, one per mode, the resonance frequency of which represents the frequency of a mode, and whose resistance accounts for electric losses (surface currents) in the cavities.

This way, the filter can be seen as a quadripole, with two ports, when plugged onto a resistor at one end and fed with some potential at the other end. One is now interested in the power which is transmitted and reflected. This leads one to define a scattering matrix S, which may be considered as the transfer function of a stable causal linear dynamical system, with two inputs and two outputs. Its diagonal terms $S_{1,1}$, $S_{2,2}$ correspond to reflections at each port, while $S_{1,2}$, $S_{2,1}$ correspond to transmission. These functions can be measured at certain frequencies (on the imaginary axis). The matrix S is approximately rational of order 4 times the number of cavities (that is 16 in the example on Figure 2), and the key step consists in expressing the components of the equivalent electrical circuit as functions of the S_{ij} (since there are no formulas expressing the lengths of the screws in terms of parameters of this electrical model). This representation is also useful to analyze the numerical simulations of the Maxwell equations, and to check the quality of a design, in particular the absence of higher resonant modes.

In fact, resonance is not studied via the electrical model, but via a low-pass equivalent circuit obtained upon linearizing near the central frequency, which is no longer conjugate symmetric (*i.e.* the underlying system may no longer have real coefficients) but whose degree is divided by 2 (8 in the example).

In short, the strategy for identification is as follows:

- measuring the scattering matrix of the filter near the optimal frequency over twice the pass band (which is 80MHz in the example).
- Solving bounded extremal problems for the transmission and the reflection (the modulus of he response being respectively close to 0 and 1 outside the interval measurement, cf. Section 3.3.1) in order to get a models for the scattering matrix as an analytic matrix-valued function. This provides us with a scattering matrix known to be close to a rational matrix of order roughly 1/4 of the number of data points.
- Approximating this scattering matrix by a true rational transfer-function of appropriate degree (8 in this example) via the Endymion or RARL2 software (cf. Section 3.3.2.2).
- A state space realization of S, viewed as a transfer function, can then be obtained, where additional symmetry constraints coming from the reciprocity law and possibly other physical features of the device have to be imposed.
- Finally one builds a realization of the approximant and looks for a change of variables that eliminates non-physical couplings. This is obtained by using algebraic-solvers and continuation algorithms on the group of orthogonal complex matrices (symmetry forces this type of transformation).

The final approximation is of high quality. This can be interpreted as a confirmation of the linearity assumption on the system: the relative L^2 error is less than 10^{-3}. This is illustrated by a reflection diagram (Figure 2). 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 [8]. 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

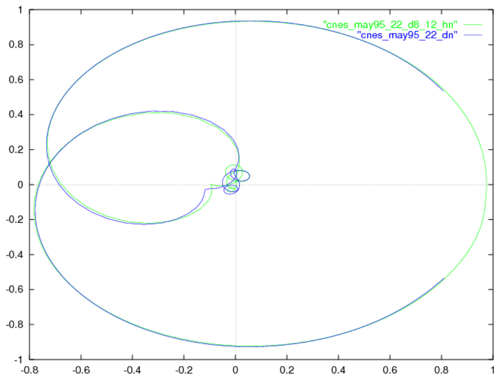

Figure 2. Nyquist Diagram. Rational approximation (degree 8) and data - S_{22}.

$$|S_{1,2}|^2 = \frac{1}{1+D^2}.$$

The filtering function appears to be the ratio of two polynomials p_1/p_2, the numerator of the reflection and transmission scattering factors, that may be chosen freely. The denominator q is then obtained as the unique stable unitary polynomial solving the classical Feldtkeller spectral equation:

$$qq^* = p_1 p_1^* + p_2 p_2^*.$$

The relative simplicity of the derivation of a filter's response, under modulus constraints, owes much to the possibility of forgetting about Feldtkeller's equation and express all design constraints in terms of the filtering function. This no longer the case when considering the synthesis N-port devices for $N > 3$, like multiplexers, routers and power dividers, or when considering the synthesis of filters under matching conditions. The efficient derivation of multiplexers responses is the subject of recent investigation by Apics, using techniques based on constrained Nevanlinna-Pick interpolation (see Section 5.2).

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 5.4. The stability check for limit cycles is now under investigation.

5. New Results

5.1. Inverse problems for Poisson-Laplace equations

Participants: Laurent Baratchart, Sylvain Chevillard, Juliette Leblond, Konstantinos Mavreas, Christos Papageorgakis, Dmitry Ponomarev.

This section is concerned with inverse problems for 3-D Poisson-Laplace equations, among which source recovery issues. Though the geometrical settings differ in Sections 5.1.1 and 5.1.5, the characterization of silent sources (those giving rise to a vanishing field) is one common problem to both cases. The latter has been resolved in the magnetization setup for thin slabs [36]. The case of volumetric distribution is currently being investigated, starting with magnetization distributions on closed surfaces to which the general volumetric case can be reduced by balayage.

5.1.1. Inverse magnetization issues in the thin-plate framework

This work is carried out in the framework of the Inria Associate Team IMPINGE, comprising Eduardo Andrade Lima and Benjamin Weiss from the Earth Sciences department at MIT (Boston, USA) and Douglas Hardin, Michael Northington, Edward Saff and Cristobal Villalobos from the Mathematics department at Vanderbilt University (Nashville, USA).

The overall goal of IMPINGE is 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). During previous years, we always considered the case when the rock is cut into slabs so thin that the magnetization distribution could be considered to lie in a plane. This year, we started considering the situation where the thickness r of the sample cannot be ignored. The thin-slab case thus appears as a limiting case when r goes to 0.

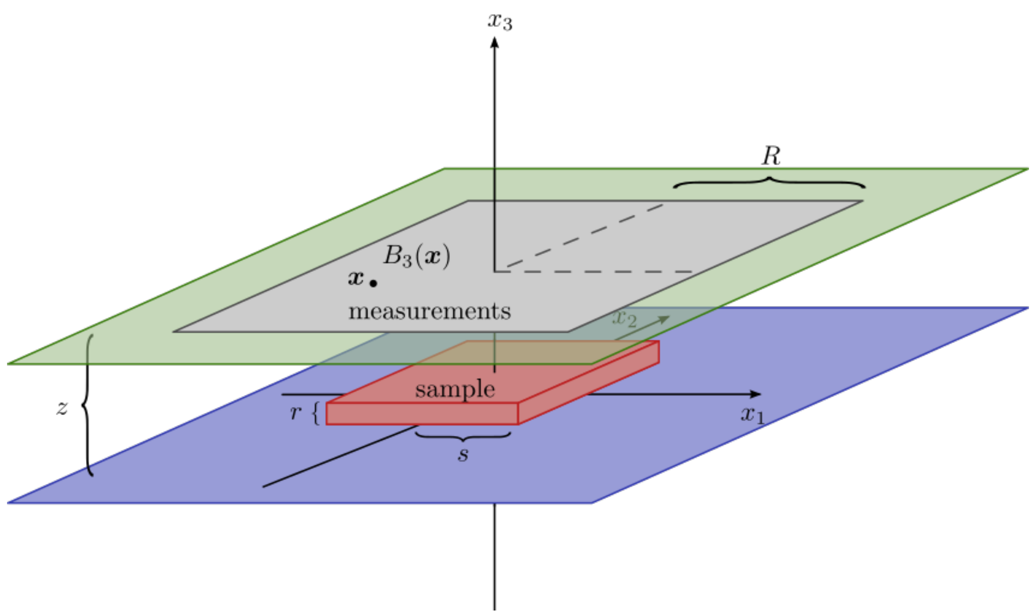

Figure 3. Schematic view of the experimental setup

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 on points of a horizontal square at height z.

We focused on net moment recovery, the net moment of a magnetization being given by its mean value on the sample. The net moment is a valuable piece of information to Physicists and has the advantage of being well-defined: whereas two different magnetizations can generate the same field, the net moment depends only on the field and not on the magnetization itself. Hence the goal may be described as building 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. This research effort was paid in two different, complementary directions.

The first approach consists in computing asymptotic expansions of the integrals $\iint B_3(x_1, x_2, z)\,\mathrm{d}x_1\mathrm{d}x_2$, $\iint x_1\, B_3(x_1, x_2, z)\,\mathrm{d}x_1\mathrm{d}x_2$ and $\iint x_2\, B_3(x_1, x_2, z)\,\mathrm{d}x_1\mathrm{d}x_2$, on several domains (namely, the 2-D balls of radius R for the 1, 2 and ∞ norm, that are squares, disks, diamonds), in terms of the moments of first and higher order of the magnetization m. Last year, we obtained formulas valid only under the thin-slab hypothesis. This year, we extended the results to the case of a volumetric magnetization. We posted a preprint [22] with these results on HAL, and our partners at MIT are currently conducting practical experiments with the SQUID to illustrate the method, before submitting it to some journal. In parallel, Fourier based techniques designed by reformulating the problem with the help of the Kelvin transform also furnish an asymptotic expansion of the net moment involving, at the first order, the above-mentioned integrals computed on disks of large radius. The computations are quite involved but allow to obtain higher-order terms. This constitutes Part III of D. Ponomarev's PhD work [11], defended this year.

The second approach attempts to generalize the previous expansions. The initial question is: given measurements of B_3, find a function $\phi(x_1, x_2)$ such that $\iint \phi(x_1, x_2) B_3(x_1, x_2)\,\mathrm{d}x_1\mathrm{d}x_2$ is best possible an estimate of the net moment components $\langle m_i \rangle$ $(i = 1, 2, 3)$, in some appropriate sense. This problem has no solution really because, for any $\epsilon > 0$, there exists a function ϕ_ϵ allowing to estimate the moment with an error bounded by ϵ. We proved that, when ϵ tends to zero, the norm of the function ϕ_ϵ tends to infinity, which hinders an accurate numerical computation of the integral since B_3 is only known on a discrete grid of points. We therefore expressed the problem as a bounded extremal problem (see Section 3.3.1): to find the best ϕ_ϵ (with the smallest possible error value ϵ) under the constraint that $\|\nabla\phi_\epsilon\|_2 \leq M$. Here, M is a user-defined parameter. We improved on the iterative algorithm devised last year and completed the theoretical justification of its convergence. Basic properties of the operators involved, which are necessary to carry out the procedure, have been derived in [21], along with perspectives on minimum L^2 regularization for the computation of local moments (which are usually not determined by the field, unlike the net moment).

We also performed preliminary numerical experiments which are very encouraging, but still need to be pushed further in connection with the delicate issue of how dense should the grid of data points be in order to reach a prescribed level of precision. An article on this topic is in preparation.

In this connection, the PhD thesis of D. Ponomarev's [11], Part II, contains a study of the 2D spectral problem for the truncated Poisson operator in planar geometry. This is a simplified (*i.e.* 2-D) setup for the relation between the magnetization and the magnetic potential, of which the magnetic field is the gradient. It is relevant because, by the familiar Courant min-max principle, the eigenvectors of the magnetization-to-field operator produce in principle an efficient basis to expand a given magnetization in short series. Describing these eigenvectors is a long-standing problem. Asymptotic formulas as the measurement height gets small with respect to the size of the sample have been obtained, both for dominant eigenvalues and eigenvectors, through connections with other spectral problems. In fact, asymptotic reductions for large and small values of the main parameters (distance h from the measurement plane to the sample support and sample support size), yield approximate solutions by means of simpler integral equations and ODEs.

5.1.2. Inverse magnetization issues from sparse spherical data

The team Apics 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 7.2.2). Recent studies let geoscientists to think that the Moon used to have a magnetic dynamo for a while, yet 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 this year 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 Apics is to enhance the numerical efficiency of post-processing data obtained with this magnetometer.

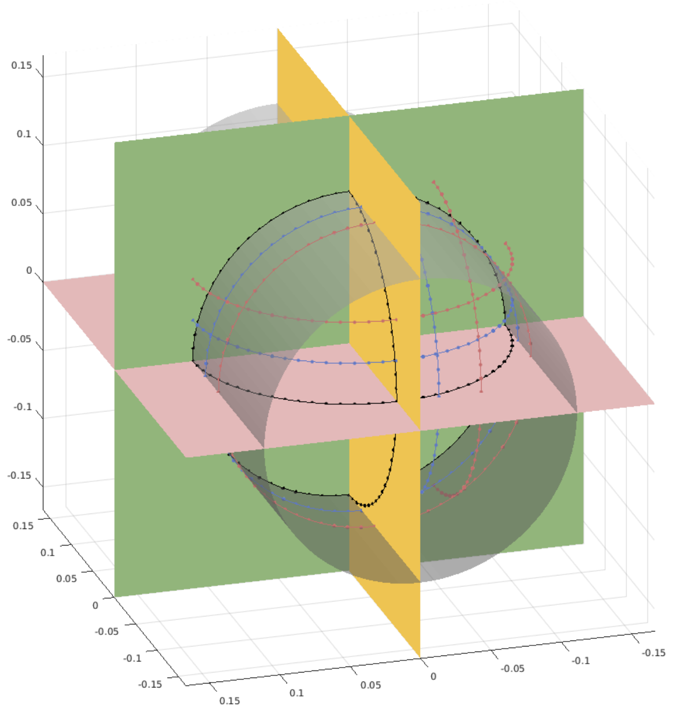

Figure 4. Typical measurements obtained with the instrument of Cerege. Measurements of the field are performed on nine circles, given as sections of three cylinders. On each circle, only one component of the field is measured: the component B_h along the axis of the corresponding cylinder (blue points), the component B_n radial with respect to the circle (black points), or the component B_τ tangential to the circle (red points).

This year, we continued the approach initiated in 2015 during K. Mavreas' internship: under the hypothesis that the field can be well explained by a single magnetic dipole, and using ideas similar to those underlying the FindSources3D tool (see Sections 3.4.2 and 5.1.5), we try to recover the position and moment of the dipole. The rational approximation technique that we are using gives, for each circle of measurements, a partial information about the position of the dipole. These partial informations obtained on all nine circles must then be combined in order to recover the exact position. Theoretically speaking, the nine partial informations are redundant and the position could be obtained by several equivalent techniques. But in practice, due to the fact that the field is not truly generated by a single dipole, and also because of noise in the measurements and numerical errors in the rational approximation step, all methods do not show the same reliability when combining the partial results. We studied several approaches, testing them on synthetic examples, with more or less noise, in order to propose a good heuristic for the reconstruction of the position. This is still on-going work.

5.1.3. Surface distributed magnetizations and vector fields decomposition

This is a joint work with Pei Dang and Tao Qian from the University of Macao.

Silent magnetizations in the thin plate case were characterized in [36] using a decomposition of $\mathbb{R}^3$-valued vector fields defined on $\mathbb{R}^2 \sim \mathbb{R}^2 \times \{0\} \subset \mathbb{R}^3$. More precisely, in rather general smoothness classes (involving all distributions with compact support), such a vector field is the sum of the traces on $\mathbb{R}^2$ of a harmonic gradient in the upper half space, a harmonic gradient in the lower half space, and of a tangential divergence-free vector field. This year the corresponding decomposition has been obtained in L^p-classes on closed surfaces, where $1 < p < \infty$ if the surface is smooth but p has to be restricted around the value 2 if the surface is only Lipschitz smooth. The proof uses elliptic regularity theory, some Hodge theory and Clifford analysis.

In the case where the curvature is constant (*i.e.* for spheres and planes), one recovers using the previous result that silent distribution have no inner harmonic gradient component, whereas in the case of more general surfaces one finds they have to satisfy a spectral equation for the double layer potential. This also furnishes a characterization of volumetric silent distributions by saying that their balayage to the boundary of the volume (which is a closed surface) is silent. An article is being written on this topic.

5.1.4. Decomposition of the geomagnetic field

This is a joint work with Christian Gerhards from the University of Vienna.

The techniques based on solving bounded extremal problems, set forth in Section 5.1.1 to estimate the net moment of a planar magnetization, may be used to approach the problem of decomposing the magnetic field of the Earth into its crustal and core components, when adapted to a spherical geometry.

Indeed, in geomagnetism it is of interest to separate the Earth's core magnetic field from the crustal magnetic field. However, satellite measurements can only sense the superposition of the two contributions. In practice, the measured magnetic field is expanded in terms of spherical harmonics and a separation into crust and core contribution is done empirically by a sharp cutoff in the spectral domain. Under the assumption that the crustal magnetic field is supported on a strict subset of the Earth's surface, which is nearly verified as some regions on the globe are only very weakly magnetic, one can state an extremal problem to find a linear form yielding an arbitrary coefficient of the expansion in spherical harmonics on the crustal field, while being nearly zero on the core contribution. An article is being prepared to report on this research.

5.1.5. Inverse problems in medical imaging

This work is conducted in collaboration with Jean-Paul Marmorat and Nicolas Schnitzler, together with Maureen Clerc and Théo Papadopoulo from the Athena EPI.

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 [6], [41] 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 (see Section 3.4.2) is being developed, in collaboration with the team Athena and the CMA. In addition to the modular and ergonomic platform version of FindSources3D, a new (Matlab) version of the software that automatically performs the estimation of the quantity of sources is being built. It uses an alignment criterion in addition to other clustering tests for the selection. 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 (for EEG data, one should consider *triple* poles). Though numerically observed in [7], 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. 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, this new version may take as inputs actual EEG measurements, like time signals, and performs a suitable singular value decomposition in order to separate independent sources.

In connection with these and other brain exploration modalities like electrical impedance tomography (EIT), we are now studying conductivity estimation problems. This is the topic of the PhD research work of C. Papageorgakis (co-advised with the Athena project-team and BESA GmbH). In layered models, it concerns the estimation of the conductivity of the skull (intermediate layer). Indeed, the skull was assumed until now to have a given isotropic constant conductivity, whose value can differ from one individual to another. A preliminary issue in this direction is: can we uniquely recover and estimate a single-valued skull conductivity from one EEG recording? This has been established in the spherical setting when the sources are known, see [14]. Situations where sources are only partially known and the geometry is more realistic than a sphere are currently under study. When the sources are unknown, we should look for more data (additional clinical and/or functional EEG, EIT, ...) that could be incorporated in order to recover both the sources locations and the skull conductivity. Furthermore, while the skull essentially consists of a hard bone part, which may be assumed to have constant electrical conductivity, it also contains spongy bone compartments. These two distinct components of the skull possess quite different conductivities. The influence of the second on the overall model is currently being studied.

5.2. Matching problems and their applications

Participants: Laurent Baratchart, Martine Olivi, David Martinez Martinez, Fabien Seyfert.

This is collaborative work with Stéphane Bila (XLIM, Limoges, France), Yohann Sence (XLIM, Limoges, France), Thierry Monediere (XLIM, Limoges, France), Francois Torrès (XLIM, Limoges, France) in the context of the ANR Cocoram (see Section 7.2.1).

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. This is for example the case when synthesizing a multiplexer: each filter is here loaded at one of its ports on a common junction. Thus, the load varies with frequency by construction, and is not purely resistive either. Likewise, 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. 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:

$$|G_{1,1}| = \left| \frac{S_{2,2} - \overline{L_{1,1}}}{1 - S_{2,2}L_{1,1}} \right| = \delta(G_{1,1}, S_{2,2}).$$

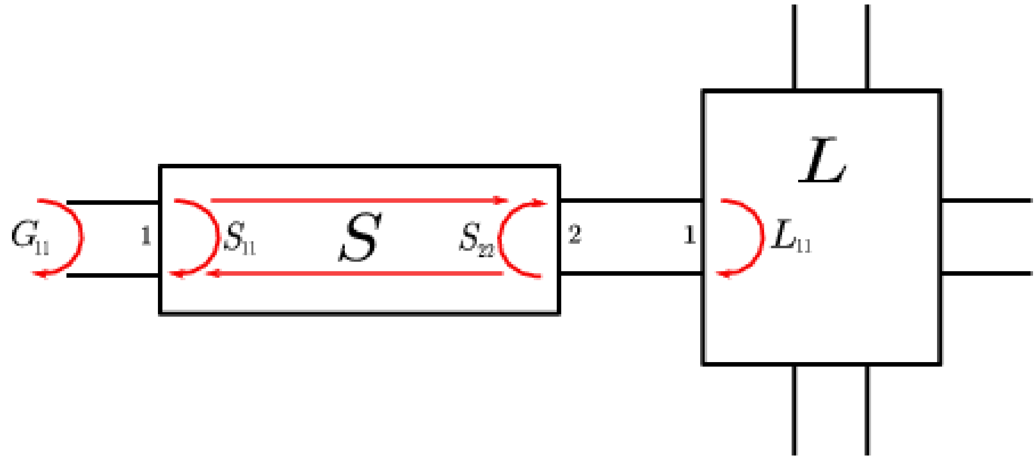

Figure 5. Filter plugged on a system with reflexion coefficient L_{11}

The matching problem of minimizing $|G_{1,1}|$ amounts therefore to minimize the pseudo-hyperbolic distance δ between the filter's reflex-ion parameter $S_{2,2}$ and the load's reflex-ion $L_{1,1}$, 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.

5.2.1. Approach based on interpolation

When the degree n of the rational function $S_{2,2}$ is fixed, the hyperbolic minimization problem is non-convex which leads us to seek methods to derive good initial guesses for classical descent algorithms. To this effect, if $S_{2,2} = p/q$ where p, q are polynomials, we considered the following interpolation problem $\mathcal{P}$: given n frequency points $w_1 \cdots w_n$ and a transmission polynomial r, to find a monic polynomial p of degree n such that:

$$j = 1..n, \qquad \frac{p}{q}(w_j) = \overline{L_{1,1}(w_j)}$$

where q is the unique monic Hurwitz polynomial of degree n satisfying the Feldtkeller equation

$$qq^* = pp^* + rr^*,$$

which accounts for the losslessness of the filter. The frequencies (w_k) are perfect matching points where $\delta(S_{2,2}(w_k), L_{1,1}(w_k)) = 0$ holds, while the real zeros (x_k) of r are perfect rejection points (i.e. $\delta(S_{2,2}(x_k), L_{1,1}(x_k)) = 1$). The interpolation problem is therefore a point-wise version of our original matching-rejection problem. The monic restriction on p and q ensures the realizability of the filter in terms of coupled resonating circuits. If a perfect phase shifter is added in front of the filter, realized for example with a transmission line on a narrow frequency band, these monic restrictions can be dropped and an extra interpolation point w_{n+1} is added, thereby yielding another interpolation problem $\widehat{\mathcal{P}}$. Our main result, states that $\mathcal{P}$ as well as $\widehat{\mathcal{P}}$ admit a unique solution. Moreover the evaluation map defined by $\psi(p) = (p/q(x_1), \cdots, p/q(x_n))$ is a homeomorphism from monic polynomials of degree n onto $\mathbb{D}^n$ ($\mathbb{D}$ the complex open disk), and ψ^{-1} is a diffeomorphism on an open, connected, dense set of $\mathbb{D}^n$. This last property has shown to be crucial for the design of an effective computational procedure based on continuation techniques. Current implementations of the latter tackle instances of $\mathcal{P}$ or $\widehat{\mathcal{P}}$ for $n = 10$ in less than 0.1 sec, and allow for a recursive use of this interpolation framework in multiplexer synthesis problems. We presented these techniques at the MTNS conference 2016 held in Mineapolis [17]. The detailed mathematical proofs can be found in [23] which is under review at SIMA, the SIAM journal on Mathematical Analysis.

5.2.2. Uniform matching and global optimality considerations

The previous interpolation procedure provides us with a matching/rejecting filtering characteristics at a discrete set of frequencies. This may 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 have shown to be quite convincing, we have no proof of their global optimality. This led us to seek alternative approaches able to assess, at least in simple cases, global optimality of the derived response. By optimality we mean, as in classical filtering, the ability to derive the uniformly best matching response in a given pass-band, while ensuring some rejection constraints on a stop-band. 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 1, and if the transmission zeros of the overall system are fixed, then 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. In this case, which is already of some practical interest for antenna matching (antennas usually exhibit a single resonance in their matching band which is decently approximated at order 1), it is therefore possible to perform filter synthesis with a guarantee on the global optimality of the obtained characteristics. The practical approach, relying on convex duality and linear programming is presented in [26], together with an implementation using a SIW (substrate integrated filter).

5.3. Sensitivities of Electrical Parameters with respect to physical parameters

Participants: Matthias Caenepeel, Martine Olivi, Fabien Seyfert.

This work was conducted in collaboration with Yves Rolain (VUB, Brussels, Belgium). The goal is to automatize and improve our computer-aided tuning (CAT) method for coupled-resonator microwave synthesis, which is based on rational approximation and circuit extraction as explained before. The novelty here lies with estimating the Jacobian of the function that relates the physical filter design parameters to the extracted coupling parameters. Lately commercial full-wave electromagnetic (EM) simulators provide the adjoint sensitivities of the S-parameters with respect to the geometrical parameters. This information allows us for an efficient estimation of the Jacobian since it no longer requires finite difference based evaluation. Our tuning method first extracts the physically implemented coupling matrix, and then estimates the corresponding Jacobian. Next it compares the extracted coupling matrix to the target coupling matrix (golden goal). Using the difference between the coupling matrices and the pseudo-inverse of the estimated Jacobian, a correction that brings the design parameters closer to the golden goal is obtained. This process is repeated iteratively until the correction becomes sufficiently small with respect to a user-specified goal. In the case of coupling structures with multiple solutions, the Jacobian is calculated for each admissible solution. This paper presents a criterion to identify the physical solution among the different possibilities. The CAT method has been applied to the design of a cascaded triplet (CT) filter implemented in a microstrip technology. This filter is a well-known examples of a non-canonical coupling structure. See [24] for details.

5.4. Stability of amplifiers

Participants: Laurent Baratchart, Sylvain Chevillard, Martine Olivi, Fabien Seyfert, Sebastien Fueyo.

This work is performed under contract with CNES-Toulouse and the University of Bilbao as well as in collaboration with Adam Cooman (VUB, Brussels, Belgium). The goal is to help design amplifiers, in particular to detect instability at an early stage of the design. Activity in this area is gaining importance with the coming of a doctoral and a postdoctoral student along with planned software developments.

Performing a stability analysis during the design of any electronic circuit is critical to guarantee its correct operation. A closed-loop stability analysis can be performed by analyzing the impedance presented by the circuit at a well-chosen node without internal access to the simulator. If any of the poles of this impedance lie in the complex right half-plane, the circuit is unstable. The classic way to detect unstable poles is to fit a rational model on the impedance. This rational approximation has to deal with model order selection, which is difficult in circuits with transmission lines. In the practical approach we develop in collaboration with Adam Cooman, a projection-based method is proposed which splits the impedance into a stable and an unstable part by projecting on an orthogonal basis of stable and unstable functions. Working with a projection instead of a rational approximation greatly simplifies the stability analysis. When the projection is mapped from the complex plane to the unit disc, it boils down to calculating a Fourier series. If a significant part of the impedance is projected on the unstable part, a low-order rational approximation is fitted on this unstable part to find the location of the unstable poles. See [25] for details. Adapting such tools to check the stability of a trajectory, linearizing around the latter, is tantamount to develop a similar theory for time-varying periodic systems. This is the subject of S. Fueyo's PhD work.

5.5. 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. During year 2016, we released version 5.0 (in June) and version 6.0 (in October) of Sollya. Among other things, these releases have heavily improved the internal handling of polynomial expressions and the speed of the faithful evaluation of functions. They also make the library API more complete and fix most of the reported bugs. Another important novelty of 2016 is that Sollya is now officially included in the Debian Linux distribution.

5.6. Asymptotics of weighted Bergman polynomials

Participant: Laurent Baratchart.

We extended this year exterior asymptotics for orthonormal polynomials with respect to a weight on a planar region Ω (so-called weighted Bergman polynomials) to the case where Ω is simply connected, asymptotically conformal and chord arc, with exterior conformal map f from the complement of the disk to the complement of Ω such that f''/f' lies in a Hardy class H^q with $q < 1$. This class of domain is more general than, say the $C^{1\alpha}$ class. Meanwhile the weight should have integrable non-tangential maximal function and non-tangential limit with positive geometric mean. As $n \to \infty$, the formula reads

$$P_n(z) = \left(\frac{n+1}{\pi}\right)^{1/2} S_{w\circ f}(\Phi(z))\,\Phi^n(z)\Phi'(z)\{1+o(1)\},$$

locally uniformly outside the convex hull of Ω, where $\Phi = f^{-1}$ and $S_{w\circ f}$ is the Szegő function of the boundary weight . The proof uses quasi-conformal mappings and some Hardy space theory, along with classical Fourier analysis of Taylor sections.

The result goes much beyond those previously known, which either assume analyticity of Ω or else constant or analytic weight. An article is being written on this topic.

6. Bilateral Contracts and Grants with Industry

6.1. Contract CNES-Inria-XLIM

This contract (reference Inria: 7066, CNES: 127 197/00) involving CNES, XLIM and Inria, focuses on the development of synthesis algorithms for N-ports microwave devices. The objective is to derive analytical procedures for the design of multiplexers and routers, as opposed to "black box optimization" which is usually employed in this field (for $N \geq 3$). Emphasis at the moment bears on so-called “star-topologies”.

6.2. Contract CNES-Inria-UPV/EHU

This contract (reference CNES: RS14/TG-0001-019) involving CNES, University of Bilbao (UPV/EHU) and Inria aims at setting up a methodology for testing the stability of amplifying devices. The work at Inria is concerned with the design of frequency optimization techniques to identify the unstable part of the linearized response and analyze the linear periodic components.

6.3. Contract BESA GmbH-Inria

This is a research agreement between Inria (Apics and Athena teams) and the German company BESA [0], which deals with head conductivity estimation and co-advising of the doctoral work of C. Papageorgakis, see Section 5.1.5. BESA is funding half of the corresponding research grant, the other half is supported by Region PACA (BDO), see Section 1.

6.4. Flextronics

Flextronics, active in the manufacturing of communication devices all over the world, bought two sets of licenses for Presto-HF and Dedale-HF. Deployment of our tools in their production facilities for wireless communication units is being studied.

7. Partnerships and Cooperations

7.1. Regional Initiatives

- Contract Provence Alpes Côte d'Azur (PACA) Region - Inria, BDO (no. 2014-05764) funding the research grant of C. Papageorgakis, see Sections 5.1.5, 6.3.
- The team participates in the project WIMAG (Wave IMAGing) funded by the IDEX UCA-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 participates in the transversal action C4PO funded by the IDEX UCA-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.

7.2. National Initiatives

7.2.1. 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. We are associated with three other teams from XLIM (Limoges University), geared respectively towards filters, antennas and amplifiers design. The core idea of the project is to realize dual band reception an emission chains by co-conceiving the antenna, the filters, and the amplifier. We are specifically in charge of the theoretical design of the filters, matching the impedance of a bi-polarized dual band antenna. This is a perfect training ground to test, apply and adapt our work on matching problems (see Section 5.2).

[0] http://www.besa.de/

7.2.2. 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 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. Apics 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 5.1 are instrumental for this purpose.

7.3. European Initiatives

7.3.1. 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.

7.4. International Initiatives

7.4.1. Inria Associate Teams Not Involved in an Inria International Labs

7.4.1.1. 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/

The associate team IMPINGE is concerned with the inverse problem of recovering a magnetization distribution from measurements of the magnetic field above rock slabs using a SQUID microscope (developed at MIT). The application domain is to Earth and planetary sciences. Indeed, the remanent magnetization of rocks provides valuable information on their history. This is a renewal of the previous Associate Team IMPINGE that ended 2015. The US team also involves a group of Mathematicians (D. Hardin, M. Northington, E.B. Saff) at Vanderbilt University.

7.4.2. Inria International Partners

7.4.2.1. Declared Inria 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).

7.5. International Research Visitors

7.5.1. Visits of International Scientists

- Christian Gerhards (Universität Wien, Vienna, Austria, September 5-9).
- Douglas Hardin (Vanderbilt University, Nashville, Tennessee, USA, June 11-21).
- Nuutti Hyvonen (Aalto University, Finland, June 13-14).
- Benjamin Lanfer (BESA, Munich, Germany, February 4-5).
- Eduardo Lima (MIT, Boston, Massachusetts, USA, June 13-17).
- Michael Northington (Vanderbilt University, Nashville, Tennessee, USA, June 11-22).
- Vladimir Peller (University of Michigan at East Lansing, June 10-24).
- Cristobal Villalobos (Vanderbilt University, Nashville, Tennessee, USA, June 8-21).

7.6. List of international and industrial partners

- Collaboration under contract with Thales Alenia Space (Toulouse, Cannes, and Paris), CNES (Toulouse), XLIM (Limoges), University of Bilbao (Universidad del País Vasco / Euskal Herriko Unibertsitatea, Spain), BESA company (Munich), 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), 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, 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 Universiät Wien (Austria), TFH-Berlin (Germany), ENIT (Tunis), KTH (Stockholm), University of Cyprus (Nicosia, Cyprus), University of Macau (Macau, China), SIAE Microelettronica (Milano).
- 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).

8. Dissemination

8.1. Promoting Scientific Activities

- L. Baratchart gave a talk at the Shanks workshop "Mathematical methods for inverse magnetization problems arising in geosciences", organized at Vanderbilt University (Nashville, USA), March 2016, a talk at "SEAM", organized by the AMS at USF (Tampa, USA), a talk at "AppOpt" organized by ICIMAF in Havana (Cuba) http://gama.uc3m.es/claroline1811/courses/APPOPT16/document/index.html and a talk at ' SIGMA'2016 (Signal-Image-Géométrie-Modélisation-Approximation). http://programme-scientifique.weebly.com/1506.html, organized by the SMAI at CIRM (Luminy, France).
- S. Chevillard gave a talk at the Shanks workshop "Mathematical methods for inverse magnetization problems arising in geosciences", organized at Vanderbilt University (Nashville, USA), March 2016.

- B. Hanzon gave a presentation at the CDC 2016 pre-workshop on "realization theory and its role in system identification" (joint work with M. Olivi and R. Peeters) https://sites.google.com/site/mihalypetreczky/workshop-cdc-2016, Las-Vegas, USA, December 11.
- J. Leblond presented a communication at the above-mentioned Shanks Workshop, at the conference PICOF 2016 (Problèmes Inverses, Contrôle, Optimisation de Formes, Autrans, France, June 1-3 2016, http://picof.sciencesconf.org/), and at the seminar Mécanique, Modélisation Mathématique et Numérique, LMNO, Univ. Caen, France, December 5, 2016.
- M. Olivi gave a talk at the conference SIGMA'2016 (Signal-Image-Géométrie-Modélisation-Approximation). http://programme-scientifique.weebly.com/1506.html, Marseille, France, October 30-November 4.
- F. Seyfert presented a communication at the 22nd International Symposium on Mathematical Theory of Netowrks and Systems https://sites.google.com/a/umn.edu/mtns-2016/, USA, Mineapolis, July 12-15, 2016.
- K. Mavreas presented a communication at the Conference Advances in Lunar Magnetism: from Paleomagnetism to Dynamos, Cargèse, France, June 1-3, 2016, http://maglune.cerege.fr/?page_id=416. Together with C. Papageorgakis, they participated to the Semaine d'Étude Mathématiques-Informatique Entreprises, Grenoble, France, October 24-28, 2016. Grenoble.
- C. Papageorgakis presented a communication at the Conference PICOF 2016 and at the Science Day in BESA company, Munich, Germany, December 15, 2016.
- D. Ponomarev presented a communication at the above-mentioned Shanks Workshop and a poster at the Conference PICOF 2016.
- D. Martinez Martinez gave a seminar at the department ELEC of the Vrije UninIversiteit of Brussels (sept. 18) and at the Universidad Polit´ecnica de Cartagena, ETSI (December 14). He gave a talk at the 2016 IEEE International Conference on Antenna Measurements & Applications, Syracuse (NY), USA, October 23-27.

8.1.1. Scientific Events Organisation

8.1.1.1. Member of the Organizing Committees

K. Mavreas and C. Papageorgakis were among the PhD students in charge of the PhD students Seminar within the Research Center.

J. Leblond was one of the co-organizers of the 3rd "Journée Mathématiques et Parité", IHP, Paris, July 8, 2016, http://postes.smai.emath.fr/apres/parite/journee2016/.

8.1.2. Scientific Events Selection

8.1.2.1. Member of the Conference Program Committees

L. Baratchart was a member of the program committee of "Mathematical Theory of Network and Systems" (MTNS) 2016, Minneapolis, Minnesota, USA.

J. Leblond was a member of the Scientific Committee of the Conference PICOF 2016.

8.1.3. Journal

8.1.3.1. Member of the Editorial Boards

L. Baratchart is sitting on the Editorial Board of the journals *Constructive Methods and Function Theory* and *Complex Analysis and Operator Theory*.

8.1.3.2. Reviewer - Reviewing Activities

L. Baratchart served as a reviewer for several journals (Annales Inst. Fourier, SIMA, Numerical Algorithms, Journal of Approx. Theory, Complex Variables and Elliptic Equations, ...)

J. Leblond was a reviewer for the journal *Multidimensional Systems and Signal Processing, Czechoslovak Mathematical Journal*.

M. Olivi was a reviewer for the journals *Automatica* and *IEEE Transactions on Automatic Control* and for the IEEE Conference on Decision and Control.

F. Seyfert was a reviewer for the journal *IEEE Microwave Theory and Techniques*.

8.1.4. Invited Talks

L. Baratchart was an invited speaker at the “25-th Summer Meeting in Mathematical Analysis”, organized by the Russian Academy of Sciences at the Euler Institute (St-Petersburg, Russia) http://gauss40.pdmi.ras.ru/ma25/, an invited speaker at the workshop “New Trends in Approximation Theory” organized by the CSM at the Fields Institute (Toronto, Canada) http://www.fields.utoronto.ca/activities/16-17/approximation, an invited speaker at the conference “Quasilinear equations, Inverse Problems and their Applications” organized by EAIP, RFBR,MIPT and Ecole Polytechnique at the Moscow Institute of Physics and Technology (Dolgoprundy, Russia) http://www.cmap.polytechnique.fr/~novikov/miptip16/, and an invited speaker at the “Complex Analysis Day” in Marne-la-Vallée.

S. Chevillard was invited to give a talk at the Fifth Approximation Days, International conference on constructive complex approximation, http://math.univ-lille1.fr/~bbecker/ja2016/, Lille, France, May 20, 2016.

J. Leblond was a plenary speaker at the Conference WiS&E 2016 (Waves in Sciences and Engineering), http://qro.cinvestav.mx/index.php/wise2016, Queretaro, Mexico, August 22-26, 2016, and an invited speaker at the Workshop SIGMA’2016 (Signal, Image, Geometry, Modelling, Approximation), https://www.ceremade.dauphine.fr/~peyre/sigma2016/, Luminy, France, October 31 - November 4, 2016.

F. Seyfert was invited to give a talk at the Workshop on Mathematical Aspects of Network Synthesis http://www-control.eng.cam.ac.uk/Main/Workshop8, Cambridge, UK, September 21-22, 2016.

8.1.5. Scientific Expertise

L. Baratchart is a member of the Mathematical panel of experts of ANR.

8.1.6. Research Administration

S. Chevillard was representative at the “comité de centre” and at the “comité des projets” (Research Center Inria-Sophia) until September 2016.

J. Leblond is an elected member of the “Conseil Scientifique” and of the “Commission Administrative Paritaire” of Inria. Until May, she was in charge of the mission “Conseil et soutien aux chercheurs” within the Research Center. She is also a member of the “Conseil Académique” of the Univ. Côte d’Azur (UCA).

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Colles: S. Chevillard is giving “Colles” at Centre International de Valbonne (CIV) (2 hours per week).

8.2.2. Supervision

PhD: D. Ponomarev, *Some inverse problems with partial data*, Université Nice Sophia Antipolis, defended on June 14, 2016 (advisors: J. Leblond, L. Baratchart).

PhD: M. Caenepeel, *The development of models for the design of RF/microwave filters*, Vrije Universiteit Brussel (VUB), defended on October 19, 2016 (advisors: Y. Rolain, M. Olivi, F. Seyfert).

PhD in progress: C. Papageorgakis, *Conductivity model estimation*, since October 2014 (advisors: J. Leblond, M. Clerc, B. Lanfer).

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 and F. Seyfert.

PhD in progress: G. Bose, Filter Design to Match Antennas, since December 2016, advisors: F. Ferrero and F. Seyfert.

PhD in progress: S. Fueyo, Cycles limites et stabilité dans les circuits,since October 2016, advisors: L. Baratchart and J.B. Pomet.

8.2.3. Juries

L. Baratchart sat on the PhD defense committee of d'Alexey Agaltsov (Ecole Polytechnique, http://www.adum.fr/script/detailSout.pl?mat=65164&site=PSaclay) and on the committee for the defense of *Habilitation à diriger des recherches* of E. Abakumov (Université Paris-Est, Marne-la-Vallée, http://umr-math.univ-mlv.fr/evenements/soutenances/?type=101).

J. Leblond was a member of the "Jury d'admissibilité du concours CR" of the Inria Research Center and of the "Comités de Sélection" for professors at UNSA (Polytech Nice) and at the University Paris-Sud Orsay (March-May 2016). She was a reviewer for the PhD thesis of Silviu Ioan Filip, Univ. Lyon, December 2016.

F. Seyfert was a member of the PhD jury of Adam Cooman at the ELEC. department of the VUB (Bruxelles, Belgium). The PhD's title is "Distorsion Analysis of Analog Electronic Circtuits Using Modulated Signals".

8.3. Popularization

- 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/. She animated two half-day workshop sessions "activités débranchées" at "l'ESPE de Nice" for primary school students (March 08 & 15), 200 students each session). She participates to the event "la fête de la science" in Nice (October 13) for scholars and in Antibes (October 22 & 23, 6200 people). She gave a talk "180'" at the "Journées Scientifiques Inria" in Rennes.
- K. Mavreas and C. Papageorgakis actively participated to events organized by the Committee MASTIC (Fête de la Science, ...).

9. Bibliography

Major publications by the team in recent years

[1] S. Amari, F. Seyfert, M. Bekheit.*Theory of Coupled Resonator Microwave Bandpass Filters of Arbitrary Bandwidth*, in "Microwave Theory and Techniques, IEEE Transactions on", August 2010, vol. 58, n^{o} 8, p. 2188 -2203.

[2] B. Atfeh, L. Baratchart, J. Leblond, J. R. Partington.*Bounded extremal and Cauchy-Laplace problems on the sphere and shell*, in "J. Fourier Anal. Appl.", 2010, vol. 16, n^{o} 2, p. 177–203, Published online Nov. 2009, http://dx.doi.org/10.1007/s00041-009-9110-0.

[3] L. Baratchart, S. Chevillard, T. Qian.*Minimax principle and lower bounds in H^2-rational approximation*, in "Journal of Approximation Theory", 2015, vol. 206, p. 17–47.

[4] L. BARATCHART, J. LEBLOND, S. RIGAT, E. RUSS.*Hardy spaces of the conjugate Beltrami equation*, in "Journal of Functional Analysis", 2010, vol. 259, n^{o} 2, p. 384-427, http://dx.doi.org/10.1016/j.jfa.2010.04.004.

[5] L. BARATCHART, F. MANDRÉA, E. B. SAFF, F. WIELONSKY.*2D inverse problems for the Laplacian: a meromorphic approximation approach*, in "Journal de Math. Pures et Appliquées", 2008, vol. 86, p. 1-41.

[6] L. BARATCHART, H. STAHL, M. YATTSELEV.*Weighted Extremal Domains and Best Rational Approximation*, in "Advances in Mathematics", 2012, vol. 229, p. 357-407, http://hal.inria.fr/hal-00665834.

[7] M. CLERC, J. LEBLOND, J.-P. MARMORAT, T. PAPADOPOULO.*Source localization using rational approximation on plane sections*, in "Inverse Problems", May 2012, vol. 28, n^{o} 5, 24, http://hal.inria.fr/inria-00613644.

[8] V. LUNOT, F. SEYFERT, S. BILA, A. NASSER.*Certified Computation of Optimal Multiband Filtering Functions*, in "IEEE Transactions on Microwave Theory and Techniques", 2008, vol. 56, n^{o} 1, p. 105-112, http://dx.doi.org/10.1109/TMTT.2007.912234.

[9] M. OLIVI, F. SEYFERT, J.-P. MARMORAT.*Identification of microwave filters by analytic and rational H2 approximation*, in "Automatica", January 2013, vol. 49, n^{o} 2, p. 317-325 [*DOI :* 10.1016/J.AUTOMATICA.2012.10.005], http://hal.inria.fr/hal-00753824.

Publications of the year

Doctoral Dissertations and Habilitation Theses

[10] M. CAENEPEEL.*Modeling technique for the efficient design of microwave bandpass filters*, Inria Sophia Antipolis - Méditerranée ; Vrije Universiteit Brussels, October 2016, https://hal.archives-ouvertes.fr/tel-01421150.

[11] D. PONOMAREV.*Some inverse problems with partial data*, Inria Sophia Antipolis - Méditerranée, June 2016, https://hal.archives-ouvertes.fr/tel-01400595.

Articles in International Peer-Reviewed Journal

[12] L. BARATCHART, A. BORICHEV, S. CHAABI.*Pseudo-holomorphic functions at the critical exponent*, in "Journal of the European Mathematical Society", 2016, vol. 18, n^{o} 9 [*DOI :* 10.4171/JEMS], https://hal.inria.fr/hal-00824224.

[13] L. BARATCHART, L. BOURGEOIS, J. LEBLOND.*Uniqueness results for inverse Robin problems with bounded coefficient*, in "Journal of Functional Analysis", 2016 [*DOI :* 10.1016/J.JFA.2016.01.011], https://hal.inria.fr/hal-01084428.

[14] M. CLERC, J. LEBLOND, J.-P. MARMORAT, C. PAPAGEORGAKIS.*Uniqueness result for an inverse conductivity recovery problem with application to EEG*, in " Rendiconti dell'Istituto di Matematica dell'Università di Trieste. An International Journal of Mathematics", 2016, vol. 48, Special issue dedicated to Giovanni Alessandrini, https://hal.archives-ouvertes.fr/hal-01303640.

[15] J. LEBLOND, D. PONOMAREV.*Recovery of harmonic functions in planar domains from partial boundary data respecting internal values*, in "Journal of Inverse and Ill-posed Problems", 2016 [*DOI :* 10.1515/JIIP-2015-0089], https://hal.archives-ouvertes.fr/hal-01242160.

[16] S. LEFTERIU, M. OLIVI, F. SEYFERT, M. OLDONI.*System identification of microwave filters from multiplexers by rational interpolation*, in "Automatica", August 2016, https://hal.inria.fr/hal-01357934.

International Conferences with Proceedings

[17] L. BARATCHART, M. OLIVI, F. SEYFERT.*A unified approach to Nevanlinna-Pick interpolation problems*, in "22nd International Symposium on Mathematical Theory of Networks and Systems", Mineapolis, United States, July 2016, https://hal.archives-ouvertes.fr/hal-01420880.

Conferences without Proceedings

[18] M. CLERC, J. LEBLOND, J.-P. MARMORAT, C. PAPAGEORGAKIS.*On some inverse conductivity recovery problem in a sphere: Uniqueness and reconstruction results with applications to EEG*, in "Problèmes Inverses, Contrôle et Optimisation de Formes (PICOF)", Autrans, France, June 2016, https://hal.inria.fr/hal-01410030.

[19] J. LEBLOND, L. BARATCHART, S. CHEVILLARD, D. PONOMAREV.*Magnetic moments recovery from partial field measurements*, in "PICOF (Problèmes Inverses, Contrôle, Optimisation de Formes)", Autrans, France, June 2016, https://hal.archives-ouvertes.fr/hal-01413094.

[20] D. MARTÍNEZ MARTÍNEZ, F. SEYFERT, M. OLIVI, J. SENCE, S. BILA, F. TORRES, T. MONÉDIÈRE, B. JARRY, A. PERIGAUD, B. FRIGUI, R. CHANTALAT.*Optimized synthesis of a microwave equalizer for matching a high performance small antenna*, in "2016 IEEE International Conference on Antenna Measurements & Applications", Syracuse, United States, October 2016, https://hal.archives-ouvertes.fr/hal-01420641.

Other Publications

[21] L. BARATCHART, S. CHEVILLARD, J. LEBLOND.*Silent and equivalent magnetic distributions on thin plates*, September 2016, Accepted for publication in Theta Series in Advanced Mathematics, https://hal.inria.fr/hal-01286117.

[22] L. BARATCHART, S. CHEVILLARD, J. LEBLOND, E. A. LIMA, D. PONOMAREV.*Moments estimation of magnetic source terms from partial data*, 2016, working paper or preprint, https://hal.inria.fr/hal-01421157.

[23] L. BARATCHART, M. OLIVI, F. SEYFERT.*Boundary nevanlinna-pick interpolation with prescribed peak points. Application to impedance matching*, October 2016, Submitted for publication to SIMA (SIAM journal on Mathematical Analysis) July 2016, https://hal.inria.fr/hal-01377782.

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Project-Team AROMATH

AlgebRa geOmetry Modelling and AlgoriTHms

IN PARTNERSHIP WITH:
National & Kapodistrian University of Athens

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Algorithmics, Computer Algebra and Cryptology

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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 exits 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 appeal for the development of new approaches. The manufacturing environment is also increasingly complex, with new type of machine tools including: turning, 5 axis 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 modelled 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. AXEL

KEYWORDS: CAO - Algebraic geometric modeler
SCIENTIFIC DESCRIPTION

Axel 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. Axel 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

Axel 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: Nicolas Douillet, Anaïs Ducoffe, Valentin Michelet, Bernard Mourrain, Meriadeg Perrinel, Stéphane Chau and Julien Wintz
- Contact: Bernard Mourrain
- URL: http://axel.inria.fr/

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).

6. New Results

6.1. Flat extensions in $_*$-algebras

Participant: Bernard Mourrain.

The main result of the paper [9] is a flat extension theorem for positive linear functionals on $_*$-algebras. The theorem is applied to truncated moment problems on cylinder sets, on matrices of polynomials and on enveloping algebras of Lie algebras.

This is a joint work with K. Schmüdgen.

6.2. On deflation and multiplicity structure

Participant: Bernard Mourrain.

The paper [6] presents two new constructions related to singular solutions of polynomial systems. The first is a new deflation method for an isolated singular root. This construction uses a single linear differential form defined from the Jacobian matrix of the input, and defines the deflated system by applying this differential form to the original system. The advantages of this new deflation is that it does not introduce new variables and the increase in the number of equations is linear in each iteration instead of the quadratic increase of previous methods. The second construction gives the coefficients of the so-called inverse system or dual basis, which defines the multiplicity structure at the singular root. We present a system of equations in the original variables plus a relatively small number of new variables that completely deflates the root in one step. We show that the isolated simple solutions of this new system correspond to roots of the original system with given multiplicity structure up to a given order. Both constructions are "exact " in that they permit one to treat all conjugate roots simultaneously and can be used in certification procedures for singular roots and their multiplicity structure with respect to an exact rational polynomial system.

This is a joint work with J. Hauenstein and A. Szanto.

6.3. On the construction of general cubature formula by flat extensions

Participant: Bernard Mourrain.

We describe a new method to compute general cubature formulae [1]. The problem is initially transformed into the computation of truncated Hankel operators with flat extensions. We then analyse the algebraic properties associated to flat extensions and show how to recover the cubature points and weights from the truncated Hankel operator. We next present an algorithm to test the flat extension property and to additionally compute the decomposition. To generate cubature formulae with a minimal number of points, we propose a new relaxation hierarchy of convex optimization problems minimizing the nuclear norm of the Hankel operators. For a suitably high order of convex relaxation, the minimizer of the optimization problem corresponds to a cubature formula. Furthermore cubature formulae with a minimal number of points are associated to faces of the convex sets. We illustrate our method on some examples, and for each we obtain a new minimal cubature formula.

This is a joint work with Marta Abril-Bucero and C. Bajaj (Univ. of Austin, Texas, USA).

6.4. Geometrically continuous splines for surfaces of arbitrary topology

Participant: Bernard Mourrain.

In the paper [10], we analyze the space of geometrically continuous piecewise polynomial functions or splines for quadrangular and triangular patches with arbitrary topology and general rational transition maps. To define these spaces of G^1 spline functions, we introduce the concept of topological surface with gluing data attached to the edges shared by faces. The framework does not require manifold constructions and is general enough to allow non-orientable surfaces. We describe compatibility conditions on the transition maps so that the space of differentiable functions is ample and show that these conditions are necessary and sufficient to construct ample spline spaces. We determine the dimension of the space of G^1 spline functions which are of degree k on triangular pieces and of bi-degree (k, k) on quadrangular pieces, for k big enough. A separability property on the edges is involved to obtain the dimension formula. An explicit construction of basis functions attached respectively to vertices, edges and faces is proposed and examples of bases of G^1 splines of small degree for topological surfaces with boundary and without boundary are detailed.

This is a joint work with N. Villamizar and R. Vidunas.

6.5. Border Basis for Polynomial System Solving and Optimization

Participant: Bernard Mourrain.

We describe in [15] the software package BORDERBASIX dedicated to the computation of border bases and the solutions of polynomial equations. We present the main ingredients of the border basis algorithm and the other methods implemented in this package: numerical solutions from multiplication matrices, real radical computation, polynomial optimization. The implementation parameterized by the coefficient type and the choice function provides a versatile family of tools for polynomial computation with modular arithmetic, floating point arithmetic or rational arithmetic. It relies on linear algebra solvers for dense and sparse matrices for these various types of coefficients. A connection with SDP solvers has been integrated for the combination of relaxation approaches with border basis computation. Extensive benchmarks on typical polynomial systems are reported, which show the very good performance of the tool.

This is a joint work with M. Abril Bucero and Ph. Trébuchet.

6.6. Bit complexity of bivariate systems

Participant: Ioannis Emiris.

The paper [14] studies the bit complexity of solving systems of bivariate polynomial equations. By means of adapted resultant formulations we thus improve upon the existing general bounds.

6.7. Compact formulae in sparse elimination

Participant: Ioannis Emiris.

This invited talk [12] describes three aspects of constructing compact formulae in toric (or sparse) elimination algebraic theory. We start with the most general existing formula for computing the mixed volume of a square algebraic system, then sketch older and recent progress in matrix formulae for the sparse resultant of an overconstrained system, and conclude with recent work in a matrix formula for the multivariate disccriminant of a specific class of well-constrained systems.

6.8. Computation of the Invariants of Finite Abelian Groups

Participant: Evelyne Hubert.

In [7] we investigate the computation and applications of rational invariants of the linear action of a finite abelian group in the nonmodular case. By diagonalization, such a group action can be described by integer matrices of orders and exponents. We make use of integer linear algebra to compute a minimal generating set of invariants along with the substitution needed to rewrite any invariant in terms of this generating set. In addition, we show how to construct a minimal generating set that consists only of polynomial invariants. As an application, we provide a symmetry reduction scheme for polynomial systems whose solution set is invariant by a finite abelian group action. Finally, we also provide an algorithm to find such symmetries given a polynomial system.

This is joint work with George Labahn (University of Waterloo, Canada).

6.9. Extraction of cylinders and cones from minimal point sets

Participants: Laurent Busé, André Galligo.

In [3], we propose new algebraic methods for extracting cylinders and cones from minimal point sets, including oriented points. More precisely, we are interested in computing efficiently cylinders through a set of three points, one of them being oriented, or through a set of five simple points. We are also interested in computing efficiently cones through a set of two oriented points, through a set of four points, one of them being oriented, or through a set of six points. For these different interpolation problems, we give optimal bounds on the number of solutions. Moreover, we describe algebraic methods targeted to solve these problems efficiently.

6.10. Resultant of an equivariant polynomial system with respect to the symmetric group

Participants: Laurent Busé, Anna Karasoulou.

Given a system of n homogeneous polynomials in n variables which is equivariant with respect to the canonical actions of the symmetric group of n symbols on the variables and on the polynomials, we prove in [4] that its resultant can be decomposed into a product of several smaller resultants that are given in terms of some divided differences. As an application, we obtain a decomposition formula for the discriminant of a multivariate homogeneous symmetric polynomial.

6.11. A Line/Trimmed NURBS Surface Intersection Algorithm Using Matrix Representations

Participant: Laurent Busé.

In the work [11], we contribute a reliable line/surface intersection method for trimmed NURBS surfaces, based on a novel matrix-based implicit representation and numerical methods in linear algebra such as singular value decomposition and the computation of generalized eigenvalues and eigenvectors. A careful treatment of degenerate cases makes our approach robust to intersection points with multiple pre-images. We then apply our intersection algorithm to mesh NURBS surfaces through Delaunay refinement. We demonstrate the added value of our approach in terms of accuracy and treatment of degenerate cases, by providing comparisons with other intersection approaches as well as a variety of meshing experiments.

This is a joint work in collaboration with Pierre Alliez from TITANE Inria project-team and Jingjing SHen and Neil Dodgson both from Cambridge University.

6.12. Effective criteria for bigraded birational maps

Participant: Laurent Busé.

In [2], we consider rational maps whose source is a product of two subvarieties, each one being embedded in a projective space. Our main objective is to investigate birationality criteria for such maps. First, a general criterion is given in terms of the rank of a couple of matrices that became to be known as *Jacobian dual matrices*. Then, we focus on rational maps from $\mathbb{P}^1 \times \mathbb{P}^1$ to $\mathbb{P}^2$ in very low bidegrees and provide new matrix-based birationality criteria by analyzing the syzygies of the defining equations of the map, in particular by looking at the dimension of certain bigraded parts of the syzygy module. Finally, applications of our results to the context of geometric modeling are discussed at the end of the paper.

This is a joint work with N. Botbol (University of Buenos Aires, ARgentina), M. Chardin (UMPC, France), S. H. Hassanzadeh (University of Rio, Brazil), A. Simis (University of Pernambuco, Brazil), Q. H. Tran (UMPC, France). It has been done in the framework of the SYRAM project.

6.13. Geometric model for shape deformation

Participants: Elisa Berrini, Bernard Mourrain.

In [13], we describe a new parametric modeller for an automatic shape optimization loop. The modeller enables the generation of shapes by selecting a set of design parameters that controls a twofold parameterization: geometrical – based on a skeleton approach – and architectural – based on the experience of practitioners, to impact the system performance. The resulting forms are relevant and effective, thanks to a smoothing procedure that ensures the consistency of the shapes produced.

The skeleton consists of a set of B-Spline curves composed of a generating curve and section curves. The deformation of the shape is performed by changing explicit parameters of the representation or implicit parameters such as architectural parameters. The new shape is obtained by minimizing a distance function between the current parameters and the target parameters in combination with a smoothing term to ensure shape consistency. Finally, a 3D surface is reconstructed around the skeleton with an iterative method handling multi-patches and boundary constraints.

Thanks to this approach, architects can directly use a CAD-model based on NURBS representations in the modeller tool that allows a straightforward modification of the initial design to improve performance. The methodology developed can be applied to any shape that can be described by a skeleton, e.g. hulls, foils, bulbous bows, but also wind turbines, airships, etc.

As application, we consider the optimization of the shape of a bulbous bow. The modeller is linked to the RANSE-CFD solver FINE/Marine. The aim is to reduce the total drag of the hull with variation of its bulbous bow shape.

6.14. Shape-optimization of 2D hydrofoils using an Isogeometric BEM solver

Participant: Panagiotis Kaklis.

In [8], an optimization procedure, based on an Isogeometric BEM solver for the potential flow, is developed and used for the shape optimization of hydrofoils. The formulation of the exterior potential-flow problem reduces to a Boundary-Integral Equation (BIE) for the associated velocity potential exploiting the null-pressure jump Kutta condition at the trailing edge. The numerical solution of the BIE is performed by an Isogeometric Boundary-Element Method (BEM) combining a generic B-splines parametric modeler for generating hydrofoil shapes, using a set of eight parameters, the very same basis of the geometric representation for representing the velocity potential and collocation at the Greville abscissas of the knot vector of the hydrofoil's B-splines representation. Furthermore, the optimization environment is developed based on the geometric parametric modeler for the hydrofoil, the Isogeometric BEM solver and an optimizer employing a controlled elitist genetic algorithm. Multi-objective hydrofoil shape optimization examples are demonstrated with respect to the criteria i) maximum lift coefficient and ii) minimum deviation of the hydrofoil area from a reference area.

This is a joint work with K. Kostas (Nazarbayev University), A. Ginnis (National Technical University of Athens), C. Politis (Technological Educational Institute of Athens).

6.15. Algebraic method for constructing singular steady solitary waves: A case study

Participant: André Galligo.

The article [5] describes the use of algebraic methods in a phase plane analysis of ordinary differential equations. The method is illustrated by the study of capillary-gravity steady surface waves propagating in shallow water. We consider the (fully nonlinear, weakly dispersive) Serre-Green-Naghdi equations with surface tension, because it provides a tractable model that, in the same time, is not too simple so the interest of the method can be emphasised. In particular, we analyse a special class of solutions, the solitary waves, which play an important role in many fields of Physics. In capillary-gravity regime, there are two kinds of localised infinitely smooth travelling wave solutions – solitary waves of elevation and of depression. However, if we allow the solitary waves to have an angular point, the “zoology” of solutions becomes much richer and the main goal of this study is to provide a complete classification of such singular localised solutions using the methods of the effective Algebraic Geometry.

This is a joint work with D. Clamond (Laboratoire Jean Alexandre Dieudonné, Université de Nice Sophia-Antipolis) and Denys Dutykh (Laboratoire de Mathématiques, Université de Savoie).

7. Partnerships and Cooperations

7.1. Regional Initiatives

7.1.1. Inria SAM Action Transverse

Participants: Paul Görlach, Evelyne Hubert.

Finding biomarkers of abnormalities of the white matter is one important problem in dMRI processing. As these biomarkers need to be independent of the orientation of the head, they are functions of the rotational invariants of the shapes that characterize the diffusion probabilities in the white matter. While the situation is well understood for second order tensors, these are not powerful enough to represent crossings in the white matter. Acquisitions made with the HARDI scheme allow for a richer description of probabilities. In particular, the project-team ATHENA has modelled them as (positive) ternary quartics (symmetric tensors of order 4). But invariants of these quartics are not well known. For a long period, only six were known, when there should be at least 12. Strategies were developed in the project-team ATHENA to compute more invariants, either algebraic [25] or polynomial [21]. The former suffered some instability issues in their evaluations, the latter did not form a minimal set. The goal of this "Transverse action" was to team up with expertise in algebraic computation and leverage the methods [23], [24], [22] [19], [7] developed in the project team AROMATH to gain more insight in this problem of rotational invariants of ternary quartics.

This action is done in collaboration with Théodore Papadopoulo (ATHENA team).

7.1.2. CIMI thematic project

Participant: Evelyne Hubert.

Labex CIMI Toulouse supports the project *Joint Implicit and Parametric Representation based on Skeleton* where the PI are Géraldine Morin (IRIT, Vortex team) and Evelyne Hubert. This project aims at developing a mathematical model and software for surfaces, based on a joint parametric and implicit representation, with a skeleton.

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. Participation in Other International Programs

7.3.1.1. PICS project

Participant: Laurent Busé.

We participate to a bilateral collaboration between France and Spain which is supported as a PICS from CNRS. This project, titled *Diophantine Geometry and Computer Algebra*, aims at exploring interactions between diophantine geometry and computer algebra by stimulating collaborations between experts in both domains. The research program focuses on five particular topics : toric varieties and height, equidistribution, Diophantine geometry and complexity, factorization of multivariate polynomials by means of toric geometry and study of singularities of toric parameterizations.

The Spanish partner is the University of Barcelona, with participants J. Burgos, C. D'Andrea, Martin Sombra, and the French partners are the university of Caen, with participants F. Amoroso and M. Weimann, the University of Paris 6, with participants M. Chardin and P. Philippon and the Inria project-team AROMATH, with participant L. Busé.

7.3.1.2. SYRAM project

Participants: Laurent Busé, Bernard Mourrain, André Galligo.

Title: Geometry of SYzygies of RAtional Maps with applications to geometric modeling (SYRAM)

We coordinate a research project which is funded by the regional program Math-AmSud for two years : 2015-2016. This project is composed by research teams from Argentina, Universidad de Buenos Aires (Nicolás Botbol, Alicia Dickenstein), Brazil, Universidade Federal de Rio de Janeiro, de Pernambuco e de Sergipe (Sayed Hamid Hassanzadeh, Aron Simis) and France, Institut de Mathématiques de Jussieu (Marc Chardin) and the Inria project-team AROMATH.

The study of rational maps is of theoretical interest in algebraic geometry and commutative algebra, and of practical importance in geometric modeling. This research proposal focuses on rational maps in low dimension, typically parameterizations of curves and surfaces embedded in the projective space of dimension three, but also dominant rational maps in dimension two and three. The two main objectives amount to unravel geometric properties of these rational maps from the syzygies of their projective coordinates. The first one aims at extending and generalizing the determination of the closed image of a rational map, as well as its geometric features, whereas the second one will focus on the study of dominant rational maps, in particular on the characterization of those that are generically one-to-one.

7.4. International Research Visitors

7.4.1. Visits of International Scientists

Cordian Riener (University of Konstanz, Germany) visited from September 4-9th, 2016 to collaborate on symmetry, orthogonal polynomials and cubature with Evelyne Hubert and Bernard Mourrain.

Lan Nguyen (University of Vietnam at Hanoï) visited to collaborate on implicitization of rational maps with Laurent Busé. His visits received the financial support of LIAFV (International Laboratory for France-Vietnam collaborations in mathematics).

Aron Simis (University of Pernambuco, Brazil) visited to collaborate on syzygies of rational maps with Laurent Busé.

Nicolas Botbol (Universidad de Buenos Aires, Argentina) visited to collaborate on distance function to rational curves and surfaces with Laurent Busé.

7.4.1.1. Internships

Paul Görlach (University of Bonn) came to work on the *CRISAM - Transverse action* between the project teams AROMATH and ATHENA (August-December).

Akshit Goyal and Deepak Bhatt (IIT Dehli) worked during their internship on “Meshing Singular Isosurfaces” and “Isosurface of the distance function” (May-July).

Antoine Deharveng, student at the engineer school of the University of Nice Sophia Antipolis, came since June 15 to work on the extraction of geometric primitives in a 3D point cloud under the supervision of Laurent Busé.

7.4.2. Visits to International Teams

7.4.2.1. Sabbatical programme

Evelyne Hubert was in Ontario from September 1st 2015 to February 29th 2016, with the sabbatical programme of Inria DPEI. For the period of January and February 2016 she was hosted and supported by University of Waterloo, visiting the Symbolic Computation Lab, and more particularly Pr. George Labahn.

Bernard Mourrain was invited at Univ. of Texas, Austin, for a collaboration with Pr. Chandajit Bajaj (7th-19th May).

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. Member of the Organizing Committees

Laurent Busé was the main organizor of the BIRS-CMO conference "*Computational Algebra and Geometric Modeling*" that took place at Oaxaca, Mexico, August 7-12 2016. He also co-organized with A. Dimca (Univ. Nice) a mini-workshop "*commutative algebra and applications*" that took place at the laboratory of mathematics of the university of Nice, September 22-23. He also co-organized a *week of studies maths-industry* (SEME) that took place at the CRI-SAM January 25-29.

Evelyne Hubert was part of the organizing committee of the collaborative research workshop *Women in Shape: Modeling Boundaries of Objects in 2- and 3-Dimensions* that took place June 6-12 at the Nesin Mathematics Village in Turkey.

8.1.2. Scientific Events Selection

8.1.2.1. Reviewer

Laurent Busé, Evelyne Hubert and Bernard Mourrain reviewed submissions for the conference ISSAC'16.

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 in Computer Science (since 2016).

Evelyne Hubert is associate editor of the Journal of Symbolic Computation (since 2007) and became a reviewer for Mathematical Reviews (MathSciNet) this year.

8.1.3.2. Reviewer - Reviewing Activities

Laurent Busé wrote reviews for the following international journals: Journal of Symbolic Computation, Journal of Algebra, Computer Aided Geometric Design, Mathematical and Computational Applications, Graphical Models, Linear Algebra and its Applications, SIAM Journal on Applied Algebra and Geometry, Transactions on Graphics, the Quarterly Journal of Mathematics and Math. Zeitschrift. He also wrote reviews for the ISSAC 2016 and the Eurographics 2017 international conferences.

Evelyne Hubert reviewed for the journal *Mathematics of Computation*, the *Journal of Symbolic Computation*, the *Journal of Pure & Applied Algebra*, the journal *Mathematics in Computer Science*, and Springer book series *Texts and Monographs in Symbolic Computation*,

Bernard Mourrain reviewed for the journal *Advances in Computational Mathematics*, the *Journal of Algebra and Applications*, the journal *Collectanea Mathematica*, the journal *Computer Aided Design*, the journal *Computer Aided Geometric Design*, the journal *Foundations of Computational Mathematics*, the *Journal of Pure and Applied Algebra*, the journal *SIAM Journal on Optimization*, the *Transactions on Mathematical Softwares*.

8.1.4. Invited Talks

Laurent Busé was invited to give a talk at the Inria project-team ARIC seminar, May 26, at the conference "Computational Algebra, Algebraic Geometry and Applications", in honor of Alicia Dickenstein, that took place at Buenos Aires, Argentina, August 1-3 2016, at the *H2020 day* organized at the CRI-SAM to give a testimony on the writing of the successful MCA-ITN proposal ARCADES.

Ioannis Emiris gave an invited talk at ACM International Symposium on Symbolic & Algebraic Computation, Waterloo, Canada, July 2016.

Evelyne Hubert was invited to give a talk at the *Computational Mathematics Colloquium* at University of Waterloo, Canada (January 2016); at the workshop on *Théorie Effective des Invariants*, at the Insitut de Mathématiques de Marseille (June 2016); at the workshop on *Symmetry, Invariants, Reduction* in RWTH Aachen University (September 2016); at the BIRS-CMO conference *Sparse Interpolation, Rational Approximation and Exponential Analysis* in Oaxaca, Mexico (November 2016). She was also invited (and supported) to partitipate to the American Institute of Mathematics workshop *Algebraic Vision* in San Jose, California (May 2016); and the BIRS-CMO conference *Computational Algebra and Geometric Modeling* in Oaxaca, Mexico (August 2016); and to the CIRM conference *Multivariate Approximation and Interpolation with Applications* where she presented a poster (September 2016).

Bernard Mourrain was invited to give a talk at the MFO workshop *Mathematical Foundations of Isogeometric Analysis* Oberwolfach, Germany (February 2016), at the conference "Computational Algebra, Algebraic Geometry and Applications", in honor of Alicia Dickenstein, that took place at Buenos Aires, Argentina, August 1-3 2016, at the BIRS-CMO conference *Computational Algebra and Geometric Modeling* in Oaxaca, Mexico (August 2016), at the CIRM conference *Multivariate Approximation and Interpolation with Applications* Marseille, France (September 2016), at the BIRS-CMO conference *Sparse Interpolation, Rational Approximation and Exponential Analysis* in Oaxaca, Mexico (November 2016).

8.1.5. Leadership within the Scientific Community

Evelyne Hubert, in collaboration with Géraldine Morin, lead a collaborative research group at the workshop *Women in Shape: Modeling Boundaries of Objects in 2- and 3-Dimensions*.

8.1.6. Scientific Expertise

Bernard Mourrain was member of the committee of the HCERES for the evaluation of IRMAR, University of Rennes.

Evelyne Hubert was a member of the admissibility jury for the *Chargé de Recherche* position in CRI-Rennes Bretagne Atlantique.

Laurent Busé was a member of the CRI-SAM committee "Actions Marquantes", March 25. He is also 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.

8.1.7. Research Administration

Evelyne Hubert is an elected member of the Inria national *Commission d'Evaluation*.

Laurent Busé is an elected member of the CPRH (Commission Permanente de Ressources Humaines) of the math laboratory of the university of Nice. He was also appointed Inria representative at the "Academic Council" and the "Research Commission" of the university of Nice.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Licence : Ioannis Emiris, Discrete Math, 53, L1, NKU Athens, Greece.

Licence : Ioannis Emiris, Soft development for algorithmic problems, 53, L3, NKU Athens, Greece

Master : Laurent Busé, Curves and Surfaces, 66h ETD, M1, EPU of the university of Nice-Sophia Antipolis.

Master : Laurent Busé, Geometric Modeling, 27h ETD, M2, EPU of the university of Nice-Sophia Antipolis.

8.2.2. Supervision

PhD in progress: Elisa Berrini, Parametric modeling for ship hull deformation and optimization. CIFRE with MyCFD, started in January 2014, supervised by Bernard Mourrain.

PhD in progress: Ahmed Blidia, New geometric models for the design and computation of complex shapes. ARCADES Marie Skłodowska-Curie ITN, started in September 2016, supervised by Bernard Mourrain.

PhD in progress: Jouhayna Harmouch, Low rank structured matrix decomposition and completion. Cotutelle Univ. Liban, started in November 2015, cosupervised by Houssam Khalil and Bernard Mourrain.

PhD in progress: Anna Karasoulou, Exploiting structure in polynomial systems. Excellence awards (Greece), started in November 2011, supervised by Ioannis Emiris.

PhD in progress: Ioannis Psarros, Geometric approximation algorithms. Thales network (Greece), started in May 2015, supervised by Ioannis Emiris.

PhD in progress: Evangelos Bartzos, Modeling motion. ARCADES Marie Skłodowska-Curie ITN, started in May 2016, supervised by Ioannis Emiris.

PhD in progress: Evangelos Anagnostopoulos, Geometric algorithms for massive datasets. Started in May 2016, supervised by Ioannis Emiris.

PhD in progress: Clement Laroche, Change of representation in CAGD. ARCADES Marie Skłodowska-Curie ITN, started in Nov. 2016, supervised by Ioannis Emiris.

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

Master in Computer Science: Paul Görlach, University of Bonn. Rotational invariants of ternary quartics. CRI-SAM tranverse action AROMATH-ATHENA. August-December 2016, 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

Evelyne Hubert was a referee for the PhD of Louis Dumont entitled *Algorithmes rapides pour le calcul symbolique de certaines intégrales de contour à paramètre*, Université Paris-Saclay, École Polytechnique, Inria Saclay Île-de-France.

Bernard Mourrain was a referee for the PhD of Emil Horobet, entitled *Tensors of low rank*, Univ. of Technology, Eindhoven, Netherland.

Laurent Busé was a referee for the PhD of Thibaut Verron entitled *Régularisation du calcul de bases de Gröbner pour des systèmes avec poids et déterminantiels, et application en imagerie médicale*, Université Pierre et Marie Curie, Paris, France, September 26.

9. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journal

[1] M. ABRIL BUCERO, C. BAJAJ, B. MOURRAIN.*On the construction of general cubature formula by flat extensions*, in "Linear Algebra and its Applications", August 2016, vol. 502, p. 104-125 [*DOI :* 10.1016/J.LAA.2015.09.052], https://hal.inria.fr/hal-01158099.

[2] N. BOTBOL, L. BUSÉ, M. CHARDIN, S. H. HASSANZADEH, A. SIMIS, Q. H. TRAN.*Effective criteria for bigraded birational maps*, in "Journal of Symbolic Computation", 2016 [*DOI :* 10.1016/J.JSC.2016.12.001], https://hal.inria.fr/hal-01278405.

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Project-Team ASCLEPIOS

Analysis and Simulation of Biomedical Images

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Computational Neuroscience and Medecine

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Project-Team ASCLEPIOS

Creation of the Project-Team: 2005 November 01

Keywords:

Computer Science and Digital Science:

3.3. - Data and knowledge analysis
3.4. - Machine learning and statistics
5.2. - Data visualization
5.3. - Image processing and analysis
5.4. - Computer vision
5.6. - Virtual reality, augmented reality
5.9. - Signal processing
6.1. - Mathematical Modeling
6.2. - Scientific Computing, Numerical Analysis & Optimization
6.3. - Computation-data interaction
7.5. - Geometry, Topology
8.2. - Machine learning
8.3. - Signal analysis
8.6. - Decision support
8.7. - AI algorithmics

Other Research Topics and Application Domains:

2.2. - Physiology and diseases
2.3. - Epidemiology
2.4. - Therapies
2.6. - Biological and medical imaging
2.6.1. - Brain imaging
2.6.2. - Cardiac imaging
2.6.3. - Biological Imaging

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Alan Garny [University of Auckland]
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Administrative Assistant

Isabelle Strobant [Inria, AI]

2. Overall Objectives

2.1. Overall Objectives

There is an irreversible evolution of medical practice toward more quantitative and personalized decision processes for prevention, diagnosis and therapy.

This evolution is supported by a constantly increasing number of biomedical devices providing *in vivo* measurements of structures and processes inside the human body, at scales varying from the organ to the cellular and even molecular level. Among all these measurements, biomedical images of various forms play an even more central role everyday, along with the exploitation of the genetic information attached to each patient.

Facing the need for a more quantitative and personalized medicine based on larger and more complex sets of measurements, there is a crucial need for developing:

1. advanced image analysis tools capable of extracting the pertinent information from biomedical images and signals;
2. advanced models of the human body to correctly interpret this information; and
3. large distributed databases to calibrate and validate the models.

3. Research Program

3.1. Introduction

Tremendous progress has been made in the automated analysis of biomedical images during the past two decades [72]. Readers who are neophytes to the field of medical imaging will find an interesting presentation of acquisition techniques of the main medical imaging modalities in [64], [62]. Regarding target applications, a good review of the state of the art can be found in the book *Computer Integrated Surgery* [60], in N. Ayache's article [67] and in recent review articles [68], [72]. The scientific journals *Medical Image Analysis* [55], *Transactions on Medical Imaging* [61], and *Computer Assisted Surgery* [63] are also good reference material. One can have a good vision of the state of the art from the proceedings of the MICCAI'2010 (Medical Image Computing and Computer Assisted Intervention [58], [59]) and ISBI'2010 (Int. Symp. on Biomedical Imaging [57]) conferences.

For instance, for rigid parts of the body like the head, it is now possible to fuse in a completely automated manner images of the same patient taken from different imaging modalities (e.g. anatomical and functional), or to track the evolution of a pathology through the automated registration and comparison of a series of images taken at distant time instants [73], [83]. It is also possible to obtain from a Magnetic Resonance Image (MRI) of the head a reasonable segmentation of skull tissues, white matter, grey matter, and cerebro-spinal fluid [86], or to measure some functional properties of the heart from dynamic sequences of Magnetic Resonance [66], Ultrasound or Nuclear Medicine images [74].

Despite these advances and successes, statistical models of anatomy are still very crude, resulting in poor registration results in deformable regions of the body, or between different subjects. If some algorithms exploit the physical modeling of the image acquisition process, only a few actually model the physical or even the physiological properties of the human body itself. Coupling biomedical image analysis with anatomical and physiological models of the human body could not only provide a better understanding of observed images and signals, but also more efficient tools for detecting anomalies, predicting evolutions, simulating and assessing therapies.

3.2. Medical Image Analysis

The quality of biomedical images tends to improve constantly (better spatial and temporal resolution, better signal to noise ratio). Not only are the images multidimensional (3 spatial coordinates and possibly one temporal dimension), but medical protocols tend to include multisequence (or multiparametric) [0] and multimodal images [0] for each single patient.

[0]Multisequence (or multiparametric) imaging consists in acquiring several images of a given patient with the same imaging modality (e.g. MRI, CT, US, SPECT, etc.) but with varying acquisition parameters. For instance, using MRI, patients followed for multiple sclerosis may undergo every six months a 3D multisequence MR acquisition protocol with different pulse sequences (called T1, T2, PD, Flair, etc.): by varying some parameters of the pulse sequences (e.g Echo Time and Repetition Time), images of the same regions are produced with quite different contrasts depending on the nature and function of the observed structures. In addition, one of the acquisitions (T1) can be combined with the injection of a contrast product (typically Gadolinium) to reveal vessels and some pathologies. Diffusion Tensor Images (DTI) can be acquired to measure the self diffusion of protons in every voxel, allowing the measurement for instance of the direction of white matter fibers in the brain (the same principle can be used to measure the direction of muscular fibers in the heart). Functional MRI of the brain can be acquired by exploiting the so-called Bold Effect (Blood Oxygen Level Dependency): slightly higher blood flow in active regions creates a subtle higher T2* signal which can be detected with sophisticated image processing techniques.

[0]Multimodal acquisition consists in acquiring from the same patient images of different modalities, in order to exploit their complementary nature. For instance, CT and MR may provide information on the anatomy (CT providing contrast between bones and soft tissues while MR within soft tissues of different nature) while SPECT and PET images may provide functional information by measuring a local level of metabolic activity.

Despite remarkable efforts and advances during the past twenty years, the central problems of segmentation and registration have not been solved in the general case. It is our objective in the short term to work on specific versions of these problems, taking into account as much *a priori* information as possible on the underlying anatomy and pathology at hand. It is also our objective to include more knowledge of the physics of image acquisition and observed tissues, as well as of the biological processes involved. Therefore the research activities mentioned in this section will incorporate the advances made in Computational Anatomy and Computational Physiology, as described in sections 3.3 and 3.4.

We plan to pursue our efforts on the following problems:

- multi-dimensional, multi-sequence and multi-modal image segmentation; and
- image Registration/Fusion.

3.3. Computational Anatomy

The aim of Computational Anatomy (CA) is to model and analyse the biological variability of the human anatomy. Typical applications cover the simulation of average anatomies and normal variations, the discovery of structural differences between healthy and diseased populations, and the detection and classification of pathologies from structural anomalies. [0]

Studying the variability of biological shapes is an old problem (cf. the book "On Shape and Growth" by D'Arcy Thompson [85]). Significant efforts have since been made to develop a theory for statistical shape analysis (one can refer to [71] for a good summary, and to the special issue of Neuroimage [84] for recent developments). Despite all these efforts, there are a number of challenging mathematical issues that remain largely unsolved. A particular issue is the computation of statistics on manifolds that can be of infinite dimension (e.g the group of diffeomorphisms).

There is a classical stratification of the problems into the following 3 levels [80]:

1. construction from medical images of anatomical manifolds of points, curves, surfaces and volumes;
2. assignment of a point to point correspondence between these manifolds using a specified class of transformations (e.g. rigid, affine, diffeomorphism);
3. generation of probability laws of anatomical variation from these correspondences.

We plan to focus our efforts on the following problems:

1. statistics on anatomical manifolds;
2. propagation of variability from anatomical manifolds;
3. linking anatomical variability to image analysis algorithms; and
4. grid-computing strategies to exploit large databases.

3.4. Computational Physiology

The objective of Computational Physiology (CP) is to provide models of the major functions of the human body and numerical methods to simulate them. The main applications are in medicine where CP can for instance be used to better understand the basic processes leading to the appearance of a pathology, to model its probable evolution and to plan, simulate, and monitor its therapy.

[0] The NIH has launched in 2005 the Alzheimer's Disease Neuroimaging Initiative (60 million USD), a multi-center MRI study of 800 patients who will be followed during several years. The aim is to establish new surrogate end-points from the automated analysis of temporal sequences, which is a challenging goal for researchers in Computational Anatomy. The data is to made available to qualified research groups involved or not in the study.

Quite advanced models have already been proposed to study at the molecular, cellular and organ level a number of physiological systems (see for instance [81], [78], [69], [82], [75]). While these models and new ones need to be developed, refined or validated, a grand challenge that we want to address in this project is the automatic adaptation of the model to a given patient by comparing the model with the available biomedical images and signals and possibly also some additional information (e.g. genetic). Building such *patient-specific models* is an ambitious goal, which requires the choice or construction of models with a complexity adapted to the resolution of the accessible measurements and the development of new data assimilation methods coping with massive numbers of measurements and unknowns.

There is a hierarchy of modeling levels for CP models of the human body [70]:

- the first level is mainly geometrical, and addresses the construction of a digital description of the anatomy [65], essentially acquired from medical imagery;
- the second level is physical, involving mainly the biomechanical modeling of various tissues, organs, vessels, muscles and bone structures [76];
- the third level is physiological, involving the modeling of the functions of the major organ systems [77] (e.g. cardiovascular, respiratory, digestive, central or peripheral nervous, muscular, reproductive, hormonal) or some pathological metabolism (e.g. evolution of cancerous or inflammatory lesions, formation of vessel stenoses, etc.); and
- a fourth level is cognitive, modeling the higher functions of the human brain [56].

These different levels of modeling are closely related to each other, and several physiological systems may interact with each other (e.g. the cardiopulmonary interaction [79]). The choice of the resolution at which each level is described is important, and may vary from microscopic to macroscopic, ideally through multiscale descriptions.

Building this complete hierarchy of models is necessary to evolve from a *Visible Human project* (essentially the first level of modeling) to a much more ambitious *Physiological Human project* (see [77], [78]). We will not address all the issues raised by this ambitious project, but instead focus on the topics detailed below. Among them, our objective is to identify some common methods for the resolution of the large inverse problem raised by the coupling of physiological models and medical images for the construction of patient-specific models (e.g. specific variational or sequential methods (EKF), dedicated particle filters). We also plan to develop specific expertise in the extraction of geometrical meshes from medical images for their further use in simulation procedures. Finally, computational models can be used for specific image analysis problems studied in section 3.2 (e.g. segmentation, registration, tracking). Application domains include

1. surgery simulation;
2. cardiac Imaging;
3. brain tumors, neo-angiogenesis, wound healing processes, ovocyte regulation, etc.

3.5. Clinical Validation

If the objective of many of the research activities of the project is the discovery of original methods and algorithms with a proof of its feasibility in a limited number of representative cases (i.e. proofs of concept) and publications in high quality scientific journals, we believe that it is important that a reasonable number of studies include a much more significant validation effort. As the BioMedical Image Analysis discipline becomes more mature, validation is necessary for the transformation of new ideas into clinical tools and/or industrial products. It also helps to get access to larger databases of images and signals, which in turn help to stimulate new ideas and concepts.

4. Highlights of the Year

4.1. Highlights of the Year

Marco Lorenzi has been recruited as Chargé de Recherche in the Asclepios team from December 2016.

4.1.1. Awards

- Nina Miolane received the l'Oréal-UNESCO Fellowship for Women In Science. She counts among the 30 awardees who have been selected by an independent jury to stress the excellence and originality of their scientific research and their dedication to share their knowledge in the broader society.
- Shuman Jia received the Best Challenge Paper Award during the 7th international workshop on Statistical Atlases and Computational Modeling of the Heart (STACOM), held in Conjunction with MICCAI 2016 in Athens, Greece.

BEST PAPERS AWARDS :

[39] **7th International Statistical Atlases and Computational Modeling of the Heart (STACOM) Workshop, Held in Conjunction with MICCAI 2016**. S. JIA, L. CADOUR, H. COCHET, M. SERMESANT.

5. New Software and Platforms

5.1. LSVF

KEYWORDS: Health - Brain - Medical Image Processing - Medical Imaging

FUNCTIONAL DESCRIPTION:

The Longitudinal Stationary Velocity Fields Framework is a set of tools based on the SVF parameterization of diffeomorphic deformations that allows a new type of longitudinal deformation-based morphometric analyses. The framework comprises tools to compute the deformation encoded by the exponential of an SVF, the log-demons registration software and the Pole ladder, an algorithm to parallel transport deformation trajectories. These tools can be organized in a Longitudinal Log-Demons Pipeline (LLDP), to estimate the longitudinal brain deformations from image data series, transport them in a common space and perform statistical groupwise analyses.

Sources are available under custom licence.

- Participants: Mehdi Hadj-Hamou, Marco Lorenzi and Xavier Pennec
- Contact: Xavier Pennec
- URL: http://team.inria.fr/asclepios/software/stationary-velocity-field-tools/
- URL: http://team.inria.fr/asclepios/software/lcclogdemons/

5.2. medInria

KEYWORDS: Segmentation - Health - DWI - Visualization - Medical Imaging

SCIENTIFIC DESCRIPTION

It 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 and renewed in 2012. 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: Jaime Garcia Guevara, Theodore Papadopoulo, Olivier Commowick, Rene-Paul Debroize, Guillaume Pasquier, Laurence Catanese, Olivier Commowick, Alexandre Abadie, Benoit Bleuze, Clement Philipot, Fatih Arslan, Florian Vichot, John Stark, Julien Wintz, Loïc Cadour, Maxime Sermesant, Michael Knopke, Nicolas Toussaint, Olivier Clatz, Pierre Fillard, Sergio Medina, Stephan Schmitt and Hakim Fadil
- Partners: HARVARD Medical School - IHU LIRYC - King's College London - UPF Barcelona - NIH
- Contact: Olivier Commowick
- URL: http://med.inria.fr

5.3. MUSIC

Multi-modality Platform for Specific Imaging in Cardiology

KEYWORDS: Health - Cardiac - Computer-assisted interventions - Cardiac Electrophysiology - Medical imaging

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: Loïc Cadour, Maxime Sermesant, Florian Vichot, Hakim Fadil, Florent Collot and Mathilde Merle
- Contact: Maxime Sermesant
- URL: https://team.inria.fr/asclepios/software/music/

5.4. SOFA

Simulation Open Framework Architecture

KEYWORDS: Physical simulation - Health - Biomechanics - GPU - Computer-assisted surgery

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.

A software consortium around SOFA is currently being set up to strengthen the perenial developement of the plateform https://www.sofa-framework.org/consortium/. The software is available under the LGPL licence.

- Participants: Chloé Audigier, Sophie Giffard-Roisin, Qiao Zheng, Roch-Philippe Molléro and Hervé Delingette
- Contact: Hervé Delingette
- URL: http://www.sofa-framework.org

5.5. VP2HF

Virtual Physiological Human for Heart Failure Platform

KEYWORDS: Health - Cardiac - Medical - Image - Processing - Medical imaging

FUNCTIONAL DESCRIPTION

The VP2HF software is developed by the Asclepios team and brings together all the research produced by the VP2HF's partners. It contains MedInria plugins implemented by teams such as UPF Barcelona, KCL, and specific tools provided by Philips (algorithms of segmentation, scar segmentation, ...). It aims at integrating in a single clinical workflow, tools to improve the therapy selection and treatment optimisation for patients suffering from heart failure.

- Participants: Maxime Sermesant, Hakim Fadil and Loïc Cadour
- Contact: Maxime Sermesant
- URL: http://www.vp2hf.eu

6. New Results

6.1. Medical Image Analysis

6.1.1. Segmentation and Anatomical Variability of the Cochlea from Medical Images

Participants: Thomas Demarcy [Correspondant], Hervé Delingette, Clair Vandersteen [IUFC, Nice], Dan Gnansia [Oticon Medical], Nicholas Ayache.

This work is supported by the National Association for Research in Technology (ANRT) through the CIFRE Grant 2013-1165 and Oticon Medical (Vallauris). Part of this work is also funded by the European Research Council through the ERC Advanced Grant MedYMA 2011-291080 (on Biophysical Modeling and Analysis of Dynamic Medical Images). This work is a collaboration with the Department of Ear Nose Throat Surgery (IUFC, Nice) and the Nice University Hospital (CHU).

Image segmentation, Surgery planning, Shape modeling, Anatomical variability, Cochlear implant, Temporal bone.

- We evaluated the optimal electrode diameter in relation to the cochlear shape [20].
- We proposed a novel framework for estimating the insertion depth and its uncertainty from segmented CT images based on a new parametric shape model [37].
- We provided a proof of concept for the estimation of postoperative cochlear implant electrode-array position from clinical CT [44] (Fig. 1).

6.1.2. Infarct Localization and Uncertainty Quantification from Myocardial Deformation

Participants: Nicolas Duchateau [Correspondant], Maxime Sermesant.

This work received the partial support from the European Union 7th Framework Programme (VP2HF FP7-2013-611823) and the European Research Council (MedYMA ERC-AdG-2011-291080).

Myocardial infarct, Computer-aided diagnosis, Dimensionality reduction, Biomechanical modeling.

- We build upon preliminary work for the automatic localization of myocardial infarct from local wall deformation, which has potential for risk stratification from routine examination such as 3D echocardiography. Non-linear dimensionality reduction serves to estimate the Euclidean space of coordinates encoding deformation patterns (training phase), and is combined with multi-scale kernel regressions to link the deformation patterns, the low-dimensional coordinates and the infarct location for new cases (testing phase).
- We extend this approach by considering the different components of myocardial strain considered in clinical practice, and by taking advantage of the space of low-dimensional coordinates to model uncertainty in the infarct localization [18].
- These concepts were tested on 500 synthetic cases with infarcts of random extent, shape, and location, generated from a realistic electromechanical model, and 108 pairs of 3D echocardiographic sequences and delayed-enhancement magnetic resonance images from real cases. Infarct prediction is made at a spatial resolution more than 10 times smaller than the current diagnosis, made regionally. Our method is accurate, and significantly outperforms the clinically-used thresholding of the deformation patterns. Uncertainty adds value to refine the diagnosis and eventually re-examine suspicious cases.

6.1.3. Longitudinal Analysis and Modeling of Brain Development

Participants: Mehdi Hadj-Hamou [Correspondant], Xavier Pennec, Nicholas Ayache, Hervé Lemaitre [Inserm U1000], Jean-Luc Martinot [Inserm U1000].

This work is partly funded through the ERC Advanced Grant MedYMA 2011-291080 (on Biophysical Modeling and Analysis of Dynamic Medical Images).

Figure 1. Cochlear implant electrode-array position (white) with respect to scala tympani (blue) and scala vestibuli (orange).

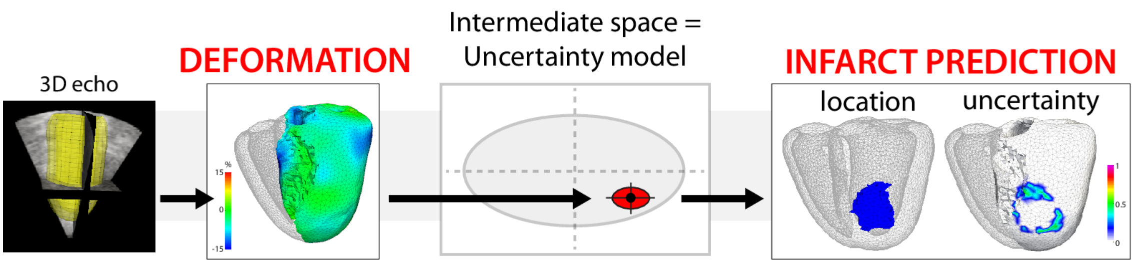

Figure 2. Overview of the proposed localization of myocardial infarct and uncertainty quantification from local wall deformation, extracted from 3D echocardiographic sequences.

Processing pipeline, Brain development, Adolescence, Longitudinal analysis, Non-rigid registration algorithm, Extrapolation.

1. We propose and detail a deformation-based morphometry computational framework, called Longitudinal Log-Demons Framework (LLDF), to estimate the longitudinal brain deformations from image data series, transport them in a common space and perform statistical group-wise analyses. It is based on freely available software and tools, and consists of three main steps (cf. Fig. 3):
   - Pre-processing;
   - Position correction; and
   - Non-linear deformation analysis.

   It is based on the LCC log-Demons non-linear symmetric diffeomorphic registration algorithm with an additional modulation of the similarity term using a confidence mask to increase the robustness with respect to brain boundary intensity artifacts.
2. This work led to a published journal publication [23].
3. The LLDF pipeline is exemplified on the longitudinal Open Access Series of Imaging Studies (OASIS) database and is applied to the study of longitudinal trajectories during adolescence, for which little is known. The aim of this project is to provide models of brain development during adolescence based on diffeomorphic registration parametrised by SVFs. We particularly focused our study on the link between sexual dimorphism and the longitudinal evolution of the brain. This work was done in collaboration with J.L. Martinot et H. Lemaître (Inserm U1000).

6.1.4. Left Atrial Wall Segmentation and Thickness Measurement using Region Growing and Marker-Controlled Geodesic Active Contour

Participants: Shuman Jia [Correspondant], Loïc Cadour, Hubert Cochet [IHU Liryc, Bordeaux], Maxime Sermesant.

The authors acknowledge the partial funding by the Agence Nationale de la Recherche (ANR)/ERA CoSysMed SysAFib and ANR MIGAT projects.

Atrial fibrillation, Left atrial wall thickness, Image segmentation, Cardiac computed tomography (CT), Region growing, Geodesic active contour.

We proposed a method to segment the left atrial (LA) wall and measure the wall thickness from cardiac computed tomography images, making use of patient-specific intensity value information and surrounding environment (see Fig. 4).

We partially implemented the method in the MUSIC software and tested our pipeline on 10 datasets. The results achieved a good match of wall thickness with manual segmentation. We received a Best Paper Award for this work [39] at the 2016 STACOM Workshop in Athens, Greece.

6.1.5. Weakly Supervised Learning for Tumor Segmentation

Participants: Pawel Mlynarski [Correspondant], Nicholas Ayache, Hervé Delingette, Antonio Criminisi [MSR].

This work is funded by the Inria-Microsoft joint center and is done in cooperation with Microsoft Research in Cambridge.

Deep Learning, Segmentation, Classification, Tumor.

- The goal of this work is to develop new machine learning methods for the localization and segmentation of tumors, without relying on the ground truth provided by experts. In particular, we study Deep Learning methods for classification and weakly supervised localization (Figure 5).
- We proposed two methods of synthesis of brain 3D MR images, in order to use them during the training of Neural Nets. The proposed methods showed to improve our performance in localization of brain tumors.

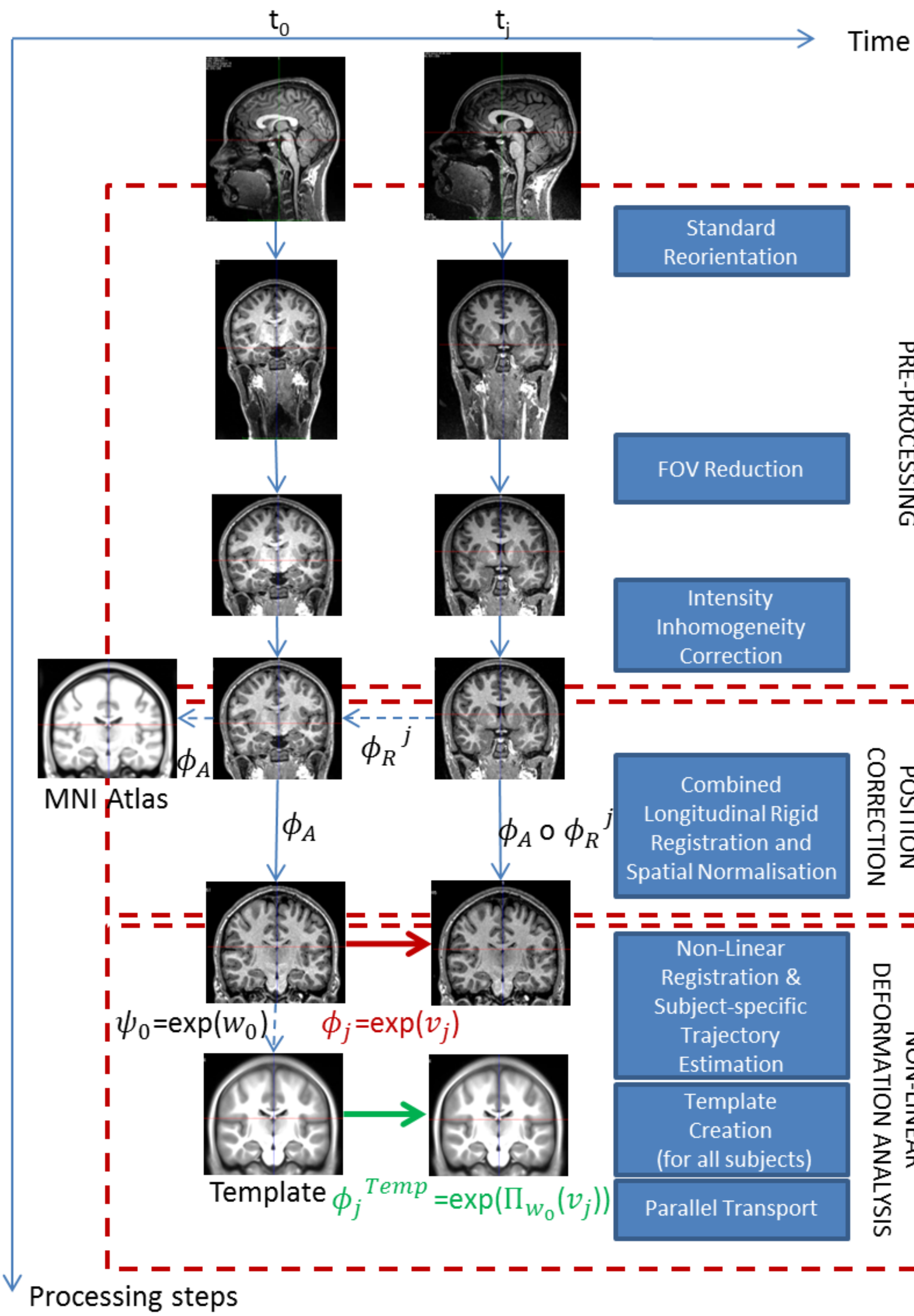

Figure 3. Processing pipeline for longitudinal analysis.

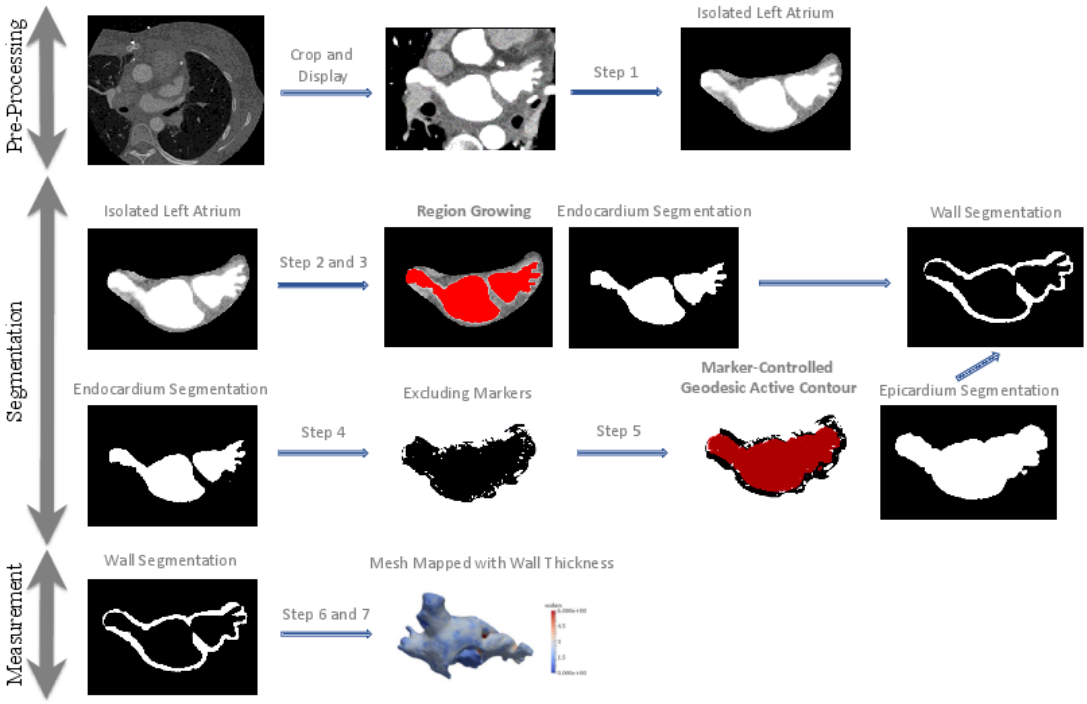

Figure 4. Flowchart of the method.

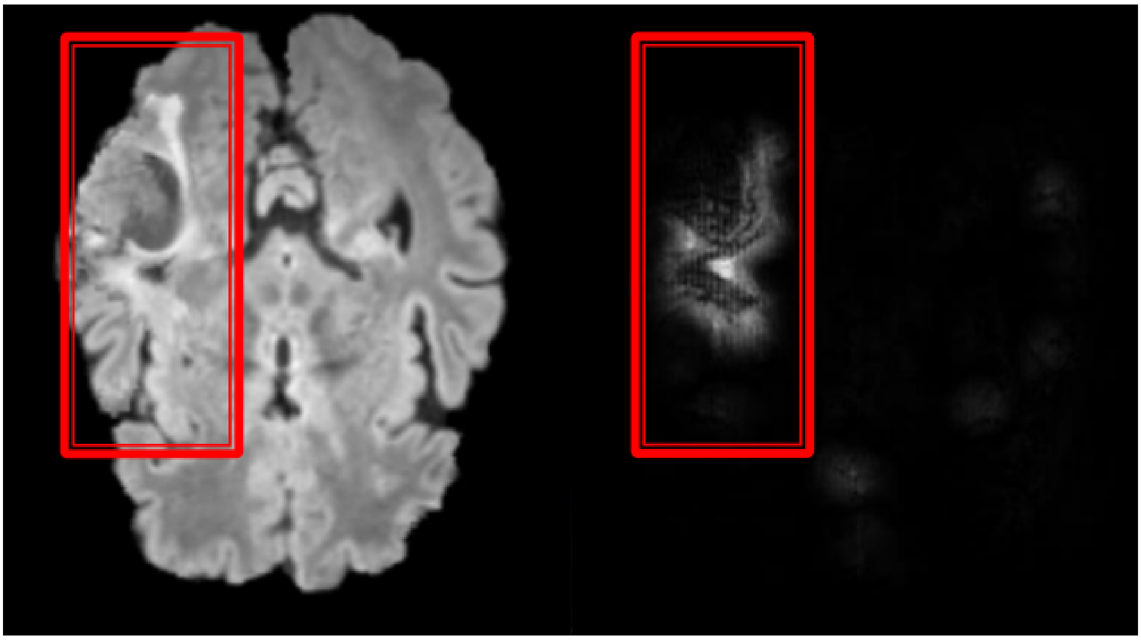

Figure 5. Left: axial slice of a brain MR image containing a tumor. Right: test of a weakly supervised (no ground truth provided during the training) Deep Learning method for an approximate localization of the tumor.

6.1.6. Inter-Operative Relocalization in Flexible Endoscopy

Participants: Anant Vemuri [Correspondant], Stéphane Nicolau, Luc Soler, Nicholas Ayache.

This work has been performed in collaboration with IHU Strasbourg and IRCAD, France.

Computer-assisted intervention, Barrett's esophagus, Biopsy relocalization, Electromagnetic tracking.

Oesophageal adenocarcinoma arises from Barrett's oesophagus, which is the most serious complication of gastro-oesophageal reflux disease. Strategies for screening involve periodic surveillance and tissue biopsies. A major challenge in such regular examinations is to record and track the disease evolution and relocalization of biopsied sites to provide targeted treatments.

In support of this work, the thesis [6] was defended before a committee of medical experts and scientific reviewers, on April 26th 2016.

References:

- Vemuri, Nicolau, Sportes, Marescaux, Soler, Ayache. Inter-Operative Biopsy Site Relocalization in Endoluminal Surgery [35].
- Nicolau, Vemuri, Soler, Marescaux. Anatomical site relocalisation using dual data synchronisation (patent) [49].

6.1.7. Learning Brain Alterations in Multiple Sclerosis from Multimodal Neuroimaging Data

Participants: Wen Wei, Nicholas Ayache, Stanley Durrleman [ARAMIS], Olivier Colliot [ARAMIS].

Multiple sclerosis, Neuroimageing.

The goal of this topic is to develop a machine learning approach that can predict different types of PET-derived brain alterations using multiple local and regional MRI measures.

6.1.8. Deep Learning for Cardiac Image Analysis

Participants: Qiao Zheng [Correspondant], Hervé Delingette, Nicholas Ayache.

Deep learning, Artificial neural network, Cardiac image.

Deep learning has proven to be very successful in computer vision and image understanding. However, its potential for medical image analysis has yet to be explored. We apply deep learning on cardiac images in order to learn cardiac image processing and anomaly detection. Our work includes data collection and preprocessing, software engineering, learning process design, etc.

6.2. Computational Anatomy

6.2.1. Inconsistency of the Estimation of the Template in Quotient Spaces

Participants: Loïc Devilliers [Correspondant], Stéphanie Allassonnière [Ecole Polytechnique], Alain Trouvé [ENS Cachan], Xavier Pennec.

Atlas computation, Template estimation, Fréchet mean, Quotient spaces, Inconsistency.

One issue in computational anatomy is to compute a template (a prototype of our data) in presence of two effects: an unknown deformation on data and the noise due to error in measurement in the ambient space considered here as an infinite dimensional linear space. The template computation can be done by minimizing an energy function (or variance) in the quotient space. In [50], we show that this method can lead to inconsistency that we quantify (see Fig. 6). This paves the way to a better understanding of the geometric and statistic foundation of the template estimation.

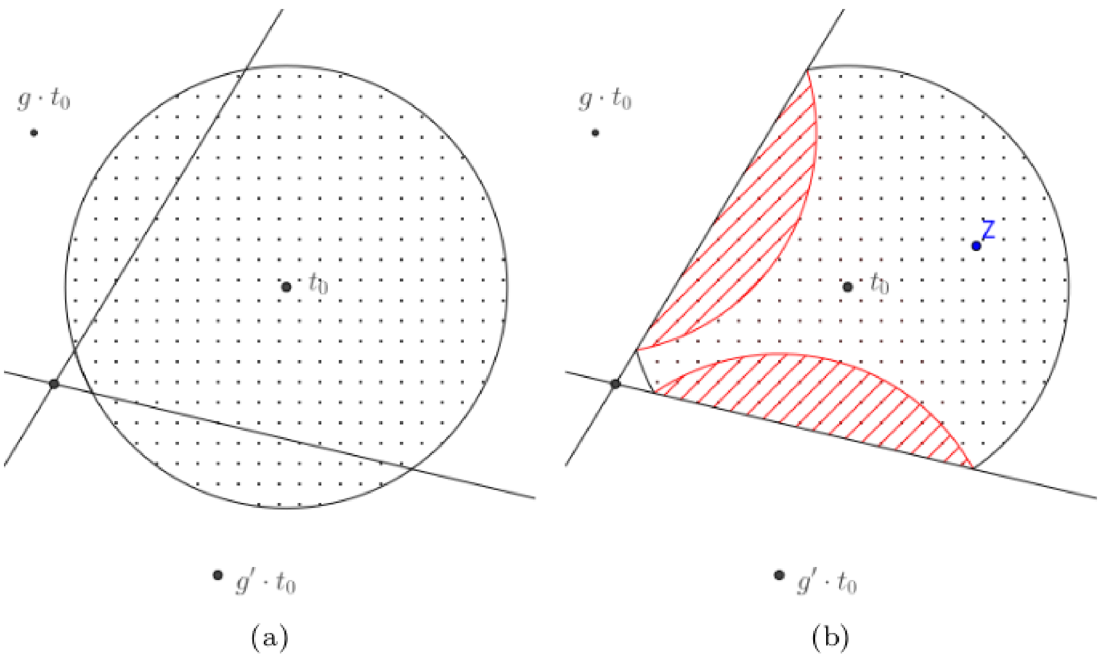

Figure 6. Geometric origin of the inconsistency: the distribution in the ambient space (panel (a)) is folded by the quotient (symmetries around the two lines, panel (b)), which biases the distribution in the quotient space.

6.2.2. Geometric Statistics for Computational Anatomy

Participants: Nina Miolane [Correspondent], Xavier Pennec.

This work is conducted jointly with the Department of Statistics of Stanford, in the context of the associated team GeomStats of the program Inria@SiliconValley.

Statistics, Computational anatomy, Differential geometry, Template shape, Asymptotic bias.

- First, we have shown in [52] that the usual algorithm of template organ shape estimation is biased (see Fig. 7). We proposed two bootstrap procedures that quantify the bias and correct it.
- In [53], we unified the template estimation problem with a manifold learning problem. We showed how the Bayesian framework enables correction in cases that are pathological if only the Maximum Likelihood estimator is used.

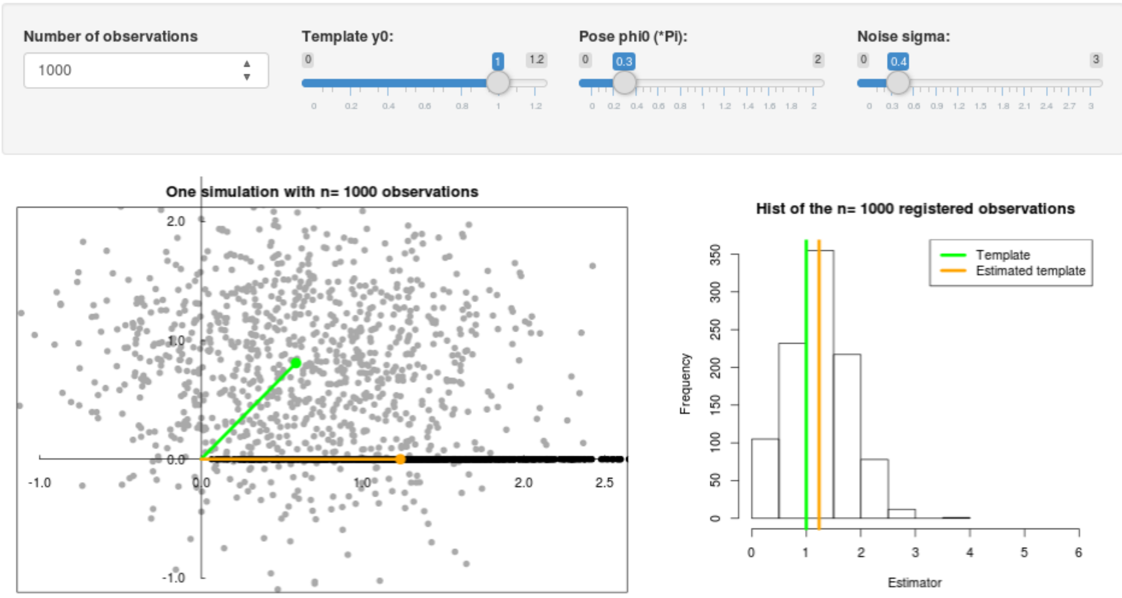

Figure 7. In this toy example, the template estimate (in orange) is biased with respect to the parameter (in green).

6.2.3. Barycentric Subspace Analysis: a new Symmetric Group-Wise Paradigm for Cardiac Motion Tracking

Participants: Marc-Michel Rohé [Correspondant], Maxime Sermesant, Xavier Pennec.

The authors acknowledge the partial funding by the EU FP7-funded project MD-Paedigree (Grant Agreement 600932).

Low-dimensional analysis, Cardiac motion, Registration, Image synthesis.

We propose a novel approach to study cardiac motion in 4D image sequences using low-dimensional subspace analysis [43]. Instead of building subspaces relying on a mean value we use a novel type of subspaces called Barycentric Subspaces, which are are implicitly defined based on $k+1$ reference images instead of being defined with respect to one reference image. This allows:

- First: to build low-dimensional representation of the cardiac motion signature which actually separates perfectly two different populations.

- Second: to build a better prior for the cardiac motion tracking, which improves the registration accuracy at end-systole by 30%.
- Third: to reconstruct the sequence of images with better accuracy than traditional single reference methods.

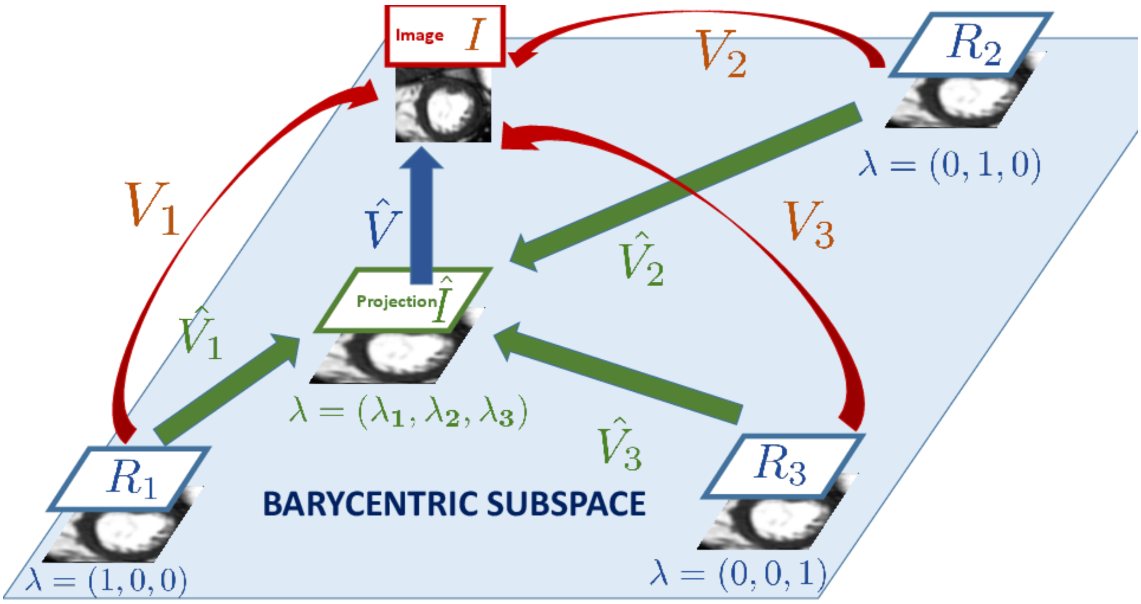

Figure 8.

6.2.4. Compact Representation of Longitudinal Deformations

Participants: Raphaël Sivera [Correspondant], Hervé Delingette, Xavier Pennec, Nicholas Ayache.

Longitudinal modeling, Learning in manifolds, Structured sparsity.

The use of a comprehensive and meaningful decomposition of a set of structural transformations would be useful to describe evolutions and to enhance diagnosis. In this context, we aim to model the brain anatomical evolution which goes along the Alzheimer's neurodegenerative disease. Based on the Stationary Velocity Fields representation of diffeomorphisms, we proposed a description of deformations in both space and time. The objective is to go beyond simple discriminative approaches (see Fig. 9) to propose a synthetic description of the disease evolution, population and subject-wise.

6.3. Computational Physiology

6.3.1. Computational Modeling of Radiofrequency Ablation for the Planning and Guidance of Abdominal Tumor Treatment

Participants: Chloé Audigier [Correspondant], Hervé Delingette, Tommaso Mansi, Nicholas Ayache.

This work is carried out between the Asclepios research group, Inria Sophia Antipolis, France and the Medical Imaging Technologies, Healthcare Technology Center, Siemens Medical Solutions USA, Princeton, NJ.

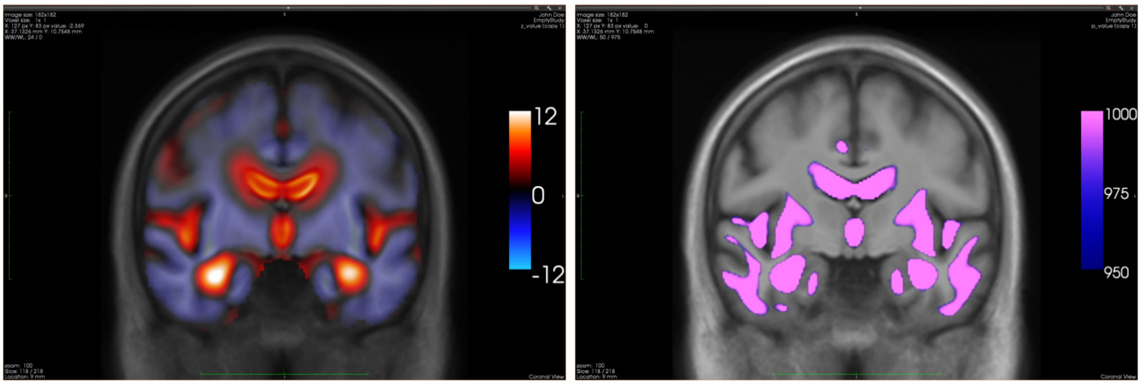

Figure 9. Left: z-values associated with group-wise differences between controls and Alzheimer-diagnosed subjects. Right: Areas of statistically significant differences.

Radio frequency ablation modeling, Patient-specific simulation, Lattice Boltzmann method, Computer model, Computational fluid dynamics, Heat transfer, Cellular necrosis, Parameter estimation, Therapy planning, Liver, Pre-clinical study, Medical imaging.

RFA is a minimally invasive therapy appropriated for liver tumor ablation. However, a patient-specific predictive tool to plan and guide the treatment is needed. We developed a computational framework for patient-specific planning of RFA with the following contributions:

- A detailed computational model of the biophysical mechanisms (heat transfer, cellular necrosis, hepatic blood flow) involved in RFA of abdominal tumors based on patient images.
- A new implementation of the bio-heat equations coupled with a cellular necrosis model using the Lattice Boltzmann Method (LBM) on Graphics Processing Units (GPU), which allows near real-time computation.
- A CFD and porous media solver using LBM algorithm to compute the patient-specific blood flow in the hepatic circulatory system and the blood flow distribution inside the parenchyma.
- A complete patient-specific geometry including hepatic venous and arterial circulation system.
- The automatic estimation of the main parameters of the model. Two personalization strategies tested and evaluated on clinical and pre-clinical data.
- The evaluation of the proposed model on a clinical dataset of ten patients.
- The evaluation on a preclinical dataset of five swines from a comprehensive experimental set-up specially designed for RFA model validation.

6.3.2. Cardiac Electrophysiology Simulation for Arrhythmia Treatment Guidance

Participants: Rocio Cabrera Lozoya [Correspondant], Maxime Sermesant, Nicholas Ayache.

Part of this work was funded by the European Research Council through the ERC Advanced Grant MedYMA 2011-291080 (on Biophysical Modeling and Analysis of Dynamic Medical Images).

Cardiac electrophysiology modeling, Intracardiac electrogram modeling, Radiofrequency ablation planning, Electroanatomical mapping.

1. We developed silico patient-specific models constructed from 3D delayed-enhanced MRI to simulate intracardiac electrograms (EGM), including abnormal EGM as they are potential radiofrequency ablation targets (see Fig. 11) [14].
2. We derived a cardiac model using personalized electro-anatomical parameters and imaging data to define the underlying ventricular tachycardia (VT) substrate and predict re-entrant VT circuits [16].

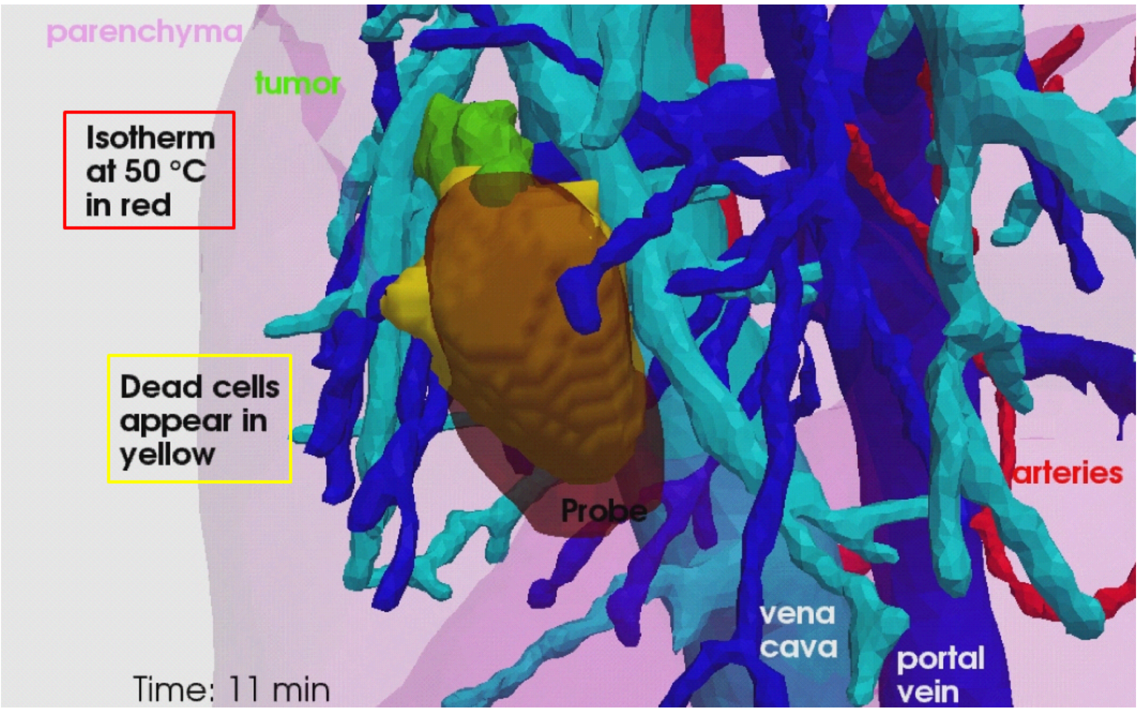

Figure 10. Computed isotherm at 50°C and computed necrosis appears in a subject-specific geometry.

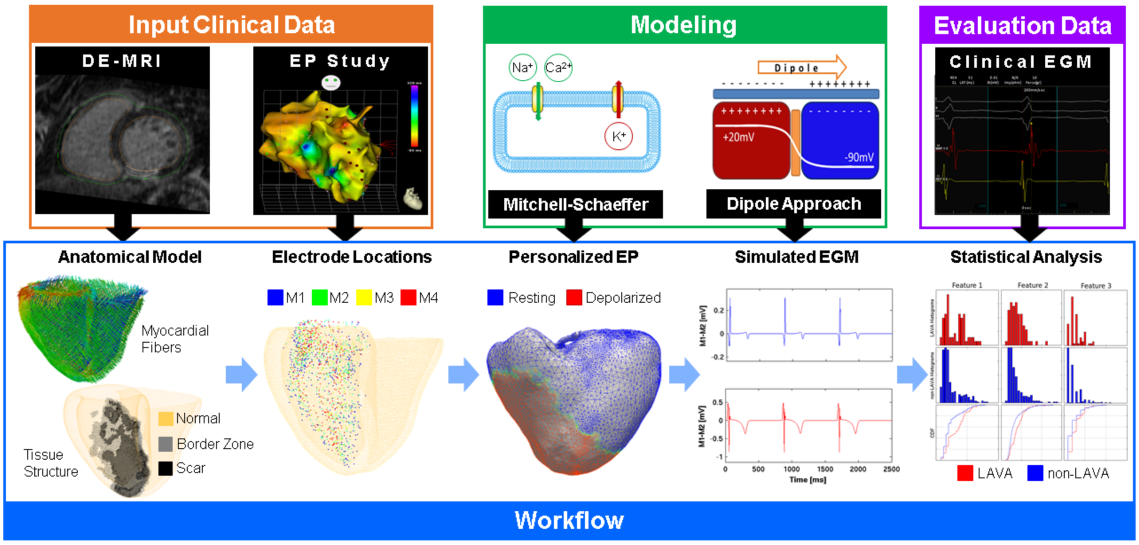

Figure 11. Pipeline developed to simulate intracardiac electrogram using patient-specific models.

6.3.3. Non-Invasive Personalisation of a Cardiac Electrophysiology Model from Body Surface Potential Mapping

Participants: Sophie Giffard Roisin [Correspondant], Maxime Sermesant, Nicholas Ayache, Hervé Delingette.

This work has been supported by the European Project FP7 under grant agreement VP2HF (no 611823) and the ERC Advanced Grant MedYMA (on Biophysical Modeling and Analysis of Dynamic Medical Images).

Cardiac modeling, Personalised simulation, Inverse problem of ECG, Electrical simulation.

Within the VP2HF project, non-invasive cardiac electrical data has been acquired at the St Thomas' Hospital, London. It consists of Body Surface Potential Mapping (BSPM), which are recordings of the electrical potential on several locations on the surface of the torso. In [19], we use non-invasive data (BSPM) to personalise the main parameters of a cardiac electrophysiological (EP) model for predicting different pacing conditions (see Fig. 12). This is an encouraging first step towards a pre-operative prediction of different pacing conditions to assist clinicians for CRT decision and procedure. We have also worked on ECG data that are more commonly used in practice. In [38], we estimated the purkinje activation from 12-lead ECG using an intermittent left bundle brand block patient dataset.

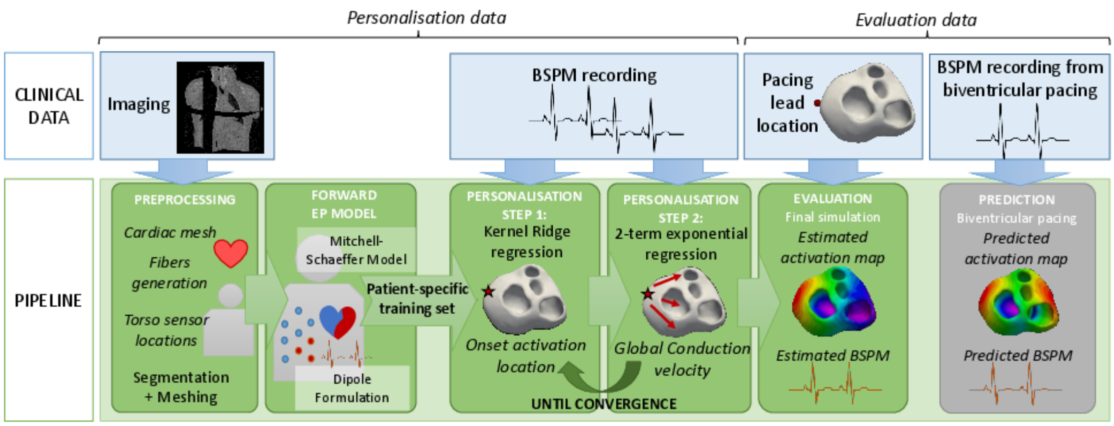

Figure 12. Personalisation framework.

6.3.4. Biophysical Modeling and Simulation of Longitudinal Brain MRIs with Atrophy in Alzheimer's Disease

Participants: Bishesh Khanal [Correspondant], Nicholas Ayache, Xavier Pennec.

This work has been partly supported by the European Research Council through the ERC Advanced Grant MedYMA (on Biophysical Modeling and Analysis of Dynamic Medical Images).

Alzheimer's Disease (AD), Modeling brain deformation, Biophysical model, Simulation.

- We completed a simulation tool that can simulate large databases of virtual realistic longitudinal MRIs with known volume changes[51]. This was based on our biophysical model of brain deformation due to atrophy in Alzheimer's Disease (AD)[25].
- We have released our simulation software, named simul@trophy, as an open source software https://inria-asclepios.github.io/simul-atrophy/.

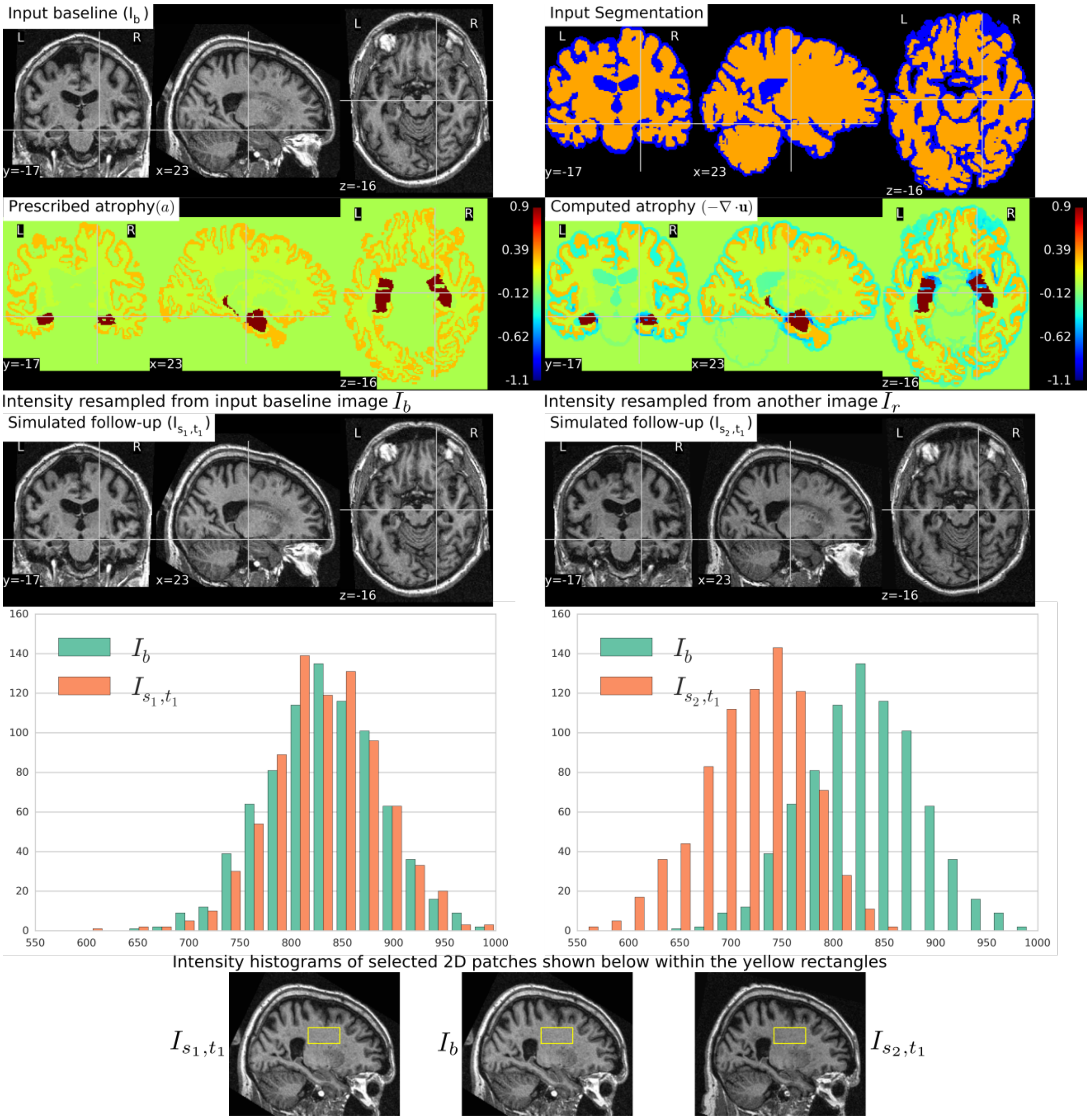

*Figure 13. **1st row:** (left) input baseline image I_b; (right) its input segmentation image. **2nd row:** (left) prescribed atrophy; (right) the atrophy computed from the simulated deformation. **3rd row:** (left) first time-point simulated follow-up image I_{s_1,t_1} where the intensity is resampled from the input baseline image I_b; (right) first time-point simulated follow-up image I_{s_2,t_2} where the intensity is resampled from a MRI taken at a different time-point than I_b, but of the same patient. **4th row:** intensity histogram comparison of the two simulated images in the third row. **5th row:** a relatively uniform region of which the histogram is shown.*

6.3.5. Brain Tumor Growth Personalization and Segmentation Uncertainty

Participants: Matthieu Lê [Correspondant], Hervé Delingette, Jan Unkelbach, Nicholas Ayache.

This work is carried out between the Ascelpios research group, Inria Sophia Antipolis, France and the Department of Radiation Oncology of the Massachusetts General Hospital, Boston, USA.

Tumor growth, Radiotherapy, Modeling, Personalization, Segmentation, Uncertainty, Bayesian.

- We elaborated a method for the synthesis of magnetic resonance images (MRIs) presenting glioblastoma [17].
- We elaborated a method for the sampling of several plausible segmentations, based on a single clinical one. This allows the uncertainty quantification of the radiotherapy plan based on several sample clinical target volumes [30].
- We elaborated a method for the Bayesian personalization of a brain tumor growth model based on clinical MRIs [28].
- We combined the segmentation sampling method with the tumor growth model personalization to personalize radiotherapy planning (see Fig. 14).

6.3.6. A Multiscale Cardiac Model for Fast Personalisation and Exploitation

Participants: Roch Philippe Molléro [Correspondant], Xavier Pennec, Hervé Delingette, Nicholas Ayache, Maxime Sermesant.

This work has been partially funded by the EU FP7-funded project MD-Paedigree (Grant Agreement 600932) and contributes to the objectives of the ERC advanced grant MedYMA (2011-291080).

Cardiac modeling, Reduced model, Multi-fidelity modeling, Parameter estimation, Finite element mechanical modeling.

We developped a multi-fidelity 0D/3D cardiac model that allows us to get reliable (and extremely fast) approximations of the global behaviour of the 3D model with 0D simulations.

By making geometrical assumptions of symmetry, we first built a reduced 0D model of the heart which is very fast (15 beats/seconds). Then, we developped an original coupling method between the parameters of the 3D model and those of the 0D model. We used this multi-fidelity of the heart (in 0D and 3D) to speed-up an efficient optimization algorithm (the genetic algorithm CMA-ES) for the 3D model. As a result, we now have a fast personalisation method for the 3D model (see 15).

This methodology lead to a publication and poster presentation at the MICCAI Conference 2016 [41].

We applied this methodology in particuar to the cohort of 34 different heart geometries and data from the project MD-PAEDIGREE.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. CIFRE PhD Fellowships

7.1.1.1. Neurelec/Oticon Medical

Participants: Thomas Demarcy [correspondent], Hervé Delingette, Nicholas Ayache, Dan Gnansia [Oticon Medical].

The work of Thomas Demarcy, *Segmentation and anatomic variability of the cochlea and other temporal bone structures from medical images*, is supported by a PhD fellowship from the Neurelec/Oticon Medical company.

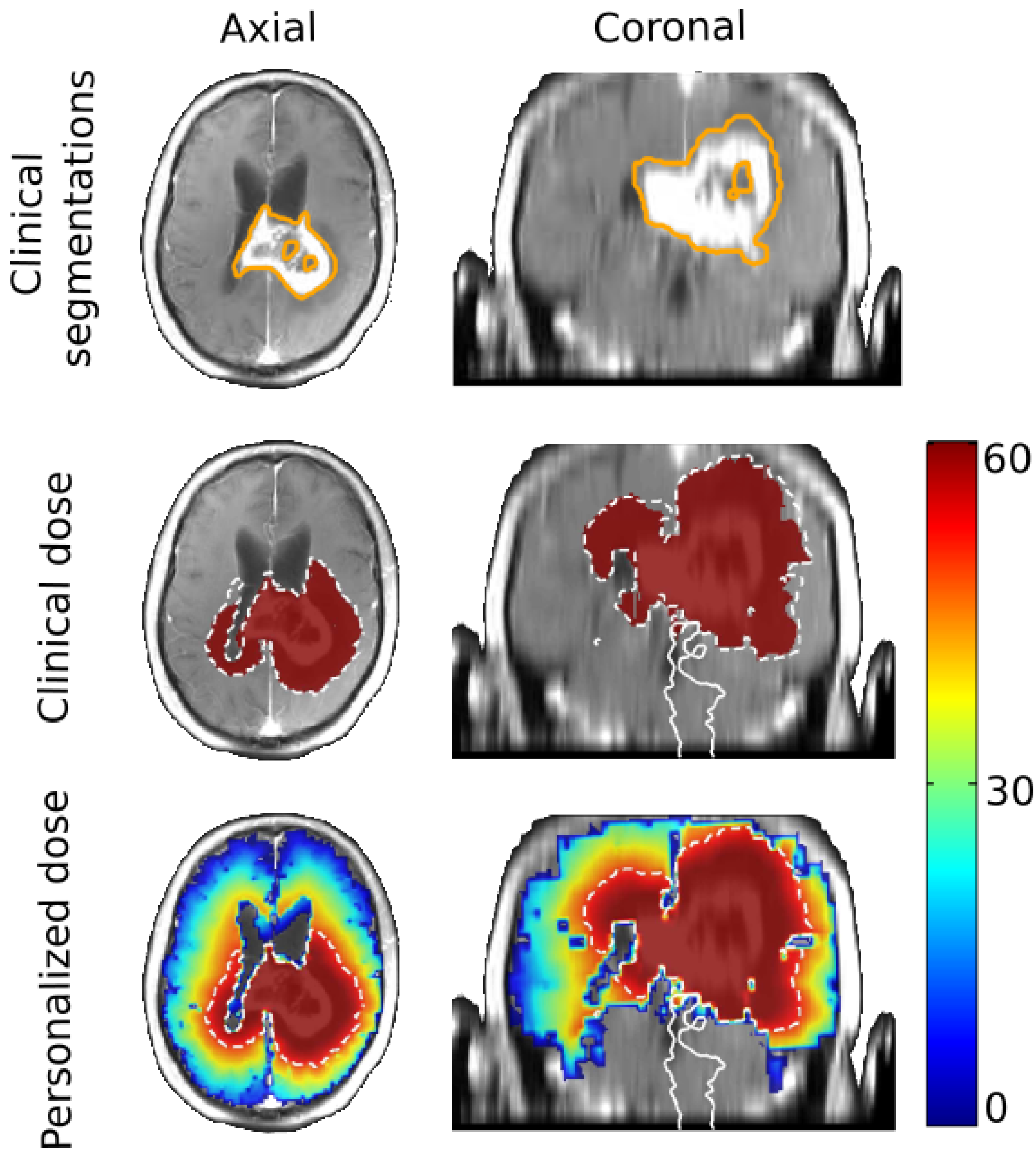

Figure 14. The clinical segmentation of the T1Gd abnormality (top, orange line) is used to define the clinical target volume (CTV, white dashed line) as a 2 cm expansion of the segmentation. In clinical settings, 60 Gy is prescribed to the CTV. We propose to personalize the prescription dose (bottom) to account for tumor infiltration and segmentation uncertainty.

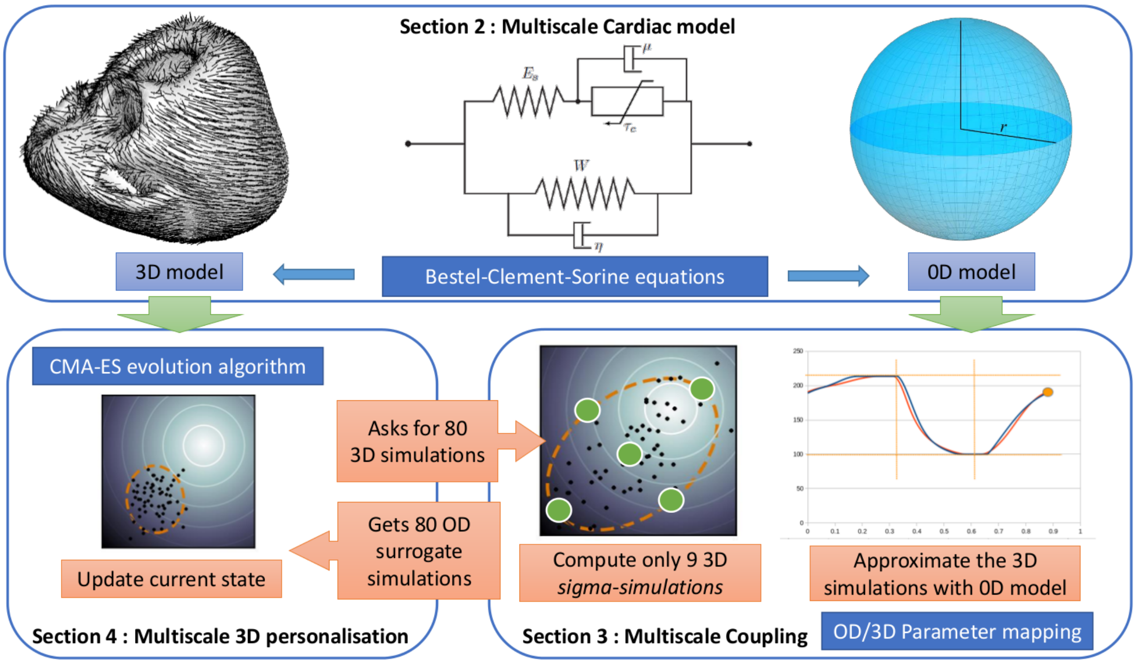

Figure 15. Multi-fidelity model and personalisation pipeline.

7.1.2. Inria - Mauna Kea Technologies I-Lab SIWA

Participants: Nicholas Ayache [correspondent], Xavier Pennec, Marzieh Kohandani Tafreshi, Rémi Cuingnet.

This I-lab involves the Mauna Kea Technologies company.

The first focus of this I-lab is to develop efficient and friendly content-based image retrieval (CBIR) tools to help users make a diagnosis. The second focus is on image registration to provide near real-time and robust image registration tools built on GPU implementations for image stabilization and super-resolution since it is a critical method for the smart atlas.

For more information, see this link[0]. The I-lab SIWA ended in March 2016.

7.1.3. 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 Loic Le Folgoc, Pawel Mlynarski as well as the post doctoral stay of Hervé Lombaert.

7.1.4. 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

[0] https://lisa.sophia.inria.fr/siwa-loasis-numerique-dinria-et-de-mauna-kea-706.html
[0] http://www.msr-inria.fr/projects/4d-cardiac-mr-images
[0] http://www.msr-inria.fr/projects/medilearn
[0] http://www.therapixel.com/

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.

7.1.5. Siemens HealthCare

Siemens Healthcare, Medical Imaging Technologies, Princeton, NJ (U.S.A). is funding the Phd work of Julian Krebs which aims at developping robust medical image registration methods

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. Consulting for Industry

Nicholas Ayache is a scientific consultant for the company Mauna Kea Technologies (Paris).

8.1.2. Collaboration with national hospitals

The Asclepios-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.

The Asclepios-project team is part of the EQUIPEX MUSIC consortium with Bordeaux University Hospital, which aim is to exploit an XMR interventional room equipped with a MUSIC workstation.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. MD PAEDIGREE

Title: Model-Driven European Paediatric Digital Repository

Programme: FP7

Period: March 2013 - February 2017

Coordinator: Ospedale Pediatrico Bambini Gesù, Rome.

Partners:

- Athena Research and Innovation Center in Information Communication & Knowledge Technologies (Greece)
- Biomolecular Research Genomics (Italy)
- Deutsches Herzzentrum Berlin (Germany)
- Empirica Gesellschaft für Kommunikations- und Technologie Forschung Mbh (Germany)
- Fraunhofer-Gesellschaft Zur Foerderung Der Angewandten Forschung E.V (Germany)
- Haute Ecole Specialisée de Suisse Occidentale (Switzerland)
- Istituto Giannina Gaslini (Italy)
- Katholieke Universiteit Leuven (Belgium)
- Lynkeus (Italy)
- Motek Medical B.V. (Netherlands)
- Ospedale Pediatrico Bambino Gesu (Italy)

Siemens Aktiengesellschaft (Germany)

Siemens Corporation (United States)

Technische Universiteit Delft (Netherlands)

University College London (United Kingdom)

Universitair Medisch Centrum Utrecht (Netherlands)

Universita Degli Studi di Roma Lapienza (Italy)

The University of Sheffield (United Kingdom)

Universitatea Transilvania Din Brasov (Romania)

Stichting Vu-Vumc (Netherlands)

Maat Francerl (France)

Inria contact: Xavier Pennec

MD-Paedigree is a clinically-led VPH project that addresses both the first and the second actions of part B of Objective ICT-2011.5.2:

1. it enhances existing disease models stemming from former EC-funded research projects (Health-e-Child and Sim-e-Child) and from industry and academia, by developing robust and reusable multi-scale models for more predictive, individualised, effective and safer healthcare in several disease areas;
2. it builds on the eHealth platform already developed for Health-e-Child and Sim-e-Child to establish a worldwide advanced paediatric digital repository.

Integrating the point of care through state-of-the-art and fast response interfaces, MD-Paedigree services a broad range of off-the-shelf models and simulations to support physicians and clinical researchers in their daily work. MD-Paedigree vertically integrates data, information and knowledge of incoming patients, in participating hospitals from across Europe and the USA, and provides innovative tools to define new workflows of models towards personalised predictive medicine. Conceived as a part of the 'VPH Infostructure' described in the ARGOS, MD-Paedigree encompasses a set of services for storage, sharing, similarity search, outcome analysis, risk stratification, and personalised decision support in paediatrics within its innovative model-driven data and workflow-based digital repository. As a specific implementation of the VPH-Share project, MD-Paedigree fully interoperates with it. It has the ambition to be the dominant tool within its purview. MD-Paedigree integrates methodological approaches from the targeted specialties and consequently analyzes biomedical data derived from a multitude of heterogeneous sources (from clinical, genetic and metagenomic analysis, to MRI and US image analytics, to haemodynamics, to real-time processing of musculoskeletal parameters and fibres biomechanical data, etc.), as well as specialised biomechanical and imaging VPH simulation models.

8.2.1.2. VP2HF

Title: Computer model derived indices for optimal patient-specific treatment selection and planning in Heart Failure

Programme: FP7

Period: October 2013 - September 2016

Coordinator: King's College, London.

Partners:

Centron Diagnostics Ltd (United Kingdom)

CHU Côte de Nacre, Caen (France)

King's College London (United Kingdom)

Philips Technologie (Germany)

Philips France (France)

Simula Research Laboratory As (Norway)

Université Catholique de Louvain (Belgium)

Universitat Pompeu Fabra (Spain)

Inria contact: Dominique Chapelle / Maxime Sermesant

Heart failure (HF) is one of the major health issues in Europe affecting 6 million patients and growing substantially because of the ageing population and improving survival following myocardial infarction. The poor short to medium term prognosis of these patients means that treatments, such as cardiac re-synchronisation therapy and mitral valve repair, can have substantial impact. However, these therapies, are ineffective in up to 50% of treated patients and involve significant morbidity and substantial cost. The primary aim of VP2HF is to bring together image and data processing tools with statistical and integrated biophysical models mainly developed in previous VPH projects, into a single clinical workflow to improve therapy selection and treatment optimisation in HF. The tools will be tested and validated on 200 patients (including 50 historical datasets) across 3 clinical sites, including a prospective clinical study on 50 patients in the last year of the project. The key innovations in VP2HF, which make it likely that the project results will be commercially exploited and have major clinical impact, are:

1. all tools to process images and signals, and to obtain the statistical and biophysical models will be integrated into one clinical software platform that can be easily and intuitively used by clinicians and tried out in the prospective clinical study;
2. to select only the appropriate parts of the tool chain, we use a decision tree stratification approach, which will add maximum value to the predictions that will be used in individual patients, so that the more resource intensive parts will be used when they will add real value.

We expect that the study will result in substantially improved efficacy of the decision making process compared with current guidelines, and that an integrated package that is used as part of clinical workflow will ensure the industrial project partners, in particular Philips, will develop project outputs into dedicated products that will have significant clinical impact.

8.2.1.3. MedYMA

Title: Biophysical Modeling and Analysis of Dynamic Medical Images

Programme: FP7

Type: ERC

Period: April 2012 - March 2017

Coordinator: Inria

Inria contact: Nicholas Ayache

During the past decades, exceptional progress was made with in vivo medical imaging technologies to capture the anatomical, structural and physiological properties of tissues and organs in patients, with an ever increasing spatial and temporal resolution. Physicians are now faced with a formidable overflow of information, especially when a time dimension is added to the already hard to integrate 3-D spatial, multimodal and multiscale dimensions of modern medical images. This increasingly hampers the early detection and understanding of subtle image modifications, which can have a vital impact on the patient's health. To change this situation, a new generation of computational models for the simulation and analysis of dynamic medical images is introduced. Thanks to their generative nature, they will allow the construction of databases of synthetic and realistic medical image sequences simulating various evolving diseases, producing an invaluable new resource for training and benchmarking. Leveraging on their principled biophysical and statistical foundations, these new models will bring an added clinical value once they have been personalized with innovative methods to fit the medical images of any specific patient. By explicitly revealing the underlying evolving biophysical processes observable in the images, this approach will yield new groundbreaking image processing tools to correctly interpret the patient's condition (computer aided diagnosis), to accurately predict the future evolution (computer aided prognosis), and to precisely simulate and monitor an optimal and personalized therapeutic strategy (computer aided therapy). First applications concern high impact diseases including brain tumors, Alzheimer's disease, heart failure and cardiac arrhythmia and will open new horizons in computational medical imaging.

8.3. International Initiatives

8.3.1. Inria Associate Teams Not Involved in an Inria International Labs

8.3.1.1. 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: 2015

See also: http://www-sop.inria.fr/asclepios/projects/GeomStats/

The scientific goal of the associated team is to develop the field of geometric statistics with key applications in computational anatomy.

Computational anatomy is an emerging discipline at the interface of geometry, statistics, image analysis and medicine that aims at analyzing and modeling the biological variability of the organs shapes at the population level. An important application in neuroimaging is the spatial normalization of subjects which is necessary to compare anatomies and functions through images in populations with different clinical conditions.

The research directions have been broken into three axes, the first two being methodologically driven and the last one being application driven. The first axis aims at generalizing the statistical framework from Riemannian to more general geometric structures and even non-manifold spaces (e.g. stratified spaces). The goal is to understand what is gained or lost using each geometric structure. The second axis aims at developing subspace learning methods in non-linear manifolds. This objective contrasts with most manifold learning methods which assumes that subspaces are embedded in a large enough Euclidean space. The third scientific direction is application driven with cross-sectional and longitudinal brain neuroimaging studies. The goal will be to extract reduced models of the brain anatomy that best describe and discriminate the populations under study. One intend for instance to show where is impact of a treatment for traumatic brain injuries.

8.3.2. Inria International Partners

8.3.2.1. Informal International Partners

8.3.2.1.1. 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.

8.3.2.1.2. 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.

8.3.2.1.3. University College London (UCL), London, UK

Marco Lorenzi holds an honorary position with the Translational Imaging Group of UCL, led by Prof. Sebastien Ourselin. His collaboration is around the topic of spatio-temporal analysis of medical images, with special focus on brain imaging analysis and biomarker development in Alzheim disease. 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.

8.3.2.1.4. Imaging Genetics Center (IGC), University of Southern California (USC), CA, USA

Marco Lorenzi is currently collaborator with the IGC for the investigation of the very 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.

8.3.2.1.5. Other International Hospitals

Collaborations with several other European hospitals have been established through the European projects VP2HF and MD PAEDIGREE.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

8.4.1.1. Research Stays Abroad

In the context of the Associated team GeomStats, part of the Inria International Lab Inria@SiliconValley, Nina Miolane spent 3 months (April to June 2016) at the Stanford Statistics Department:

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

- **X. Pennec** organized a workshop on the Geometry of shapes Workshop (Math in the Mine) from June 26 to July 2, 2016, at la Minière de Vallauria, Alpes Maritimes, FR.

9.1.1.2. Member of the Organizing Committees

- **M. Sermesant** was a co-chair of the MICCAI 2016 Workshop Statistical Atlases and Computational Models of the Heart (STACOM 2016), which was held in Athens, Greece, on October 17, 2016. He also co-organised the Cardiac Imaging Research Day at the French Radiologists Conference.

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

- **X. Pennec** was a member of the program committee of RFIA RFP 2016 (Reconnaissance de Formes et Perception) (Clermont-Ferrand, FR), the 2nd Int. W. on Differential Geometry in Computer Vision Diff-CVML’16, Las Vegas, USA), and of the Workshop on Biomedical Image Registration (WBIR 2016, Las-Vegas, USA).
- **H. Delingette** was program committee member of the conference on Medical Image Computing and Computer Assisted Intervention (MICCAI 2016), the MICCAI 2016 workshop on Simulation and Synthesis of Medical Imaging (SASHIMI’16), and the Eurographics conference on Visual Computing for Biology and Medicine (VCBM’16).

9.1.2.2. Reviewer

- **H. Delingette** was a reviewer for the International Symposium on Biomedical Imaging (ISBI'16), the international conference on computer-aided interventions (IPCAI'16), the conference on Medical Image Computing and Computer Assisted Intervention (MICCAI 2016), the European Conference on Computer Vision (ECCV 2016), the International Conference on Computer Vision and Pattern Recognition (CVPR 2016).
- **M. Sermesant** was a reviewer for the MICCAI 2016 conference.
- **X. Pennec** was a reviewer for the conference on Medical Image Computing and Computer Assisted Intervention (MICCAI 2016), the European Conference on Computer Vision (ECCV 2016) and the int. Workshop on Representation, analysis and recognition of shape and motion FroM Imaging data (RFMI 2016).

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*[0]. 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)*.

9.1.3.2. Reviewer - Reviewing Activities

- **H. Delingette** was a reviewer for the following journals: *Medical Image Analysis* (Elsevier), IEEE Transactions in Medical Imaging, IEEE Transactions in Biomedical Engineering, Computer Vision and Image Understanding, Biomedical Engineering, Computers in Biology and Medicine and Journal of Fluids and Structures.
- **X. Pennec** was a reviewer for the following journals: Biometrika, Chaos, Proceedings on the London Mathematical Society (PLMS), SIAM journal on Imaging Sciences (SIIMS), Medical Image Analysis (MedIA), IEEE Transactions on Pattern Analysis (PAMI), NeuroImage (NIMG).
- **M. Sermesant** was a reviewer for the following journals: 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.

9.1.4. Invited Talks

- **Nicholas Ayache** gave the following invited lectures:
  - To honor Michel Lazdunski, Nice Hospital, January 2016
  - Science and Society event, Toulouse, May 2016
  - Institut Universitaire de France, Annual Event, Rennes, June 2016
  - Connected Health, Monaco, June 2016
  - SSIMA Summer School, Bucharest, July 2016
  - MISS Summer School, Favigna, August 2016
  - Academy of Sciences , Sept 2016
  - IHU Liryc, Bordeaux, Sept 2016
- **Hervé Delingette** gave the following invited lectures at the:

[0] http://www.elsevier.com/wps/find/journaleditorialboard.cws_home/620983/editorialboard

- MICCAI 2016 Programme Committee Workshop on May 27th in London.
- Biomedical Image Analysis Seminar at University of Basel on November 22nd.

- **Xavier Pennec** gave invited lectures at the following events:
  - Colloquium of the Dieudonné Lab (LJAD), Nice University, October 10, 2016.
  - VIth Int. W. on Representation, analysis and recognition of shape and motion FroM Imaging data (RFMI 2016), Sidi Bou Said village, Tunisia, October 27-29 2016.
  - International Workshop on Geometry, PDE's and Lie Groups in Image Analysis, Eindhoven (NL) 24-26 August 2016.
  - Workshop on Geometry and Stochastics of Nonlinear, Functional and Graph Data, Bornholm (DK), 15-19 August 2016.
  - 12th IEEE IVMSP Workshop 2016, Bordeaux (FR), July 11-12, 2016.
  - Statistical Analysis of Manifold-Valued Data and Beyond: Nottingham workshop, 4-6 April 2016, UK.
  - Mathematical Imaging and Surface Processing, Mathematisches Forschungsinstitut Oberwolfach (DE), 24-30 January 2016.
- **Maxime Sermesant** gave an invited lecture at the Virtual Physiological Human Summer School, Barcelona.

9.1.5. Leadership within the Scientific Community

- **H. Delingette** is a member of the MICCAI Society Board of Directors from 2016 to 2019.
- **Nicholas Ayache** is a member of the French Academy of Sciences in the section of Mechanics and Informatics.

9.1.6. Scientific Expertise

- **Nicholas Ayache** was invited in Nagoya, Japan in February 2016 to evaluate a national program on the "Multidisciplinary Computational Anatomy Initiative" funded by the MEXT. He has been a member of the Research Council of the "Fondation pour la Recherche Médicale (FRM)" since January 2015.
- **Xavier Pennec** was an evaluator for the Fonds de la Recherche Scientifique-FNRS, Belgium, the Alpes Grenoble Innovation Recherche (AGIR) projects, and for the PhD fellowships of Ecole Normale cachan.
- **H. Delingette** was an evaluator for the ECOS Sud France-Chili program, for the European Research Concil, for the Comet program in Austria (FWF), for the International Graduate School of Science and Engineering (IGSSE) of the Technical University of Munich.
- **M. Sermesant** is a member of the Medical Simulation Working Group of Aviesan.

9.1.7. Research Administration

- **Nicholas Ayache** is a member of the scientific council of the Ile de France region since 2016.
- **Xavier Pennec** 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, in charge of the relationships of Inria-Sophia with the Nice University Hospital (CHU), of and the board of the Ecole doctorale STIC.
- **H. 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.

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.

Master: X. Pennec and H. Delingette, Computational Anatomy and Physiology, 21h course (28.5 ETD), Master CBB - Computational Biology and Biomedicine, Univ. Nice-Sophia Antipolis.

Master: M. Sermesant, Computational Anatomy and Physiology, 3h course (4.5 ETD), Master CBB - Computational Biology and Biomedicine, Univ. Nice-Sophia Antipolis.

Master: X. Pennec is co-responsible of the Master CBB - Computational Biology and Biomedicine, Univ. Nice-Sophia Antipolis.

9.2.2. Theses Defended

- Pietro Gori , *Statistics on the brain connectivity of patients with neurological diseases*, University of Paris. Started in 2012. Thesis in collaboration with the Aramis project-team, co-directed by O. Colliot, S. Durrleman and N. Ayache. Defended on January 8, 2016.
- Mehdi Hadj-Hamou, *Biophysical modeling of the anatomical evolution of the brain*, Nice Sophia Antipolis University. Co-directed by N. Ayache and X. Pennec. Defended on December 14, 2016.
- Bishesh Khanal, *Modeling the atrophy of the brain in Alzheimer's disease*, Nice Sophia Antipolis University. Co-directed by X. Pennec and N. Ayache. Defended on July 20, 2016.
- Nina Miolane, *Geometric Statistics in Computational Anatomy: Template Estimation and Subspace Learning in Manifolds, Lie groups and Stratified Spaces*, Nice-Sophia Antipolis University. Directed by X. Pennec. Defended on December 16, 2016.
- Anant Vemuri, *Inter-operative biopsy site relocalization in gastroscopy : application to oesophagus*, Nice Sophia Antipolis University. Co-directed by S. Nicolau and N. Ayache. Defended on April 26th 2016.
- Matthieu Lê, *Brain tumor growth modeling : application to radiotherapy imaging*, Nice Sophia Antipolis University. Co-directed by H. Delingette and N. Ayache. Defended on June 23rd 2016.
- HdR : Maxime Sermesant, When Cardiac Biophysics Meets Groupwise Statistics: Complementary Modelling Approaches for Patient-Specific Medicine, Universite Nice Sophia Antipolis, June 9.

9.2.3. PhD in progress

Marc-Michel Rohé, *Analyse statistique spatio-temporelle des formes, déformations, flots et propriétés physiologiques du cœur*, Nice Sophia Antipolis University. Started in 2014. Co-directed by X. Pennec and M. Sermesant.

Sophie Giffard-Roisin, *Non-invasive Estimation of Cardiac Electrophysiological Parameters*, Nice Sophia Antipolis University. Started in 2014. Co-directed by N. Ayache and M. Sermesant.

Roch Molléro, *Uncertainty quantification in personalized electromechanical models. Application to cardiomyopathies and obesity*, Nice Sophia Antipolis University. Started in 2014. Co-directed by N. Ayache and M. Sermesant.

Thomas Demarcy, *Segmentation and anatomic variability of the cochlea and other temporal bone structures from medical images*, Nice Sophia Antipolis University. Started in 2014. Directed by H. Delingette.

Loïc Devilliers, *Consistency of statistics on infinite dimensional orbifolds – Applications to computational anatomy*, Nice Sophia Antipolis University. Started in October 2015. Co-directed by X Pennec and St. Allassonière.

Raphaël Sivera, *Analyse statistique de l'évolution de structures morphologiques partir de séquences temporelles d'IRM*, Nice Sophia Antipolis University. Started in October 2015. Co-directed by N. Ayache and H. Delingette.

Pawel Mlynarski, *Tumor segmentation based on Random Forests and Convolutional Neural Networks trained on partially annotaded data*, Nice Sophia Antipolis University. Started in December 2015. Co-directed by N. Ayache and H. Delingette.

Qiao Zheng, *Deep learning for cardiac image analysis*, Nice Sophia Antipolis University. 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*, Nice Sophia Antipolis University. Started in 2016. Co-directed by M. Sermesant and X. Pennec.

Wen Wei, *Learning Brain Alterations in Multiple Sclerosis from Multimodal Neuroimaging Data*, Nice Sophia Antipolis University. Started in 2016. Co-directed by N.Ayache and O.Colliot.

Julian Krebs, *Robust image registration based on machine learning*, Nice Sophia Antipolis University. Started in 2016. Co-directed by H. Delingette and N. Ayache.

9.2.4. Juries

N. Ayache was co-supervisor of the PhD theses of Matthieu Lê (Univ. of Nice Sophia Antipolis), Anant Vemuri (Univ. of Nice Sophia Antipolis), Pietro Gori (University of Paris), Mehdi Hadj-Hamou (Univ. of Nice Sophia Antipolis), and Bishesh Khanal (Univ. of Nice Sophia Antipolis). He was a member of the PhD thesis committee of Nina Miolane (Univ. of Nice Sophia Antipolis).

Hervé Delingette was co-supervisor of the PhD thesis of Matthieu Lê (Univ. of Nice Sophia Antipolis). He was a reviewer in the PhD thesis committee of Vincent Jaouen (Univ. of Tours) and of Tom Haeck (University KUL Leuven, Belgium). He was a member of the PhD thesis committee of Bishesh Khanal (Univ. of Nice Sophia Antipolis).

Xavier Pennec was supervisor or co-supervisor of the PhD theses of Bishesh Khanal (Univ. of Nice Sophia Antipolis), Mehdi Hadj-Hamou (Univ. of Nice Sophia Antipolis) and Nina Miolane (Univ. of Nice Sophia Antipolis).

Maxime Sermesant was a reviewer and a member of the PhD jury of Andjela Davidovic, Bordeaux University (Dec 9).

9.3. Popularization

- Nina Miolane participated to the following popularization events:
  - Speaker at Unesco France's Ceremony for 70th Anniversary.
  - Speaker at the Women Forum Global Meeting 2016. How to bring more women in the sci-tech workforce?
  - Speaker at the L'Oreal-Unesco Prizes Ceremony 2016.
  - Journal regional de France 3 Azur (Oct. 31 2016)
  - Invited on "Le Club de la Tete au Carre". France Inter (National Radio), Oct. 14 2016.
- M. Sermesant gave general audience lectures in regional high schools, during the Science Festival in Juan-les-Pins Congress center (Oct 23), and during the Inria-Industry meeting (Dec 1).

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Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] M. HADJ-HAMOU.*Beyond Volumetry in Longitudinal Deformation-Based Morphometry: Application to Sexual Dimorphism during Adolescence*, Universite Nice Cote d'Azur, December 2016, https://hal.inria.fr/tel-01416569.

[2] B. KHANAL.*Modeling and simulation of realistic longitudinal structural brain MRIs with atrophy in Alzheimer's disease*, Université Nice Sophia Antipolis, July 2016, https://tel.archives-ouvertes.fr/tel-01384678.

[3] M. LEˆ.*Brain tumor growth modeling : application to radiotherapy*, Université Nice Sophia Antipolis, June 2016, https://tel.archives-ouvertes.fr/tel-01376688.

[4] N. MIOLANE.*Geometric Statistics for Computational Anatomy*, Inria Sophia Antipolis, December 2016, https://hal.inria.fr/tel-01411886.

[5] M. SERMESANT.*When Cardiac Biophysics Meets Groupwise Statistics: Complementary Modelling Approaches for Patient-Specific Medicine*, Université de Nice - Sophia Antipolis, June 2016, Habilitation à diriger des recherches, https://hal.inria.fr/tel-01337145.

[6] A. S. VEMURI.*Inter-operative biopsy site relocalization in gastroscopy : application to oesophagus*, Université Nice Sophia Antipolis, April 2016, https://tel.archives-ouvertes.fr/tel-01310047.

Articles in International Peer-Reviewed Journal

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[11] J. L. BRUSE, E. CERVI, K. MCLEOD, G. BIGLINO, M. SERMESANT, X. PENNEC, A. M. TAYLOR, S. SCHIEVANO, T.-Y. HSIA.*Looks Do Matter! Aortic Arch Shape After Hypoplastic Left Heart Syndrome Palliation Correlates With Cavopulmonary Outcomes*, in "The Annals of Thoracic Surgery", September 2016, p. S0003-4975(16)30748-2 [*DOI :* 10.1016/J.ATHORACSUR.2016.06.041], https://hal.inria.fr/hal-01421202.

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Project-Team ATHENA

Computational Imaging of the Central Nervous System

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Computational Neuroscience and Medecine

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Project-Team ATHENA

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Keywords:

Computer Science and Digital Science:

3. - Data and knowledge
3.1. - Data
3.3. - Data and knowledge analysis
3.4. - Machine learning and statistics
5. - Interaction, multimedia and robotics
5.1. - Human-Computer Interaction
5.2. - Data visualization
5.3. - Image processing and analysis
5.9. - Signal processing
6. - Modeling, simulation and control
6.1. - Mathematical Modeling
6.2. - Scientific Computing, Numerical Analysis & Optimization
6.3. - Computation-data interaction
7. - Fundamental Algorithmics
7.8. - Information theory
7.9. - Graph theory
8. - Artificial intelligence
8.2. - Machine learning
8.3. - Signal analysis

Other Research Topics and Application Domains:

1. - Life sciences
1.3. - Neuroscience and cognitive science
1.3.1. - Understanding and simulation of the brain and the nervous system
1.3.2. - Cognitive science
1.4. - Pathologies
2.2.2. - Nervous system and endocrinology
2.2.6. - Neurodegenerative diseases
2.5. - Handicap and personal assistances
2.5.1. - Sensorimotor disabilities
2.5.2. - Cognitive disabilities
2.5.3. - Assistance for elderly
2.6.1. - Brain imaging
2.6.2. - Cardiac imaging
2.7. - Medical devices
2.7.1. - Surgical devices

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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 Anatomical 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 anatomical 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 Anatomical 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 major anatomical 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 anatomical 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 [90], Merboldt et al [94] and Taylor et al [103]. 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) [102], [72]. Historically, the first model in dMRI is the 2nd order diffusion tensor (DTI) [70], [69] which assumes the EAP to be Gaussian centered at the origin. DTI has now proved to be extremely useful to study the normal and pathological human brain [91], [80]. 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 drived 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 [93] and [92]).

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) [107] and High Angular Resolution Diffusion Imaging (HARDI) methods such as Q-ball imaging [105] and other multi-tensors and compartment models [100], [101], [63], [62], [98] 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. Those contributions are fundamental and have already started to impact on the Diffusion MRI, HARDI and Q-Ball Imaging community [79]. They are at the core of our probabilistic and deterministic tractography algorithms devised to best exploit the full distribution of the fiber ODF (see [76], [5] and [77],[6]).

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 [109], [110] or 4th order Tensor Model [68]. For more details, we refer the reader to our articles in [81], [100] where we review HOT models and to our articles in [92], 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. Indeed, DKI is fast gaining popularity in the domain for characterizing the diffusion propagator or EAP by its deviation from Gaussianity. Hence it is an important tool in the clinic for characterizing the white-matter's integrity with biomarkers derived from the 3D 4th order kurtosis tensor (KT) [84].

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 [62], [63]. 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 increase, as the strength and speed of gradients increase and as new acquisition techniques appear [4], these imaging modalities raise a large amount of mathematical and computational challenges at the core of the research we develop at ATHENA [83], [100].

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 [75]. 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 [95].

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 [95], [73], [74]. 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 [95], [73], [74].

We have also contributed to design optimal acquisition schemes for single and multiple q-shell experiments. In particular, the method proposed in [4] 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 [82]

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

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

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 [64], AxCaliber [65] and NODDI [108] 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 [67], [66], the Solid Harmonic (SoH) basis [78], the Simple Harmonic Oscillator based Reconstruction and Estimation (SHORE) basis [96] and more recent Mean Apparent Propagator or MAP-MRI basis [97].

However, although great improvements have been made in the last twenty years, 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 is still considerable room for improvement to take dMRI from the benchside to the bedside.

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 objectives we would like to achieve in order to lead to a decisive advance and breakthrough in this field.

Then, 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 and FA 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 [7].

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 [8]. Using additional a priori anatomical [11] 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.

3.2. 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 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 and SPECT 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 [3].
- 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 [89], [10] and means to calibrate them [106] 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.

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 major anatomical imaging modality that will be considered to recover the CNS connectivity.

4.2. Applications of M/EEG

Applications of EEG and MEG:
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.

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 are developing research collaborations with the Neurelec company in Sophia Antipolis (subsidiary of Oticon Medical) and with the leading EEG software company BESA based in Munich. We collaborate with Nice University Hospital on the usage of BCI-based communication for ALS [0] patients.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

R. Deriche and the ATHENA team has been awarded by an ERC Advanced Grant from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (ERC AdG agreement No 694665 “Computational Brain Connectivity Mapping” started on Sept. 1st, 2016.)

Guillermo Guallardo, PhD has been awarded by a Merit Abstract Award by the 2016 OHBM Annual Meeting in Geneva, Switzerland for his work entitled *Efficient Population-Representative Whole-Cortex Parcellation Based on Tractography* [34].

5.1.2. Press coverage

Brain-Computer Interfaces developped in Athena attracted attention of the media, at regional and national levels: Nice Matin, Le Dauphiné Libéré and Le Figaro Santé have published articles about our translational research on the P300 speller. This system enables severely disabled patients, who are deprived of voluntary motor control, to communicate by using only their visual attention.

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

6. New Software and Platforms

6.1. Coadapt P300 Stimulator

KEYWORDS: Health - Brain-Computer Interface
FUNCTIONAL DESCRIPTION

In the domain of Brain Computer Interfaces, extracting relevant features requires a precise timing of all events occurring in the system. In particular, when dealing with evoked responses as in the P300 speller, the timing of the visual stimulations must be well controlled. To alleviate some timing issues with the P300 speller initially provided with OpenViBE, we have implemented an external visual stimulator that allows to flash the visual targets, in a time-robust manner. In 2016 a new generation of this software has been coded, which will be released publicly in 2017. It is being tested outside of Inria by a few beta-testers.

- Participants: Nathanaël Foy, Dieter Devlaminck, Loic Mahe, Maureen Clerc, Théodore Papadopoulo, Emmanuel Maby and Jérémie Mattout
- Partner: INSERM
- Contact: Maureen Clerc
- http://openvibe.inria.fr/coadapt-p300-stimulator-tutorial/

6.2. DIPY

Diffusion Imaging in Python
KEYWORDS: MRI - Medical imaging
FUNCTIONAL DESCRIPTION

Dipy is a free and open source software project focusing mainly on diffusion magnetic resonance imaging (dMRI) analysis. Nonetheless, as we solve problems in dMRI some of the solutions are applicable to the greater medical imaging and image processing communities. See for example our registration and denoising tutorials.

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

6.3. The White Matter Query Language

KEYWORDS: Neuroanatomy - Diffusion MRI - Automatic Segmentation - DSL
FUNCTIONAL DESCRIPTION The White Matter Query Language (WMQL) is a technique to formally describe white matter tracts and to automatically extract them from diffusion MRI volumes. This query language allows us to construct a dictionary of anatomical definitions describing white matter tracts. The definitions include adjacent gray and white matter regions, and rules for spatial relations. This enables the encoding of anatomical knowledge of the human brain white matter as well as the automated coherent labeling of white matter anatomy across subjects.

- Participants: Demian Wassermann
- Contact: Demian Wassermann
- URL:http://tract-querier.readthedocs.org/en/latest/

6.4. FindSources3D

KEYWORDS: Health - Neuroimaging - Visualization - Medical - Image - Processing
FUNCTIONAL DESCRIPTION

FindSources3D is a Matlab software program dedicated to the resolution of inverse source problems in electroencephalogrphy (EEG). From pointwise measurements of the electric potential, numerically obtained or taken by electrodes on the scalp, FindSources3D estimates pointwise dipolar current sources within the brain.

- Participants: Juliette Leblond, Maureen Clerc, Théodore Papadopoulo and Jean Paul Marmorat
- Contact: Juliette Leblond
- URL: http://www-sop.inria.fr/apics/FindSources3D/en/index.html

6.5. High Performance Diffusion MRI

KEYWORDS: Health - Neuroimaging - Medical imaging
FUNCTIONAL DESCRIPTION

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. These algorithms and software 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. This library has been transfered to the Company *Olea Medical*, where it will be at the heart of the new dMRI module to be included in the *Olea Sphere* platform.

- Participants: Aurobrata Ghosh, Théodore Papadopoulo, Rachid Deriche and Demian Wassermann
- Contact: Rachid Deriche

6.6. MedInria

KEYWORDS: Segmentation - Health - DWI - Visualization - Medical imaging
SCIENTIFIC DESCRIPTION

It 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 and renewed in 2012. 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: Jaime Garcia Guevara, Théodore Papadopoulo, Olivier Commowick, Rene-Paul Debroize, Guillaume Pasquier, Laurence Catanese, Olivier Commowick, Alexandre Abadie, Benoit Bleuze, Clement Philipot, Fatih Arslan, Florian Vichot, John Stark, Julien Wintz, Loïc Cadour, Maxime Sermesant, Michael Knopke, Nicolas Toussaint, Olivier Clatz, Pierre Fillard, Sergio Medina, Stephan Schmitt and Hakim Fadil
- Partners: HARVARD Medical School - IHU - LIRYC - IHU - Strasbourg - NIH
- Contact: Olivier Commowick
- URL: http://med.inria.fr

6.7. OpenMEEG

KEYWORDS: Health - Neuroimaging - Medical imaging
FUNCTIONAL DESCRIPTION

OpenMEEG provides state-of-the art tools for processing EEG and MEG data. It incorporates a newly proposed, symmetric BEM for the forward problem, and a distributed source inverse problem, with three different types of regularizations, two of which are original, based on norms of the surface gradient of the source distribution. OpenMEEG is a free, open software written in C++, and can be accessed either through a command line interface or through a user-friendly interface. OpenMEEG is being used for functional neuroimaging, through third-party software (Brainstorm and Fieldtrip), as can be noticed by the citations to our articles [9] and [89].

- Participants: Théodore Papadopoulo, Maureen Clerc, Alexandre Gramfort, Emmanuel Olivi, Kai Dang, Geoffroy Adde, Perrine Landreau, Renaud Keriven and Jan Kybic
- Contact: Théodore Papadopoulo
- URL: http://openmeeg.github.io/

6.8. OpenVIBE

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

FUNCTIONAL DESCRIPTION

OpenViBE is a software platform for real-time neurosciences (that is, for real-time processing of brain signals). It can be used to acquire, filter, process, classify and visualize brain signals in real time from various signal sources. OpenViBE is free and open source software. It works on Windows and Linux operating systems.

- Participants: Yann Renard, Anatole Lécuyer, Fabien Lotte, Bruno Renier, Vincent Delannoy, Laurent Bonnet, Baptiste Payan, Jozef Legeny, Jussi Tapio Lindgren, Alison Cellard, Loic Mahe, Guillaume Serriere, Marsel Mano, Maureen Clerc, Théodore Papadopoulo, Laurent Bougrain, Jeremy Frey and Nathanaël Foy
- Partners: CEA-List - GIPSA-Lab - INSERM
- Contact: Anatole Lécuyer
- URL: http://openvibe.inria.fr

7. New Results

7.1. Modeling in Diffusion MRI

7.1.1. Computational brain connectivity mapping: A core health and scientific challenge

Participant: Rachid Deriche.

One third of the burden of all the diseases in Europe is due to problems caused by diseases affecting brain. Although exceptional progress have been obtained for exploring the brain during the past decades, it is still terra-incognita and calls for specific efforts in research to better understand its architecture and functioning. To take up this great challenge of modern science and to solve the limited view of the brain provided just by one imaging modality, this article advocates the idea developed we develop in my research group of a global approach involving new generation of models for brain connectivity mapping and strong interactions between structural and functional connectivities. Capitalizing on the strengths of integrated and complementary non invasive imaging modalities such as diffusion Magnetic Resonance Imaging (dMRI) and Electro and Magneto-Encephalography (EEG & MEG) will contribute to achieve new frontiers for identifying and characterizing structural and functional brain connectivities and to provide a detailed mapping of the brain connectivity, both in space and time. Thus leading to an added clinical value for high impact diseases with new perspectives in computational neuro-imaging and cognitive neuroscience.

The work leading to the objectives listed in this article has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (ERC Advanced Grant agreement No 694665 started on Sept. 1st, 2016).

This article has been published in [15].

7.1.2. A survey of current trends in diffusion MRI for structural brain connectivity

Participants: Aurobrata Ghosh [University College London, UK], Rachid Deriche.

In this work, we review the state of the art in diffusion magnetic resonance imaging (dMRI) and we present current trends in modelling the brain's tissue microstructure and the human connectome. dMRI is today the only tool that can probe the brain's axonal architecture in vivo and non-invasively, and has grown in leaps and bounds in the last two decades since its conception. A plethora of models with increasing complexity and better accuracy have been proposed to characterise the integrity of the cerebral tissue, to understand its microstructure and to infer its connectivity. Here, we discuss a wide range of the most popular, important and well-established local microstructure models and biomarkers that have been proposed from these models. Finally, we briefly present the state of the art in tractography techniques that allow us to understand the architecture of the brain's connectivity.

This work has been published in [17].

7.1.3. Multi-Spherical Diffusion MRI: Exploring Diffusion Time Using Signal Sparsity

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

Effective representation of the four-dimensional diffusion MRI signal - varying over three-dimensional q-space and diffusion time t - 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 qt-space, which we call qt-dMRI. To drastically reduce the number of diffusionweighted images (DWIs) we need to represent the qt-space, we regularize the fitting of qt-dMRI by imposing both signal smoothness and sparsity. As the main contribution, qt-dMRI provides the framework for estimating time-dependent q-space indices (qt-indices), providing new means for studying subdiffusion 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 excellent reproducibility of estimated qt-index values and trends. In the hopes of opening up new t-dependent venues of studying nervous tissues, qt-dMRI is the first of its kind in being specifically designed to provide open interpretation of the qt-diffusion signal.

This work has been partly published in [31]. The test-retest study has been submitted to ISMRM'17 and an extended version has been submitted to Neuroimage.

7.1.4. Noise Floor Removal via Phase Correction of Complex Diffusion-Weighted Images: Influence on DTI and q-space Metrics

Participants: Marco Pizzolato, Rutger Fick, Timothé Boutelier [Olea Medical, La Ciotat], Rachid Deriche.

The non-Gaussian noise distribution in magnitude Diffusion-Weighted Images (DWIs) can severely affect the estimation and reconstruction of the true diffusion signal. As a consequence, also the estimated diffusion metrics can be biased. In this work, we study the effect of phase correction, a procedure that re-establishes the Gaussianity of the noise distribution in DWIs by taking into account the corresponding phase images. We quantify the debiasing effects of phase correction in terms of diffusion signal estimation and calculated metrics. We perform in silico experiments based on a MGH Human Connectome Project dataset and on a digital phantom, accounting for different acquisition schemes, diffusion-weightings, signal to noise ratios, and for metrics based on Diffusion Tensor Imaging and on Mean Apparent Propagator Magnetic Resonance Imaging, i.e. q-space metrics. We show that phase correction is still a challenge, but also an effective tool to debias the estimation of diffusion signal and metrics from DWIs, especially at high b-values.

This work has been published in [39] and [60].

7.2. Tissue Microstructures features recovery & applications

7.2.1. MAPL: Tissue microstructure estimation using Laplacian-regularized MAP-MRI and its application to HCP data

Participants: Rutger Fick, Demian Wassermann, Emanuel Caruyer, Rachid Deriche.

The recovery of microstructure-related features of the brain's white matter is a current challenge in diffusion MRI. To robustly estimate these important features from diffusion MRI data, we propose to analytically regularize MAP-MRI's coefficient estimation using the norm of the Laplacian of the reconstructed signal. We first compare our approach, which we call MAPL, with competing state-of-the-art functional basis approaches. We show that it outperforms the original MAP-MRI implementation and the recently proposed modified Spherical Polar Fourier (mSPF) basis with respect to signal fitting, EAP and ODF reconstruction in noisy, sparsely sampled data of a physical phantom with reference gold standard data. Then, to reduce the variance of parameter estimation using multi-compartment tissue models, we propose to use MAPL's signal fitting and extrapolation as a preprocessing step. We study the effect of MAPL on the estimation of axon diameter using a simplified Axcaliber model and axonal dispersion using the Neurite Orientation Dispersion and Density Imaging (NODDI) model. We show the positive effect of using it as a preprocessing step in estimating and reducing the variances of these parameters in the Corpus Callosum of six different subjects of the MGH Human Connectome Project. Finally we correlate the estimated axon diameter, dispersion and restricted volume fractions with Fractional Anisotropy (FA) and clearly show that changes in FA significantly correlate with changes with all estimated parameters. Overall, we illustrate the potential of using a well-regularized functional basis together with multi-compartment approaches to recover important microstructure tissue parameters with much less variability, thus contributing to the challenge of better understanding microstructure-related features of the brain's white matter.

This work has been published in [16]

7.2.2. Quantifying White Matter Microstructure with a Unified Spatio-Temporal Diffusion Weighted MRI Continuous Representation

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

A current problem Diffusion MRI (dMRI) based microscopy under the narrow pulse approximation is how to best exploit the 4D (q-space + diffusion time) nature of the signal. Assaf et al. showed that exploring the dMRI attenuation at different diffusion times provides information on the distribution of axonal diameters within a voxel in their seminal work: AxCaliber. However, AxCaliber requires knowing beforehand the predominant orientation of the axons within the analyzed volume to adjust the q-space sampling accordingly. In this work, we show that our novel sparse representation of the 3D+t dMRI signal, enables the recovery of axonal diameter distribution parameters without the need to know the axonal direction at acquisition time.

This work has been published in [61]

7.2.3. A sensitivity analysis of Q-space Indices with respect to changes in axonal diameter, dispersion and tissue composition

Participants: Rutger Fick, Marco Pizzolato, Demian Wassermann, Mario Zuccheli [Dpt of Computer Science, University of Verona], Gloria Menegaz [Dpt of Computer Science, University of Verona], Rachid Deriche.

In Diffusion MRI, q-space indices are scalar quantities that describe properties of the ensemble average propagator (EAP). Their values are often linked to the axonal diameter – assuming that the diffusion signal originates from inside an ensemble of parallel cylinders. However, histological studies show that these assumptions are incorrect, and axonal tissue is often dispersed with various tissue compositions. Direct interpretation of these q-space indices in terms of tissue change is therefore impossible, and we must treat them as as scalars that only give non-specific contrast – just as DTI indices. In this work, we analyze the sensitivity of q-space indices to tissue structure changes by simulating axonal tissue with changing axonal diameter, dispersion and tissue compositions. Using human connectome project data we then predict which indices are most sensitive to tissue changes in the brain. We show that, in both multi-shell and single-shell (DTI) data, q-space indices have higher sensitivity to tissue changes than DTI indices in large parts of the brain. Based on these results, it may be interesting to revisit older DTI studies using q-space indices as a marker for pathology.

This work has been published in [32]

7.2.4. Assessing the feasibility of estimating axon diameter using diffusion models and machine learning

Participants: Rutger Fick, Neda Sepasian [Eindhoven University of Technology, The Netherlands], Marco Pizzolato, Andrada Ianus [Centre for Medical Image Computing, Dept. of Computer Science, UCL, London, UK], Rachid Deriche.

Axon diameter estimation has been a focus of the diffusion MRI community for the past decade. The main argument has been that while diffusion models always overestimate the true axon diameter, their estimation still correlates with changes in true value. Until now, this remains more as a discussion point. The aim of this paper is to clarify this hypothesis using a recently acquired cat spinal cord data set, where the diffusion MRI signal of both a multi-shell and Ax- Caliber acquisition have been registered with the underlying histology values. We find that the axon diameter as estimated by signal models and AxCaliber does not correlate with their true sizes for axon diameters smaller than 3 microns. On the other hand, we also train a random forest machine learning algorithm to map signal-based features to histology values of axon diameter and volume fraction. The results show that, in this dataset, this approach leads to a more reliable estimation of physically relevant axon diameters than using sophisticated diffusion models.

This work has been submitted to ISBI'2017.

7.2.5. Rotational Invariants of Ternary Quartics

Participants: Paul Görlach, Evelyne Hubert, Théodore Papadopoulo, Rachid Deriche.

This work has been developed in the framework of an "Action Transverse" with the AROMATH team (see section 9.1.1). It aims at creating building blocks for biomarkers for the case of a representation of the diffusion information (acquired using HARDI sequences) as a ternary quartic. Previous work in the team had some drawbacks such as instabilities in the non-polynomial formulae [99] or missing guarantees of the polynomial results [85] (e.g. unknown completeness or impossibility to establish the redundancy of the obtained expressions). This work proposes an alternative construction based on rational expressions and shares some of the best characteristics of the two previous approaches: the set is complete and generative – and thus also generates polynomial invariants –, the number of generators is close to minimal (13 instead of 12 and the expression relating these 13 formulae is known), and has an improved stability compared to the non-polynomial approach. The obtained formulae are furthermore nested making their computation much more effective than previous approaches. Furthermore, the method is generic and can in theory be expanded to higher polynomial degrees.

7.3. Towards microstructural based tractography

7.3.1. White matter tractography guided by anatomical and microstructural priors

Participants: Gabriel Girard [SCIL, Sherbrooke University, CA], Maxime Descoteaux [SCIL, Sherbrooke University, CA], Kevin Whittingstall [SCIL, Sherbrooke University, CA], Rachid Deriche.

Diffusion-weighted magnetic resonance imaging is a unique imaging modality sensitive to the microscopic movement of water molecules in biological tissues. By characterizing the movement of water molecules, it is possible to infer the macroscopic neuronal pathways of the brain. The technique, so-called tractography, had become the tool of choice to study non-invasively the human brain's white matter in vivo. For instance, it has been used in neurosurgical intervention planning and in neurodegenerative diseases monitoring. In this thesis, we report biases from current tractography reconstruction and suggest methods to reduce them. We first use anatomical priors, derived from a high resolution T1-weighted image, to guide tractography. We show that knowledge of the nature of biological tissue helps tractography to reconstruct anatomically valid neuronal pathways, and reduces biases in the estimation of complex white matter regions. We then use microstructural priors, derived from the state-of-the-art diffusionweighted magnetic resonance imaging protocol, in the tractography reconstruction process. This allows tractography to follow the movement of water molecules not only along neuronal pathways, but also in a microstructurally specific environment. Thus, the tractography distinguishes more accurately neuronal pathways and reduces reconstruction errors. Moreover, it provides the mean to study white matter microstructure characteristics along neuronal pathways. Altogether, we show that anatomical and microstructural priors used during the tractography process improve brain's white matter reconstruction

This work has been published in [12].

7.3.2. *Microstructure driven tractography in the human brain*

Participants: Gabriel Girard [SCIL, Sherbrooke University, CA], Alessandro Daducci [SP Lab - Laboratoire de Traitement du signal, EPFL], Kevin Whittingstall [SCIL, Sherbrooke University, CA], Rachid Deriche, Maxime Descoteaux [SCIL, Sherbrooke University, CA], Demian Wassermann.

Diffusion-weighted (DW) magnetic resonance imaging (MRI) tractography has become the tool of choice to probe the human brain's white matter (WM) in vivo. However, the relationship between the resulting streamlines and underlying WM microstructure characteristics, such as axon diameter, remains poorly understood. In this work, we reconstruct human brain fascicles using a new approach to trace WM fascicles while simultaneously characterizing the apparent distribution of axon diameters within the fascicle. This provides the mean to estimate the microstructure characteristics of fascicles while improving their reconstruction in complex tissue configurations.

This work has been published in [24].

7.3.3. *Reducing Invalid Connections with Microstructure Driven Tractography*

Participants: Gabriel Girard [SCIL, Sherbrooke University, CA], Kevin Whittingstall [SCIL, Sherbrooke University, CA], Alessandro Daducci [SP Lab - Laboratoire de Traitement du signal, EPFL], Jean-Philippe Thiran [SP Lab - Laboratoire de Traitement du signal, EPFL], Laurent Petit [GIN - IMN UMR 5293 CNRS CEA Université de Bordeaux], Rachid Deriche, Demian Wassermann, Maxime Descoteaux [SCIL, Sherbrooke University, CA].

Diffusion-weighted imaging (DWI) tractography has become the tool of choice to probe the human brain's white matter (WM) in vivo. However, tractography algorithms produce a large number erroneous/invalid streamlines largely due to complex ambiguous local fiber configurations (e.g. crossing, kissing or fanning). Moreover, the relationship between the resulting streamlines and the underlying WM microstructure characteristics, such as axon diameter, remains poorly understood. The distinctive aspect of our tractography algorithm from previous methods is the active use of microstructure information about fascicles during the tracking. This enables us to solve areas of complex tissue configuration and separate parallel fascicles with different microstructure characteristics, hence improving the overall tractography process.

This work has been published in [35]

7.3.4. *Quantitative evaluation of Fiber Orientations Extractions*

Participants: Thinhinane Megherbi [LRPE, USTHB, Alger], Gabriel Girard [SCIL, Sherbrooke University, CA], Maxime Descoteaux [SCIL, Sherbrooke University, CA], Fatima Oulebsir Boumghar [LRPE, USTHB, Alger], Rachid Deriche.

Recovering the fiber orientations in each voxel constitutes an important step for the fiber tracking algorithms. In fact, the reliability of the resulted connectivity depends on how well the local fiber orientations were extracted. Based on the tractography results we evaluated and compared different methods of fiber orientations extraction. Thus, we analyzed quantitatively the resulted connectivity by using the Tractometer tool. This later allows by measuring a number of metrics to quantify the connections reliability and the tractography performance. All the methods of fiber orientations extraction were evaluated on two types of tractography algorithms, deterministic and probabilistic algorithms. Furthermore, all of these methods have been executed on two types of data, high angular resolution data acquired with 60 gradient directions and low angular resolution data, acquired with 30 gradient directions. These two types of data were corrupted with a Ricien noise of ratio SNR=20, 10. In this work, we present the results obtained by our validation and comparison work.

This work has been published in [37]

7.4. Perfusion MRI & PLI

7.4.1. Unveiling the dispersion kernel in DSC-MRI by means of dispersion-compliant bases and control point interpolation techniques

Participants: Marco Pizzolato, Rutger Fick, Timothé Boutelier [Olea Medical, La Ciotat], Rachid Deriche.

In DSC-MRI the presence of dispersion affects the estimation, via deconvolution, of the residue function that characterizes the perfusion in each voxel. Dispersion is descibed by a Vascular Transport Function (VTF) which knolewdge is essential to recover a dispersion-free residue function. State-of-the-art techniques aim at characterizing the VTF but assume a specific shape for it, which in reality is unknown. We propose to estimate the residue function without assumptions by means of Dispersion-Compliant Bases (DCB). We use these results to find which VTF model better describes the in-vivo data for each tissue type by means of control point interpolation approaches.

This work has been published in [57].

7.4.2. Elucidating dispersion effects in perfusion MRI by means of dispersion-compliant bases

Participants: Marco Pizzolato, Rutger Fick, Timothé Boutelier [Olea Medical, La Ciotat], Rachid Deriche.

Dispersion effects in perfusion MRI data have a relevant influence on the residue function computed from deconvolution of the measured arterial and tissular concentration time-curves. Their characterization allows reliable estimation of hemodynamic parameters and can reveal pathological tissue conditions. However the time-delay between the measured concentration time-curves is a confounding factor. We perform deconvolution by means of dispersion-compliant bases, separating dispersion from delay effects. In order to characterize dispersion we introduce shape parameters, such as the dispersion time and index. We propose a new formulation for the dispersed residue function and perform in-silico experiments that validate the reliability of our approach against the block-circulant Singular Value Decomposition. We successfully apply the approach to stroke MRI data and show that the calculated parameters are coherent with physiological considerations, highlighting the importance of dispersion as an effect to be measured rather than discarded.

This work has been published in [38].

7.4.3. Improved vascular transport function characterization in DSC-MRI via deconvolution with dispersion-compliant bases

Participants: Marco Pizzolato, Rutger Fick, Timothé Boutelier [Olea Medical, La Ciotat], Rachid Deriche.

Bolus dispersion phenomena affect the residue function computed via deconvolution of DSC-MRI data. Indeed the obtained effective residue function can be expressed as the convolution of the true one with a Vascular Transport Function (VTF) that characterizes the dispersion. The state-of-the-art technique CPI+VTF allows to estimate the actual residue function by assuming a model for the VTF. We propose to perform deconvolution representing the effective residue function with Dispersion-Compliant Bases (DCB) without assumptions on the VTF, and then apply the CPI+VTF on DCB results. We show that DCB improve robustness to noise and allow to better characterize the VTF.

This work has been published in [60].

7.4.4. Perfusion Deconvolution in DSC-MRI with Dispersion-Compliant Bases

Participants: Marco Pizzolato, Timothé Boutelier [Olea Medical, La Ciotat], Rachid Deriche.

Perfusion imaging of the brain via Dynamic Susceptibility Contrast MRI (DSC-MRI) allows characterization of tissue perfusion by recovering the tissue impulse response function and scalar parameters such as the cerebral blood flow (CBF), blood volume (CBV) and mean transit time (MTT). However, the presence of bolus dispersion causes the data to reflect macrovascular properties, in addition to tissue perfusion. In this case, when performing deconvolution of the measured arterial and tissue concentration time-curves it is only possible to recover the effective, i.e. dispersed, response function and parameters. We introduce Dispersion-Compliant Bases (DCB) to represent the response function in the presence and absence of dispersion. We perform in silico and in vivo experiments, and show that DCB deconvolution outperforms oSVD and the state-of-the-art CPI+VTF techniques in the estimation of effective perfusion parameters, regardless of the presence and amount of dispersion. We also show that DCB deconvolution can be used as a pre-processing step to improve the estimation of dispersion-free parameters computed with CPI+VTF, which employs a model of the vascular transport function to characterize dispersion. Indeed, in silico results show a reduction of relative errors up to 50% for dispersion-free CBF and MTT. Moreover, the DCB method recovers effective response functions that comply with healthy and pathological scenarios, and offers the advantage of making no assumptions about the presence, amount, and nature of dispersion.

This work has been submitted for publication in Medical Image Analysis.

7.4.5. Solving the inclination sign ambiguity in three dimensional polarized light imaging with a PDE-based method

Participants: Abib Olushola Yessouffou Alimi, Marco Pizzolato, Rutger Fick, Rachid Deriche.

Three dimensional Polarized Light Imaging (3D-PLI) is a contrast-enhancing technique that measures the spatial fiber architecture in the postmortem human brain or heart at a sub-millimeter resolution. In a voxel, the 3D fiber orientation is defined by the direction angle and the inclination angle whose sign is unknown. To have an accurate explanation of fiber orientation, it is compulsory to clear up this sign ambiguity. A tilting process provides information about the true inclination sign, however the technique is highly sensitive to noise. In this work, a partial differential equations based method is proposed to reduce the noise: the total variation model of Rudin-Osher-Fatemi is extended to 3D orientation vector images to restore the sign. The proposed algorithm is evaluated on synthetic and human heart data and results show that the true sign of the inclination angle can be successfully extracted

This work has been submitted to ISBI'2017.

7.5. Structural Connectivity Network

7.5.1. Extracting the Core Structural Connectivity Network: Guaranteeing Network Connectedness Through a Graph-Theoretical Approach

Participants: Demian Wassermann, Dorian Mazauric [ABS Project Team], Guillermo Gallardo Diez, Rachid Deriche.

In this work, we present a graph-theoretical algorithm to extract the connected core structural connectivity network of a subject population. Extracting this core common network across subjects is a main problem in current neuroscience. Such network facilitates cognitive and clinical analyses by reducing the number of connections that need to be explored. Furthermore, insights into the human brain structure can be gained by comparing core networks of different populations. We show that our novel algorithm has theoretical and practical advantages. First, contrary to the current approach our algorithm guarantees that the extracted core subnetwork is connected Girardagreeing with current evidence that the core structural network is tightly connected. Second, our algorithm shows enhanced performance when used as feature selection approach for connectivity analysis on populations.

This work has been published in [26].

7.5.2. Groupwise Structural Parcellation of the Cortex: A Sound Approach Based on Logistic Models

Participants: Guillermo Gallardo Diez, Rutger Fick, William Wells, Rachid Deriche, Demian Wassermann.

Current theories hold that brain function is highly related with long-range physical connections through axonal bundles, namely extrinsic connectivity. However, obtaining a groupwise cortical parcellation based on extrinsic connectivity remains challenging. Current parcellation methods are computationally expensive; need tuning of several parameters or rely on ad-hoc constraints. Furthermore, none of these methods present a model for the cortical extrinsic connectivity. To tackle these problems, we propose a parsimonious model for the extrinsic connectivity and an efficient parceling technique based on clustering of tractograms. Our technique allows the creation of single subject and groupwise parcellations of the whole cortex. The parcellations obtained with our technique are in agreement with structural and functional parcellations in the literature. In particular, the motor and sensory cortex are subdivided in agreement with the human homunculus of Penfield. We illustrate this by comparing our resulting parcels with the motor strip mapping included in the Human Connectome Project data.

This work has been published in [33] and an extended version has been submitted to Neuroimage.

7.5.3. Efficient Population-Representative Whole-Cortex Parcellation Based on Tractography

Participants: Guillermo Gallardo Diez, Rachid Deriche, Demian Wassermann.

The human brain is arranged in areas based on criteria such as cytoarchitecture or extrinsic connectivity. Current hypotheses attribute specialized functions to several areas of this patchwork. Hence, parcellating the cortex into such areas and characterizing their interaction is key to understanding brain function. Diffusion MRI enables the exploration of physical connections through axonal bundles, namely extrinsic connectivity. Current theories hold that brain function is determined by extrinsic connectivity. However, obtaining a population-representative parcellation based on extrinsic connectivity remains challenging (Jbabdi 2013). Particularly, whole-cortex parcellation methods (Moreno-Dominguez 2014; Parisot 2015) are computationally expensive and need tuning of several parameters. Our main contribution is an efficient technique to create single-subject and population-representative parcellations based on tractography. Our method creates a dendrogram using only one parameter: the minimum size of each parcel. Then, by choosing cutting criteria, we can explore different parcellation granularities without recomputing the dendrogram. Experiments show that our parcellations are consistent within subjects with anatomical (Desikan 2006) and functional (Barch 2013) parcellations existent in the literature.

This work has been published in [34].

7.6. Clinical and Neurocognitive Applications of Diffusion MRI

7.6.1. Brain correlates of apathy in Kleine Levin syndrome: a mean apparent propagator study

Participants: Anne-Charlotte Philippe [ICM, CENIR, Paris], Sophie Lavault [ICM, CENIR, Paris], Rutger Fick, Demian Wassermann, Romain Valabregue [ICM, CENIR, Paris], Richard Levy [ICM, CENIR, Paris], Isabelle Arnulf [ICM, CENIR, Paris], Stéphane Lehericy [ICM, CENIR, Paris], Rachid Deriche.

Kleine-Levin syndrome (KLS) is a rare neurological disorder characterized by episodes of severe hypersomnia, apathy, cognitive impairment, derealization and behavioral disturbances. Between episodes, patients have normal sleep, mood and behavior. Apathy is a prominent clinical feature of KLS but its pathophysiology is not known. Here we used mean apparent propagator to investigate white matter changes in KLS and correlated diffusion changes with apathy scores. Results showed that the corpus callosum was involved in KLS during episodes and mean RTAP measures in the corpus callosum correlated with apathy scores. Results were in accordance with known motivation-based circuits involving the orbitomedial frontal cortex.

This work has been submitted to ISMRM'2017.

7.6.2. Comparison of Biomarkers in Transgenic Alzheimer Rats Using Multi-shell Diffusion MRI

Participants: Rutger Fick, Madelaine Daianu [Imaging Genetics Center, Mark & Mary Stevens Neuroimaging & Informatics Institute, USC, USA], Marco Pizzolato, Demian Wassermann, Russel Jacobs [Imaging Genetics Center, Mark & Mary Stevens Neuroimaging & Informatics Institute, USC, USA], Paul Thompson [Imaging Genetics Center, Mark & Mary Stevens Neuroimaging & Informatics Institute, USC, USA], Terrence Town [Imaging Genetics Center, Mark & Mary Stevens Neuroimaging & Informatics Institute, USC, USA], Rachid Deriche.

In this study, we assessed the evolution of diffusion MRI (dMRI) derived markers from different white matter models as progressive neurodegeneration occurs in transgenic Alzheimer rats (TgF344-AD) at 10, 15 and 24 months. We compared biomarkers reconstructed from Diffusion Tensor Imaging (DTI), Neurite Orientation Dispersion and Density Imaging (NODDI) and Mean Apparent Propagator (MAP)-MRI in the hippocampus, cingulate cortex and corpus callosum using multi-shell dMRI. We found that NODDI's dispersion and MAP-MRI's anisotropy markers consistently changed over time, possibly indicating that these measures are sensitive to age-dependent neuronal demise due to amyloid accumulation. Conversely, we found that DTI's mean diffusivity, NODDI's isotropic volume fraction and MAP-MRI's restriction-related metrics all followed a two-step progression from 10 to 15 months, and from 15 to 24 months. This two-step pattern might be linked with a neuroinflammatory response that may be occuring prior to, or during microstructural breakdown. Using our approach, we are able to provide for the first time-preliminary and valuable insight on relevant biomarkers that may directly describe the underlying pathophysiology in Alzheimer's disease.

This work has been published in [30].

7.7. MEEG and Diffusion MRI

7.7.1. Cortical surface parcellation via dMRI using mutual nearest neighbor condition

Participants: Brahim Belaoucha, Maureen Clerc, Théodore Papadopoulo.

This work aims at parcellating the cortical surface from individual anatomy. With respact to previous works, it works for the whole brain and produces connected patches. The parcellation is obtained using the Mutual Nearest Neighbor (MNN) criterion to obtain regions with similar structural connectivity. The structural connectivity is obtained by applying a probabilistic tractography on the diffusion MRI (dMRI). Several similarity measures of connectivity are compared. The results of our method are compared to some of the atlases that can be found in the literature. We show that these atlases have lower similarity of structural connectivity than the proposed algorithm implying that the regions of the atlases may have lower functional homogeneity.

This work has been published in [27].

7.7.2. Iterative estimation of focal sources and their interactions constrained by dMRI

Participants: Brahim Belaoucha, Mouloud Kachouane, Théodore Papadopoulo.

This work aims at further exploiting the dMRI constraints: not only sources are constrained anatomically by patches (extracted by the method of the previous paragraph) but their dynamical behaviour is constrained by a brain network extracted from an individual dMRI. The framework reconstructs spatially localized sources from Magnetoencephalogra-phy (MEG)/Electroencephalography (EEG) using spatiotemporal constraints extracted from dMRI. The spatial reconstruction is based on our previous work on patch reconstruction [71]. The source dynamics are represented by a Multivariate Autoregressive (MAR) model whose matrix elements are constrained by the anatomical connectivity obtained from dMRI. The framework assumes that the whole brain dynamic follows a constant MAR model in a time window of interest. The source activations and the MAR model parameters are estimated iteratively. The proposed framework outperforms the two-stage approaches which have traditionally been used to estimate source interactions. Such approaches first reconstruct sources and then compute the MAR model for the localized sources. They showed good results when working in high signal-to-noise ratio (SNR) settings, but fail in detecting the true interactions when working in low SNR. Our framework iteratively refines both the reconstruction and the MAR model in two steps: sources activations are first estimated for a given MAR model and then, the MAR model is estimated for a given source reconstruction. These two steps are repeated until a stopping criterion is achieved. The work is exploratory in nature and for now focuses on simulations made with real MR data. We could confirm that accurate reconstructions and MAR models can be obtained with our method in both high and low noise levels.

This work has been published in [28], [21].

7.8. MEG, EEG

7.8.1. ECoG

Participants: Maureen Clerc, Analisa Pascarella [CNR-IAC Roma], Michele Piana [University of Genova].

Electrocorticography (ECoG) measures the distribution of the electrical potentials on the cortex produced by the neural currents. A full interpretation of ECoG data requires solving the ill-posed inverse problem of reconstructing the spatio-temporal distribution of the neural currents. This study addresses the ECoG source modeling developing a beamformer method. New method: We computed the lead-field matrix by using a novel routine provided by the OpenMEEG software. We performed an analysis of the numerical stability of the ECoG inverse problem by computing the condition number of the lead-field matrix for different configurations of the electrodes grid. We applied a Linear Constraint Minimum Variance (LCMV) beamformer to both synthetic data and a set of real measurements recorded during a rapid visual categorization task. For all considered grids the condition number indicates that the ECoG inverse problem is mildly ill-conditioned. For realistic SNR we found a good performance of the LCMV algorithm for both localization and waveforms reconstruction. Comparison with existing method: The flow of information reconstructed by analyzing real data seems consistent with both invasive monkey electrophysiology studies and non-invasive (MEG and fMRI) human studies. Despite a growing interest from the neuroscientific community, solving the ECoG inverse problem has not quite yet reached the level of systematicity found for EEG and MEG. Starting from an analysis of the numerical stability of the problem we considered the most widely utilized method for modeling neurophysiological data based on the beamformer method in the hope to establish benchmarks for future studies.

This work has been published in [18].

7.8.2. Conductivity estimation

Participants: Maureen Clerc, Christos Papageorgakis, Juliette Leblond [APICS project-team], Jean-Paul Marmorat [CMA Ecole des Mines Paritech].

Considering a geometry made of three concentric spherical nested layers, each with constant homogeneous conductivity, we establish a uniqueness result in inverse conductivity estimation, from partial boundary data in presence of a known source term. We make use of spherical harmonics and linear algebra computations, that also provide us with stability results and a robust reconstruction algorithm. As an application to electroencephalography (EEG), in a spherical 3-layer head model (brain, skull, scalp), we numerically estimate the skull conductivity from available data (electrical potential at electrodes locations on the scalp, vanishing current flux) and given pointwise dipolar sources in the brain. This work was supported by the Région Provence-Alpes-Côte d'Azur, France, and BESA GmbH, Germany.

This work has been published in [14] and [29].

7.8.3. Efficient lead field computation a la Reduced Basis Methods

Participants: Kostiantyn Maksymenko, Maureen Clerc, Théodore Papadopoulo.

Bioelectric source analysis in the human brain from scalp electroencephalography (EEG) signals is sensitive to geometry and conductivity properties of the different head tissues. These conductivities can vary a lot across subjects so non-invasive methods of conductivity estimation are required. To achieve this, we should have a possibility to compute a forward EEG problem solution for a large number of conductivity configurations. We propose a method of approximation of these solutions using a relatively small number of basis points, which will allow us to dramatically decrease required computing time.

7.9. Modeling electrical stimulation

7.9.1. Cochlear implants

Participants: Kai Dang, Maureen Clerc, Pierre Stahl [Oticon Medical], Dan Gnansia [Oticon Medical], Clair Vandersteen [Nice University Hospital], Nicolas Guevara [Nice University Hospital].

In cochlear implants, the hybrid common ground is a combination of a classic monopolar stimulation with a standard common ground. This new stimulation montage allows the current to return from both the non-stimulating electrodes on the electrode array and the reference electrode placed between the skull and scalp. In theory, this lead to reach a compromise between the current focality and the efficiency of the stimulation. Even if this stimulation type has already been adopted by some implant manufacturers, the 3D geometry of its current pathways remains to be studied. The study is two-fold. First, an in-vitro experiment aimed to measure the electrical field produced by the hybrid common ground stimulation. An electrode array of an XP implant (Oticon Medical, Neurelec) was placed in saline solution and the electrical field was recorded by a probe that moves along the programmed grid. During the stimulation, the current waveforms on all the grounding electrodes were also recorded. Second, an in-situ measurement was conducted. Another XP device was implanted into a human specimen. The same procedure as in the in-vitro measurement was performed to record, this time, the current waveforms only. The recorded two groups of current data were compared with each other to investigate how the current path is modified by the geometry of a human cochlea. The potential distribution measured during the in-vitro experiment was also compared with other stimulation types such as monopolar. The energy consumption of the stimulation was also computed from the collected data.

This work has been published in [58]. We thank the GRAPHDECO project-team for lending us THE 3D printer which was used in the in-vitro experiment.

7.10. Brain-Computer Interfaces

7.10.1. A new reference book in Brain-Computer Interfaces

Participants: Maureen Clerc, Laurent Bougrain [Neurosys project-team], Fabien Lotte [POTIOC project-team], All Ipl Bci-Lif Members.

Most of the results in Brain-Computer Interfaces are conducted in the context of the Inria Project-Lab BCI-LIFT (see contracts section). Researchers of this Inria Project-Lab (Maureen Clerc, Laurent Bougrain and Fabien Lotte) have edited a reference book in 2016 on the topic of Brain-Computer Intefaces. It consists of two volumes, “Foundations and Methods” (in French [54] and in English [1]) and “Technology and Applications” (in French [55] and in English [53]).

7.10.2. A Separability Marker Based on High-Dimensional Statistics for Classification Confidence Assessment

Participants: Nathalie Gayraud, Maureen Clerc, Nathanaël Foy, Alain Rakotomamonjy [University of Rouen].

This work provides a theoretical analysis framework for features that belong to the high dimensional Riemannian manifold of symmetric positive definite matrices. In non-invasive EEG-based Brain Computer Interfaces, such as the P300 speller, these are sample covariance matrices of the epoched EEG signal that are classified into two classes. An analysis of the class shape on the manifold is performed, and the separability level of the two classes is evaluated. The main contribution is the Separability Marker (SM)-confidence method, a method that appends a confidence marker to the prediction of a binary classifier whose decision function is based on the comparison of Riemannian distances.

This work has been published in [23].

7.10.3. Comparison of Hierarchical and Non-Hierarchical Classification for Motor Imagery Based BCI Systems

Participants: Nathalie Gayraud, Maureen Clerc, Cecilia Lindig-León [Neurosys project-team], Laurent Bougrain [Neurosys project-team].

Motor imagery (MI) based BCI systems record and analyze the brain activity to determine users' intentions while imagining moving some parts of their body. In order to build systems that are able to detect several commands, multiclass schemes need to be applied. Hierarchical methods allow solving multiclass problems by using a tree of binary classifiers, whose root discriminates between two groups, each one containing a half of the classes. Each succeeding node includes again only one half of the classes from the selected group, and the process is recursively repeated until each node contains a single class, from which the final decision can be inferred. In this study we compare a series of multiclass approaches to assert the benefits of hierarchical classification. The compared methods are based on two effective techniques for MI-discrimination, namely, Common Spatial Patterns (CSP) and Riemannian geometry, for which the hierarchical and non-hierarchical approaches have been considered. We include the CSP by Joint Diagonalization method (CSP by JAD), which corresponds with a non-hierarchical approach; and its hierarchical counterpart, namely, Binary CSP. In addition, the non-hierarchical Minimum Distance to Riemannian Mean method (MDRM) [4] is also evaluated, together with its analogous hierarchical approach; a contribution of the present work called Hierarchical MDRM algorithm (HMDRM). All these methods have been applied on dataset 2a of the BCI competition IV to facilitate their comparison. The highest accuracies were reached by the BCSP and HMDRM methods, confirming the effectiveness of hierarchical algorithms.

This work has been published in [36].

7.10.4. Motor imagery learning using Functional Electrical Stimulation

Participants: Maureen Clerc, Saugat Bhattacharyya [CAMIN project-team], Mitsuhiro Hayashibe [CAMIN project-team].

Functional Electrical Stimulation (FES) stimulates the affected region of the human body thus providing a neuroprosthetic interface to non-recovered muscle groups. FES in combination with Brain-computer interfacing (BCI) has a wide scope in rehabilitation because this system can directly link the cerebral motor intention of the users with its corresponding peripheral mucle activations. Such a rehabilitative system would contribute to improve the cortical and peripheral learning and thus, improve the recovery time of the patients. In this paper, we examine the effect of electrical stimulation by FES on the electroencephalography (EEG) during learning of a motor imagery task. The subjects are asked to perform four motor imagery tasks over six sessions and the features from the EEG are extracted using common spatial algorithm and decoded using linear discriminant analysis classifier. Feedback is provided in form of a visual medium and electrical stimulation representing the distance of the features from the hyperplane. Results suggest a significant improvement in the classification accuracy when the subject was induced with electrical stimulation along with visual feedback as compared to the standard visual one.

This work has been published in [13] and [22].

7.10.5. Brain training with neurofeedback

Participants: Maureen Clerc, Lorraine Perronnet [Hybrid project-team], Anatole Lécuyer [Hybrid project-team], Fabien Lotte [Potioc project-team], Christian Barillot [Visages project-team].

Neurofeedback is a promising tool for brain rehabilitation and peak performance training. Neurofeedback approaches usually rely on a single brain imaging modality such as EEG or fMRI. Combining these modalities for neurofeedback training could allow to provide richer information to the subject and could thus enable him/her to achieve faster or more specific self-regulation. Yet unimodal and multimodal neurofeedback have never been compared before. In the present work, we introduce a simultaneous EEG-fMRI experimental protocol in which participants performed a motor-imagery task in unimodal and bimodal NF conditions. With this protocol we were able to compare for the first time the effects of unimodal EEG-neurofeedback and fMRI-neurofeedback versus bimodal EEG-fMRI-neurofeedback by looking both at EEG and fMRI activations. We also propose a new feedback metaphor for bimodal EEG- fMRI-neurofeedback that integrates both EEG and fMRI signal in a single bi-dimensional feedback (a ball moving in 2D). Such a feedback is intended to relieve the cognitive load of the subject by presenting the bimodal neurofeedback task as a single regulation task instead of two. Additionally, this integrated feedback metaphor gives flexibility on defining a bimodal neurofeedback target. Participants were able to regulate activity in their motor regions in all NF conditions. Moreover, motor activations as revealed by offline fMRI analysis were stronger during EEG-fMRI-neurofeedback than during EEG-neurofeedback. This result suggests that EEG-fMRI-neurofeedback could be more specific or more engaging than EEG-neurofeedback. Our results also suggest that during EEG-fMRI-neurofeedback, participants tended to regulate more the modality that was harder to control. Taken together our results shed light on the specific mechanisms of bimodal EEG-fMRI-neurofeedback and on its added-value as compared to unimodal EEG-neurofeedback and fMRI-neurofeedback.

This work has been published in [51] and [50].

7.10.6. Out-of-the-lab P300 speller

Participants: Maureen Clerc, Théodore Papadopoulo, Nathanaël Foy, Federica Turi, Étienne Guerlais.

New developments have been performed in the context of ADT OpenViBE-X to robustify the P300 speller system, correcting some timing issues (in OpenViBE), and making the system easier to use and install. This has been validated by the use of our system out-of-the-lab, by a patient in Chambéry (see article [104]).

This work has been published in [48]and [49].

7.10.7. Clinical study with the CoAdapt P300 speller

Participants: Maureen Clerc, Théodore Papadopoulo, Marie-Hélène Soriani [Nice University Hospital], Claude Desnuelle [Nice University Hospital], Violaine Guy [Nice University Hospital], Mariane Bruno [Nice University Hospital].

Amyotrophic Lateral Sclerosis (ALS) is a progressive neurodegenerative disease which, a few years after onset, restricts patients' communication capacity. In this study, the usability by disabled patients with ALS of a visual Brain-Computer Interface (BCI), the P300-speller, is evaluated as a viable alternative to existing assistive communication tools. After clinical evaluation of their physical, cognitive and language capacities, 20 patients with ALS were included. The study consisted of two 3-block sessions, at 2 to 4-week interval, using a P300-speller BCI in several modes of operation in view of evaluating its usability in its 3 components: effectiveness, efficiency and satisfaction. Over all participants, the system is effective (100% of participants successfully achieved copy spelling and free spelling tasks). It is also efficient (over 95% of correct symbols were selected by 65% of participants). The average number of correct symbols/min ranged from 3.6 (without word prediction) to 5.04 (with word prediction). Participants expressed satisfaction through an average of 8.7/10 measuring comfort, ease of use and utility. Patients quickly learned how to operate this system and were able to use it with good performance without much learning effort. Word prediction and other algorithmic optimizations improve the information transfer rate and make such systems competitive with existing solutions of alternative communication such as eye trackers.

This work was published in [25].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Grants with Industry

- The Olea Medical company from La Ciotat (FR) funds 50% of the PhD of Marco Pizzolato, supervised by Rachid Deriche, which is funded by the PACA Region for the remaining 50%.
- The dMRI Library has been transfered to the Olea Medical company.

- The BESA company (Brain Electrical Source Analysis) from Germany funds 50% of the PhD of Christos Papageorgakis, co-supervised by Maureen Clerc (Athena) and Juliette Leblond (Apics), which is funded by the PACA Region for the remaining 50%.
- The Neurelec company (Cochlear Implants) has obtained a CIFRE PhD funding for Kai Dang, supervised by Maureen Clerc.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. Inria SAM Action Transverse

Participants: Paul Görlach, Evelyne Hubert [Aromath project team], Théodore Papadopoulo, Rachid Deriche.

Finding biomarkers of abnormalities of the white matter is one important problem in dMRI processing. As these biomarkers need to be independent of the orientation of the head, they are functions of the rotational invariants of the shapes that characterize the diffusion probabilities in the white matter. While the situation is well understood for second order tensors, these are not powerful enough to represent crossings in the white matter. Acquisitions made with the HARDI scheme allow for a richer description of probabilities, which have been modelled in the literature team as (positive) ternary quartics (tensors of order 4). But invariants of these quartics are not well known. For a long period, only six (out of 12 in theory) were known. Previous work in the ATHENA team developed some new strategies to compute more invariants. But these were ever non-polynomial and had some stability problems [99]. Another strategy [85] was leading to polynomial and stable invariants, but the approach was generating a number of invariants (more than 12) for which it was impossible to extract an irreducible family. The goal of this "Transverse action" was to join forces with the team AROMATH and leverage the methods they developed [87], [88], [86] to have a better insight in this problem of rotational invariants of ternary quartics.

9.1.2. Inria SAM Action Marquante

Participants: Demian Wassermann, Maureen Clerc, Théodore Papadopoulo, Amandine Audino.

Duration: *october 2016 to January 2018*

Elucidating the structure-function relationship of the brain is one of the main open question in neuroscience. The capabilities of diffusion MRI-based techniques to quantify the connectivity strength between brain areas, namely structural connectivity (SC), in combination with modalities such as electro encephalography (EEG) to quantify brain function have enabled advances in this field. However, the actual relationship between these SC measures and measures of information transport between neuronal patches is still far from being determined.

In this project, we will address this problem by establishing a relationship between diffusion MRI (dMRI) SC measures and electrical conductivity on the human brain cortex. We will exploit the Athena's competences in dMRI (Deriche-Wassermann) and EEG (Clerc-Papadopoulo) and our collaboration with the neurosurgical service at CHU Nice (Fontaine-Almairac). In successfully addressing this problem, we will set the bases to solve the current open problem of non-invasively measuring cortico-cortical (CC) connectivity in the human brain. This will boost the understanding of cognitive function as well as neurosurgical planning for the treatment of pathologies such as drug-resistant epilepsy and resection of glioblastomas.

9.2. National Initiatives

9.2.1. Inria Project Lab

9.2.1.1. IPL BCI-LIFT

Participants: Maureen Clerc, Théodore Papadopoulo, Nathanaël Foy, Nathalie Gayraud, Federica Turi.

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. For more information, refer to the BCI-LIFT website.

9.2.2. ANR

9.2.2.1. ANR MRSEI LEMONS

Participants: Maureen Clerc, Théodore Papadopoulo.

Duration:*october 2015 to april 2017* The ANR MRSEI LEMONS aims to consolidate a European Network by organizing meetings and visits, in order to submit a proposal for a MSCA-ITN. The European consortium is led by Inria (coordinator Maureen Clerc).

9.2.2.2. ANR MOSIFAH

Participants: Rachid Deriche, Rutger Fick, Demian Wassermann, Maureen Clerc, Théodore Papadopoulo.

Duration: *October 2013 to September 2017*

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.

Appropriate diffusion models will be explored including second and fourth order DTI models as well as HARDI models such as the single shell Q-Ball Imaging (QBI). These various types of images will be processed within the right Riemannian mathematical framework to provide tensor as well as Ensemble Average Propagator (EAP) and Orientation Distribution Function (ODF) fields. Virtual cardiac fiber structure (VCFS) will then be modelled using myocardial fiber information derived from each of these imaging modalities. Finally, diffusion behavior of water molecules in these VCFSs will be simulated by means of quantum spin theory, which allows computing ex vivo and in vivo virtual diffusion magnetic resonance (MR) images at various scales ranging from a few microns to a few millimeters. From the obtained virtual diffusion MR images, multiscale and probabilistic atlas describing the 3D fiber architecture of the heart ex vivo and in vivo will be constructed. Meanwhile, the simulation involving a large number of water molecules, grid computing will be used to cope with huge computation resource requirement.

We expect to construct a complete database containing a very wide range of simulated (noise and artifact-free) diffusion images that can be used as benchmarks or ground-truth for evaluating or validating diffusion image processing algorithms and create new virtual fiber models allowing mimicking and better understanding the heart muscle structures. Ultimately, the proposed research can open a completely novel way to approach the whole field of heart diseases including the fundamental understanding of heart physiology and pathology, and new diagnosis, monitoring and treatment of patients.

9.2.2.3. ANR VIBRATIONS

Participants: Théodore Papadopoulo, Maureen Clerc, Rachid Deriche, Demian Wassermann.

Duration: *February 2014 to January 2018*

Computational modeling, under the form of a “virtual brain” is a powerful tool to investigate the impact of different configurations of the sources on the measures, in a well-controlled environment.

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.

The project follows a three-fold strategy:

- construct virtual brain models with both dynamic aspects (reproducing both hyperexcitability and hypersynchronisation alterations observed in the epileptic brain) and a realistic geometry based on actual tractography measures performed in patients
- explore the parameter space though large-scale simulations of source configurations, using parallel computing implemented on a computer cluster.
- confront the results of these simulations to simultaneous recordings of EEG, MEG and intracerebral EEG (stereotactic EEG, SEEG). The models will be tuned on SEEG signals, and tested versus the surface signals in order to validate the ability of the models to represent real MEG and EEG signals.

The project constitutes a translational effort from theoretical neuroscience and mathematics towards clinical investigation. A first output of the project will be a database of simulations, which will permit in a given situation to assess the number of configurations that could have given rise to the observed signals in EEG, MEG and SEEG. A second – and major - output of the project will be to give the clinician access to a software platform which will allow for testing possible configurations of hyperexcitable regions in a user-friendly way. Moreover, representative examples will be made available to the community through a website, which will permit its use in future studies aimed at confronting the results of different signal processing methods on the same 'ground truth' data.

9.2.3. ADT

9.2.3.1. ADT BOLIS

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

Duration: *December 2014 to December 2016*

ADT BOLIS aims to:

- build a sofware platform dedicated to inverse source localisation, building upon the elements of software found in FindSources3D. The platform will be modular, ergonomic, accessible and interactive. It will offer a detailed visualisation of the processing steps and the results. The 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).
- Upgrade medInria to use the latest libraries versions involved (this most notably encompasses VTK 6, Qt 5, and DTK 1.0). Then, these new versions will be used to implement a composer (a graphical tool to chain various actions in medInria) and to develop python scripting (for chaining actions and for adding non-regression testing).

9.2.3.2. ADT OpenViBE-X

Participants: Théodore Papadopoulo, Maureen Clerc, Nathanaël Foy.

Duration: *October 2014 to October 2016*

The OpenViBE-X ADT addresses the OpenViBE Brain Computer Interfaces (BCI) platform, in order to:

1. make BCI easier to apprehend by end-users
2. enrich the interaction with multimodal biosignals (eye gaze, heart-rate)
3. implement methods for auto-calibration and online adaptation of the classification
4. provide support, maintenance and dissemination for this software.

The OpenViBE platform is a central element to BCI research at Inria, and in the international community.

9.2.4. Other Funding Programs

9.2.4.1. Big Brain Theory: MAXIM'S

Participants: Demian Wassermann, Alexandra Petiet [ICM, CENIR, Paris], Stéphane Lehericy [ICM, CENIR, Paris], Julien Valette [Institut d'Imagerie Biomédicale, CEA, France], Virginie Callot [Center for Magnetic Resonance in Biology and Medicine - UMR 7339,Center for Magnetic Resonance in Biology and Medicine - UMR 7339].

Shedding light on the specificity of microstructural MRI biomarkers of axonal and myelin integrity using multi-modal imaging in rodents and quantitative histological correlations.

Magnetic Resonance Imaging (MRI) biomarkers (BMs) of axonal and myelin integrity suffer from lack of specificity at the microstructural level, which hinders our understanding of disease mechanisms. A better knowledge of the role of the white matter (WM) microstructure in normal and abnormal function relies on the development of MRI metrics that can provide (i) increased specificity to distinct attributes of WM such as local fiber architecture, axon morphology, myelin content, and (ii) specific markers of axonal vs. myelin pathologies. Advanced diffusion-weighted (DW) imaging techniques based on biophysical models of cerebral tissues and cellular compartments can extract for example mean axonal diameters or cellular geometry. In addition, diffusion-weighted spectroscopy (DWS) offers new insights into the diffusion properties of intracellular metabolites. More specifically, probing metabolite diffusion at different time scales allows assessing fiber diameter and length, and the specific compartmentalization of different metabolites in different cell types allows differentiating between astrocytic and neuronal microstructural parameters. Although very promising, these novel techniques still need extensive histological validation.

We propose to develop these two cutting-edge MRI techniques – DW-MRI and DWS, at 11.7T to investigate axonopathy and myelinopathy in well-established mouse models with a single lesion type, and to validate these new microstructural BMs with multivariate quantitative histological analyses.

Duration: *March 2016 to March 2019*

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. 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 comput ational nature and added clini cal value** will open new perspectives in neuroimaging.

9.3.1.2. ChildBrain ETN

ATHENA is an Associated Partner in this European Training Network: the team will participate 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.

9.4. International Initiatives

9.4.1. Inria Associate Teams Not Involved in an Inria International Labs

9.4.1.1. LargeBrainNets

Title: Characterizing Large-scale Brain Networks Using Novel Computational Methods for dMRI and fMRI-based Connectivity

International Partner (Institution - Laboratory - Researcher):

Stanford (United States) - Stanford Cognitive and Systems Neuroscience Laboratory - Vinod Menon

Start year: Jan. 2016

Partners: ATHENA project-team,

See also: http://www-sop.inria.fr/members/Demian.Wassermann/large-brain-nets.html

In the past two decades, brain imaging of neurotypical individuals and clinical populations has primarily focused on localization of function and structures in the brain, revealing activation in specific brain regions during performance of cognitive tasks through modalities such as functional MRI. In parallel, technologies to identify white matter structures have been developed using diffusion MRI. More recently, interest has shifted towards developing a deeper understanding of the brain's intrinsic architecture and its influence on cognitive and affective information processing. Using for this resting state fMRI and diffusion MRI to build the functional and structural networks of the human brain.

The human brain is a complex patchwork of interconnected regions, and graph-theoretical approaches have become increasingly useful for understanding how functionally connected systems engender, and constrain, cognitive functions. The functional nodes of the human brain and their structural inter-connectivity, collectively the "connectome", are, however, poorly understood. Critically, there is a dearth of computational methods for reliably identifying functional nodes of the brain and their structural inter-connectivity in vivo, despite an abundance of high-quality data from the Human Connectome Project (HCP). Devising and validating methods for investigating the human connectome has therefore taken added significance.

The first major goal of this project is to develop and validate appropriate sophisticated computational and mathematical tools for identifying functional nodes at the whole-brain level and measuring structural and functional connectivity between them, using state-of-the-art human brain imaging techniques and open-source HCP data. To this end, we will first develop and validate novel computational tools for (1) identifying stable functional nodes of the human brain using resting-state functional MRI and (2) measuring structural connectivity between functional nodes of the brain using multi-shell high-angular diffusion MRI. Due to the complementarity of the two imaging techniques fMRI and dMRI, our novel computational methods methods, the synergy between the two laboratories of this associate team will allow us to reveal in unprecedented detail the structural and functional connectivity of the human brain.

The second major goal of this project is to use our newly developed computational tools to characterize normal structural and functional brain networks in neurotypical adults.

9.4.2. Inria International Partners

9.4.2.1. Informal International Partners

- SCIL Laboratory, Sherbrooke University, CA (Maxime Descoteaux)
- CMRR, University of Minnesota, USA (Christophe Lenglet)
- Verona University, It (Gloria Menegaz)
- Department of CISE, the University of Florida, Gainesville, USA (Baba C. Vemuri)
- Centre for Medical Image Computing (CMIC), Dept. Computer Science, UCL, UK (D. Alexander)
- SBIA, University of Pennsylvania Medical School, USA (R. Verma).
- University Houari Boumedienne (USTHB, Algiers) (L. Boumghar) and University of Boumerdes, (D. Cherifi), Algeria.
- BESA company on EEG/MEG modeling.
- CRM, Centre de Recherche Mathématiques, Montréal, Canada.

9.4.3. Participation in Other International Programs

9.4.3.1. Program: Collaborative Research in Computational Neuroscience (NSF – ANR)

Project acronym: NEUROREF

Project title: *Building MRI Reference Atlases to Analyze Brain Trauma and Post- Traumatic Stress*

Start date: 2016-10-01, End date: 2019-12-31

P.I : D. Wassermann (Athena) – S. Bouix (Harvard Medcical School)

Partners: ATHENA project-team,

International Partner (Institution - Laboratory - Researcher):

Harvard Medical School (United States) - Psychiatry and Neuroimaging Lab - Sylvain Bouix

Abstract:

While mild traumatic brain injury (mTBI) has become the focus of many neuroimaging studies, the understanding of mTBI, particularly in patients who evince no radiological evidence of injury and yet experience clinical and cognitive symptoms, has remained a complex challenge. Sophisticated imaging tools are needed to delineate the kind of subtle brain injury that is extant in these patients, as existing tools are often ill-suited for the diagnosis of mTBI. For example, conventional magnetic resonance imaging (MRI) studies have focused on seeking a spatially consistent pattern of abnormal signal using statistical analyses that compare average differences between groups, i.e., separating mTBI from healthy controls. While these methods are successful in many diseases, they are not as useful in mTBI, where brain injuries are spatially heterogeneous. The goal of this proposal 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. New algorithms will be developed to create Individualized Brain Abnormality (IBA) maps that will have a number of clinical and research applications. In this proposal, this technology will be used to analyze a previously acquired dataset from the INTRuST Clinical Consortium, a multi-center effort to study subjects with Post- Traumatic Stress Disorder (PTSD) and mTBI. Neuroimaging abnormality measures will be linked to clinical and neuropsychological assessments. This technique will allow us to tease apart neuroimaging differences between PTSD and mTBI and to establish baseline relationships between neuroimaging markers, and clinical and cognitive measures. Upon completion of this project, a set of tools, which have the potential to establish radiological evidence of brain injury in mTBI, will have been designed and evaluated, thereby enhancing both the diagnosis and monitoring of progression/recovery of injury, as well assessing the efficacy of therapies on the injured brain.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

- Sadegh Masjoodi (PhD Student, Tehran University of Medical Sciences, Iran) visited ATHENA from April 2nd, 2016 to Sept, 10, 2016
- Lorenza Brusini (PhD Student, Univ. of Verona, Italy), visited ATHENA from Jan. 2016 until Apr 2016.
- Maria Carla Piastra (PhD Student, Univ. Clinic of Münster, Germany), visited ATHENA from Jul 2016 until Aug 2016.
- Mouloud Kachouane (PhD Student, Univ. USTHB, Alger) visited ATHENA from Nov. 2015 until Aug 2016.
- Thinhinane Megherbi (PhD Student, Univ. USTHB, Alger) visited ATHENA from Jan. 2016 until Feb. 2016.
- Vinod Menon (Stanford Medical School) visited ATHENA during June 2016
- John Kolchaka (Stanford Medical School) visited ATHENA during June 2016

9.5.1.1. Internships

Graeme Baker

Date: May 2016 – Sept 2016

Queen's University,
Supervisor: Rachid Deriche

Nahuel Lascano
Date: Jun 2016 – Sept 2016
University of Buenos Aires,
Supervisor: Demian Wassermann

Leonel Exequiel Gomez
Date: Jun 2016 – Sept 2016
University of Buenos Aires,
Supervisor: Demian Wassermann

Paul Gorlach
Date: Jul 2016 – Dec. 2016
University of Buenos Aires,
Supervisor: Theo Papadopoulo and Evelyne Hubert

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

- R. Deriche is Adj. Director at the Doctoral School EDSTIC (Website: http://edstic.i3s.unice.fr/index.html)
- T. Papadopoulo (since september 2011) is a co-coordinator of the Master of Science in Computational Biology and Biomedicine from University of Nice Sophia Antipolis (Website: http://cbb.unice.fr). The scientific goal of this program is to focus on the human being from different perspectives (understanding and modeling functional aspects or interpreting biomedical signals from various devices) and at different scales (from molecules to organs and the whole organism).

10.1.1.2. Member of the Organizing Committees

- M. Clerc organized, with Bruno Cessac from Biovision team,the conference neurostim2016.inria.fr on neurostimulation of the sensory and central nervous systems.

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

- R. Deriche is member of the conference Programme Committee (PC) of the International Symposium on Biomedical Imaging (ISBI), member of the PC of MICCAI 2016 Workshop on Computational Diffusion MRI and member of the PC of MFCA 2016 MICCAI workshop on Mathematical Foundations of Computational Anatomy.
- Demian Wassermann, member of the Program Committee of MICCAI 2016.
- Maureen Clerc was member of the BCI Meeting 2016 Program Committee.

10.1.2.2. Reviewer

- R. Deriche serves several international institutions in reviewing applications : ERC Grants, Swiss National Science Foundation, the Netherlands Organisation for Scientific Research (NWO)...
- R. Deriche serves several international conferences (Isbi, MICCAI, ISMRM...) and international workshops (CD-MRI Miccai, MFCA Miccai...).

- T. Papadopoulo serves several international conferences as a reviewer (ICIP, EMBC, MICCAI, ISBI, CDMRI, HBM).
- D. Wassermann serves several international institutions in reviewing applications: ANR, the Netherlands Organisation for Scientific Research (NWO), ...
- D. Wassermann serves several international conferences as a reviewer (MICCAI, ISMRM, HBM, CDMRI, etc)

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- R. Deriche is member of the Editorial Board of the Journal of Neural Engineering, Associate Editor of SIAM Journal on Imaging Sciences (SIIMS), editorial board member at Springer for the book series entitled Computational Imaging and Vision and member of the Editorial Board of the Medical Image Analysis Journal
- M. Clerc is member of the Editorial Board of Biomedical Engineering OnLine, and of the ISTE-Wiley book series.

10.1.3.2. Reviewer - Reviewing Activities

- 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 Transactions on Biomedical Engineering, Frontiers Neuroscience, Journal of Physics A, International Journal on Computer Vision,...).
- D. Wassermann serves several international journals (NeuroImage, IEEE Transactions on Medical Imaging, Human Brain Mapping, Medical Image Analysis Journal,...).

10.1.4. Invited Talks

- M. Clerc gave invited talks at: Seminar SIESTE (ENS Lyon, March 2016), Imaging Seminar in Paris (Institut Henri Poincaré, November 2016)
- R. Deriche gave two plenary talks at the *13th IEEE International Conference on Signal Processing, November 7, 2016* in Chengdu and at the *Big Data in Medical Imaging Forum, November 10th, 2016* in Guiyang, both in China.
- R. Deriche gave a plenary talk at the *Summer school on Brain Connectomics, September 20, 2016* in Verona, Italy.
- T. Papadopoulo gave an invited talk in the ChildBrain symposium at the *Biomag conference, October 6, 2016* in Seoul, Korea [20].
- D. Wassermann gave a invited talks at: Stanford Medical School and at the Brain and Spine Institute, Paris.

10.1.5. Leadership within the Scientific Community

- M. Clerc coordinates the Inria Project Lab BCI-LIFT.
- R. Deriche is the P.I of the ERC AdG CoBCoM.

10.1.6. Scientific Expertise

- M. Clerc is a member of the Inria Evaluation Committee since 2015.
- M. Clerc is a member of the Scientific Committee of Académie 4 of University Côte d'Azur.
- R. Deriche is a member of the Scientific Committee of Académie 2 of University Côte d'Azur.
- R. Deriche serves several international institutions in reviewing applications : ERC Grants, Swiss National Science Foundation, the Netherlands Organisation for Scientific Research (NWO).

10.1.7. Research Administration

- M. Clerc is Déléguée Scientifique Adjointe (vice-head of Science) of the Sophia Antipolis Inria Research Center since 2014.
- M. Clerc is member of the Commission Scientifique Interne (CoSI) of Inria since 2014.
- R. Deriche is Chair of the 2015 and 2016 Inria Sophia Antipolis recruitment commitees
- R. Deriche is member of 4 Scientific Councils: University of Nice Sophia Antipolis, ITMO ITS (Institut des Technologies pour la Santé), Olea Medical Company (http://www.olea-medical.com/ and the GIS UNS-ENSL-CNRS-Inria.
- R. Deriche is member of the Administration Council of AFRIF (Association Française pour la Reconnaissance et l'Interprétation des Formes) and member of the Academic Council of UCA (Nice Côte d'Azur University)
- T. Papadopoulo is the head of the DTK platform committee of the Sophia Antipolis Inria Research Center since 2016.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Tutorial course by M. Clerc at ChildBrain Winter School (Jyväskylä, Finland, January 2016) : "Advanced Signal Processing".

Tutorial course by M. Clerc at IEEE International Conference on Systems Man and Cybernetics (Budapest, Hungary, October 2016): "Why bother with avanced modeling in BCI ? Lessons from neuroimaging".

Master: R. Deriche, Variational approaches and Geometrical Flows for Computational Brain Imaging, 36 ETD, M2 "Computational Biology and Biomedicine", University of Nice Sophia Antipolis, France.

Master: R. Deriche, Advanced Image Processing Techniques, 12 ETD, M1 International CBB & Ubinet, University of Nice Sophia Antipolis, France.

Master: T. Papadopoulo, *3D Computer Vision*, 12 ETD, M1 International Ubinet, University of Nice Sophia Antipolis, France.

Master: T. Papadopoulo, *Inverse Problems in Brain Functional Imaging*, 36 ETD, M2 "Computational Biology and Biomedicine", University of Nice Sophia Antipolis, France.

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

Master: D. Wassermann, *Introduction to Computer Science*, 24 ETD, M2, "Computational Biology and Biomedicine", University of Nice Sophia Antipolis, France.

Master: D. Wassermann, *Machine Learning in Neuroimaging*, 36 ETD, University of Buenos Aires, Argentina

10.2.2. Supervision

PhD in progress: Rutger Fick, "Microstructure Recovery via dMRI", started Oct. 2013, Université Nice Sophia Antipolis. Supervisor: Rachid Deriche.

PhD in progress: Kai Dang, "Modeling and characterizing electrical conductivity for cochlear implantation", started Dec. 2013, Université Nice Sophia Antipolis. Supervisor: Maureen Clerc.

PhD defended in April 20, 2016: Gabriel Girard, "fMRI & dMRI", started Sept. 2012, Supervisors: Rachid Deriche & Maxime Descoteaux (University of Sherbrooke, CA).

PhD in progress: Mouloud Kachouane, "Invariants and biomarqueurs in dMRI", started Oct. 2012, Supervisors: Rachid Deriche & L. Boumghar (USTHB, Algiers).

PhD in progress: Thinhinane Megherbi, “HARDI & High Order Tensors”, started Sept. 2011, Supervisors: Rachid Deriche & L. Boumghar (USTHB, Algiers)

PhD in progress: Marco Pizzolato, “Diffusion & Perfusion MRI: From bench to bedside” started Dec. 2013, Université Nice Sophia Antipolis. Supervisor: Rachid Deriche.

PhD in progress: Abib Alimi, “Diffusion & PLI” started Nov, 1st, 2016, Université Nice Sophia Antipolis. Supervisor: Rachid Deriche.

PhD in progress: Isa Costantini, “Brain Connectomics” started Oct. 1st, 2016, Université Nice Sophia Antipolis. Supervisor: Rachid Deriche.

PhD in progress: Brahim Belaoucha, “Using diffusion MR information to reconstruct networks of brain activations from MEG and EEG measurements”, Université Nice Sophia Antipolis, started Oct. 2013, Supervisor: Theo Papadopoulo.

PhD in progress: Kostiantyn Maksymenko, “Inverse problem in EEG/MEG/SSEG: towards a better consideration of anatomo-functional constraints ”, Université Nice Sophia Antipolis, started Oct. 2016, Supervisor: Theo Papadopoulo and Maureen Clerc.

PhD in progress: Guillermo Gallardo Diez, “Connectivity-Based Brain Parcellation”, started Nov. 2015, Université Nice Sophia Antipolis. Supervisors: D. Wassermann/ R. Deriche

PhD in progress: Nathalie Gayraud, “Structured Dictionary Learning”, University Nice Sophia Antipolis, started November 2015, supervisor: Maureen Clerc.

PhD in progress: Federica Turi, “User-adapted Brain Computer Interaction”, University Nice Sophia-Antipolis, started October 2016, supervisor: Maureen Clerc.

Master: Kostiantyn Maksymenko, “Efficient lead field computation a la Reduced Basis Methods”, Supervised by T. Papadopoulo and M. Clerc.

Master: Paul Görlach, “Rotational Invariants of Ternary Quartics”, Supervised by E. Hubert and T. Papadopoulo. Clerc.

Master: Nahuel Lascano, “Weigthed Newtwork Representations of Structural Connectivity”, Supervised by D. Wassermann.

Master: Leonel Exequiel Gomez, “Super-resolution approaches to Multi-Shell dMRI”, Supervised by D. Wassermann.

Internship: Federica Turi, “Novel flashing strategies for the P300-speller”, Supervised by M. Clerc.

10.2.3. Juries

- M. Clerc participated in PhD juries of: Michaël Acquadro (Grenoble, April 2016) as reviewer, Tafkarinas Medani (Paris 6, September 2016) as reviewer, Flavie Torrecillos (Marseille, October 2016) as examiner, Andéol Evain (Rennes, December 2016) as examiner.
- M. Clerc participated in HDR jury of Sophie Achard as reviewer (Grenoble, March 2016) and Fabien Lotte (Bordeaux, September 2016) as examiner.
- M. Clerc participated in the recruitment jury of Professor in section 26 in University Nice Sophia Antipolis.
- M. Clerc participated in the recruitment jury for CR2/CR1 in Inria Sophia Antipolis.
- R. Deriche chaired the recruitment jury for CR2/CR1 in Inria Sophia Antipolis.
- R. Deriche chaired the PhD jury of Simona Schiavi at Ecole Polytechnique, Paris Saclay, Dec. 1st, 2016.
- R. Deriche chaired the PhD jury of Mehdi Hadj-Hamou at Nice University, Dec. 14th, 2016.
- R. Deriche participated in the PhD Jury of P. Gori at ICM, Paris, Jan. 8th, 2016
- R. Deriche participated in the PhD Jury of G. Girard at Sherbrooke University, April, 20, 2016.

- T. Papadopoulo participated in the PhD Jury of G. Girard as reviewer at Sherbrooke University, April, 20, 2016.
- T. Papadopoulo participated in the PhD Jury of A. Pillain as reviewer at Telecom Bretagne, October, 12, 2016.

10.3. Popularization

During the “Semaine du Cerveau” (Brain Awareness week) in March 2016, Maureen Clerc organized a “Cafe Technologique” about Brain-Computer Interfaces, in which over 100 attendees could see a live demo of the P300 speller with both clinical-grade and consumer-grade devices.

Maureen Clerc participated in a “Gala for Amyotrophic Lateral Sclerosis” at the AXA Headquarters in Paris, a fundraising event, where she presented the P300 speller project.

11. Bibliography

Major publications by the team in recent years

[1] M. Clerc, L. Bougrain, F. Lotte (editors). *Brain-Computer Interfaces 1*, Wiley-ISTE, July 2016, http://eu.wiley.com/WileyCDA/WileyTitle/productCd-1848218265.html.

[2] M. Clerc, L. Bougrain, F. Lotte (editors). *Brain-Computer Interfaces 2*, Wiley-ISTE, July 2016, http://eu.wiley.com/WileyCDA/WileyTitle/productCd-1848219636.html.

[3] C. Bénar, T. Papadopoulo, B. Torrésani, M. Clerc.*Consensus Matching Pursuit for Multi-Trial EEG Signals*, in "Journal of Neuroscience Methods", 2009, vol. 180, p. 161–170 [*DOI :* DOI: 10.1016/j.jneumeth.2009.03.005], http://www.sciencedirect.com/science/article/B6T04-4VWHVX5-2/2/e6ebdc581a60cde843503fe30f9940d1.

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[10] 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.

[11] D. WASSERMANN, N. MAKRIS, R. YOGESH, M. SHENTON, R. KIKINIS, M. KUBICKI, C.-F. WESTIN.*The white matter query language: a novel approach for describing human white matter anatomy*, in "Brain Structure and Function", December 2016, vol. 221, n^o 9, 4705—4721 [*DOI :* DOI: 10.1007/S00429-015-1179-4], http://link.springer.com/article/10.1007%2Fs00429-015-1179-4.

Publications of the year

Doctoral Dissertations and Habilitation Theses

[12] G. GIRARD.*White matter tractography guided by anatomical and microstructural priors*, Université Nice Sophia Antipolis, April 2016, https://tel.archives-ouvertes.fr/tel-01369022.

Articles in International Peer-Reviewed Journal

[13] S. BHATTACHARYYA, M. CLERC, M. HAYASHIBE.*A study on the effect of electrical stimulation as a user stimuli for motor imagery classification in Brain-Machine Interface*, in "European Journal of Translational Myology", June 2016, vol. 26, n^o 2, p. 165-168 [*DOI :* 10.4081/EJTM.2016.6041], https://hal-lirmm.ccsd.cnrs.fr/lirmm-01402537.

[14] M. CLERC, J. LEBLOND, J.-P. MARMORAT, C. PAPAGEORGAKIS.*Uniqueness result for an inverse conductivity recovery problem with application to EEG*, in "Rendiconti dell'Istituto di Matematica dell'Università di Trieste. An International Journal of Mathematics", 2016, vol. 48, Special issue dedicated to Giovanni Alessandrini, https://hal.archives-ouvertes.fr/hal-01303640.

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Invited Conferences

[20] T. PAPADOPOULO.*Modelling thin tissue compartiments using the immersed FEM (continuous Galerkin)*, in "Biomag 2016 - 20th International Conference on Biomagnetism", Seoul, South Korea, October 2016, https://hal.inria.fr/hal-01412820.

International Conferences with Proceedings

[21] B. BELAOUCHA, T. PAPADOPOULO.*Iterative two-stage approach to estimate sources and their interactions* , in "20th International Conference on Biomagnetism (BIOMAG2016)", Seoul, South Korea, October 2016, https://hal.inria.fr/hal-01377967.

[22] S. BHATTACHARYYA, M. CLERC, M. HAYASHIBE.*A Study on the Effect of Electrical Stimulation During Motor Imagery Learning in Brain-Computer Interfacing*, in "SMC: Systems, Man, and Cybernetics", Budapest, Hungary, October 2016, https://hal.archives-ouvertes.fr/hal-01402794.

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Conferences without Proceedings

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Team AYIN

Models of spatio-temporal structure for high-resolution image processing

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
Vision, perception and multimedia interpretation

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Team AYIN

Creation of the Team: 2012 January 01, end of the Team: 2016 June 30

Keywords:

Computer Science and Digital Science:

3.4.1. - Supervised learning
3.4.2. - Unsupervised learning
3.4.4. - Optimization and learning
3.4.5. - Bayesian methods
3.4.7. - Kernel methods
5.3. - Image processing and analysis
5.3.2. - Sparse modeling and image representation
5.3.3. - Pattern recognition
5.4. - Computer vision
5.4.1. - Object recognition
5.4.4. - 3D and spatio-temporal reconstruction
5.4.5. - Object tracking and motion analysis
5.9.2. - Estimation, modeling
5.9.3. - Reconstruction, enhancement
5.9.4. - Signal processing over graphs
5.9.6. - Optimization tools
6.1.4. - Multiscale modeling
6.2.3. - Probabilistic methods
6.2.4. - Statistical methods
6.2.6. - Optimization
6.3.1. - Inverse problems

Other Research Topics and Application Domains:

2.6. - Biological and medical imaging
3.1. - Sustainable development
3.3. - Geosciences
3.4. - Risks
3.5. - Agronomy

1. Members

Research Scientist

Josiane Zerubia [Team leader, Inria, Research Scientist, HDR]

PhD Student

Ihsen Hedhli [cosupervised with the University of Genoa, granted by the Italian government, until April 2016]

2. Overall Objectives

2.1. Overall Objectives

The AYIN team is devoted to the modeling of spatio-temporal structures, for use in the analysis of high-resolution image data, with particular application to images arising in remote sensing, broadly interpreted, and skin care.

The latest and upcoming generations of imaging sensors, for example, in remote sensing (Pleiades, EnMAP, Sentinel) and medicine (Philips, Christie Medical), result in large volumes of heterogeneous data with high spatial, spectral, and temporal resolution. High resolution imagery (this may refer to spatial, spectral, or temporal resolutions) is a rich source of information about the imaged scene, information that is unavailable in lower resolution data. In particular, spatial and spatio-temporal structures abound, and frequently constitute the information of greatest interest in practice. As a result, such imagery is vital to advances in a range of applications (urban monitoring, precision agriculture, skin disease diagnosis, *etc.*). The high resolution and high volume of the imagery presents new challenges, however, that must be overcome if the potential of the data is to be realized. Extracting the available information requires the development of new modeling techniques adapted to the nature and profusion of structures, and the design of corresponding algorithms, which must in turn be implemented in a time- and space-efficient way if the techniques are to be made operational.

The overall scientific objective of the AYIN team is precisely to advance the state of theory and practice in this area by the development of such modeling techniques and the design of such algorithms. We make use of a variety of methodologies in order to achieve this goal, taking a broadly Bayesian point of view. This point of view suggests dividing the modeling task into two parts: modeling of the scene, *i.e.* describing the scenes to be expected in any given application; and modeling of the image, *i.e.* describing the images to be expected from any given scene. AYIN focuses on spatio-temporal and spectral structure, leading to the modeling of geometrical properties on the one hand, and large, coherent structures in images and image sequences on the other. The new models also require new algorithms, for dealing with the nuisance parameters they contain, and for extracting the desired information. This forms a third major component of AYIN's research. The models and algorithms are developed in parallel with their application to information extraction from very high resolution images, in particular data arising in remote sensing and skin care.

3. Research Program

3.1. Geometric and shape modeling

One of the grand challenges of computer vision and image processing is the expression and use of prior geometric information via the construction of appropriate models. For very high resolution imagery, this problem becomes critically important, as the increasing resolution of the data results in the appearance of a great deal of complex geometric structure hitherto invisible. AYIN studies various approaches to the construction of models of geometry and shape.

3.1.1. Stochastic geometry

One of the most promising approaches to the inclusion of this type of information is stochastic geometry, which is an important research direction in the AYIN team. Instead of defining probabilities for different types of image, probabilities are defined for configurations of an indeterminate number of interacting, parameterized objects located in the image. Such probability distributions are called 'marked point processes'. New models are being developed both for remote sensing applications, and for skin care problems, such as wrinkle and acne detection.

3.1.2. *Contours, phase fields, and MRFs with long-range interactions*

An alternative approach to shape modeling starts with generic 'regions' in the image, and adds constraints in order to model specific shapes and objects. AYIN investigates contour, phase field, and binary field representations of regions, incorporating shape information via highly-structured long-range interactions that constrain the set of high-probability regions to those with specific geometric properties. This class of models can represent infinite-dimensional families of shapes and families with unbounded topology, as well as families consisting of an arbitrary number of object instances, at no extra computational cost. Key sub-problems include the development of models of more complex shapes and shape configurations; the development of models in more than two spatial dimensions; and understanding the equivalences between models in different representations and approaches.

3.1.3. *Shapes in time*

AYIN is concerned with spectral and spatio-temporal structures. To deal with the latter, the above scene modeling approaches are extended into the time dimension, either by modeling time dependence directly, or, in the field-based approaches, by modeling spacetime structures, or, in the stochastic geometry approach, by including the time t in the mark. An example is a spatio-temporal graph-cut-based method that introduces directed infinite links connecting pixels in successive image frames in order to impose constraints on shape change.

3.2. Image modeling

The key issue that arises in modeling the high-resolution image data generated in AYIN's applications, is how to include large-scale spatial, temporal, and spectral dependencies. AYIN investigates approaches to the construction of image models including such dependencies. A central question in the use of such models is how to deal with the large data volumes arising both from the large size of the images involved, and the existence of large image collections. Fortunately, high dimensionality typically implies data redundancy, and so AYIN investigates methods for reducing the dimensionality of the data and describing the spatial, temporal, and spectral dependencies in ways that allow efficient data processing.

3.2.1. *Markov random fields with long-range and higher-order interactions*

One way to achieve large-scale dependencies is via explicit long-range interactions. MRFs with long-range interactions are also used in AYIN to model geometric spatial and temporal structure, and the techniques and algorithms developed there will also be applied to image modeling. In modeling image structures, however, other important properties, such as control of the relative phase of Fourier components, and spontaneous symmetry breaking, may also be required. These properties can only be achieved by higher-order interactions. These require specific techniques and algorithms, which are developed in parallel with the models.

3.2.2. *Hierarchical models*

Another way to achieve long-range dependencies is via shorter range interactions in a hierarchical structure. AYIN works on the development of models defined as a set of hierarchical image partitions represented by a binary forest structure. Key sub-problems include the development of multi-feature models of image regions as an ensemble of spectral, texture, geometrical, and classification features, where we search to optimize the ratio between discrimination capacity of the feature space and dimensionality of this space; and the development of similarity criteria between image regions, which would compute distances between regions in the designed feature space and would be data-driven and scale-independent. One way to proceed in the latter case consists in developing a composite kernel method, which would seek to project multi-feature data into a new space, where regions from different thematic categories become linearly or almost linearly separable. This involves developing kernel functions as a combination of basis kernels, and estimating kernel-based support vector machine parameters.

3.3. Algorithms

Computational techniques are necessary in order to extract the information of interest from the models. In addition, most models contain 'nuisance parameters', including the structure of the models themselves, that must be dealt with in some way. AYIN is interested in adapting and developing methods for solving these problems in cases where existing methods are inadequate.

3.3.1. Nuisance parameters and parameter estimation

In order to render the models operational, it is crucial to find some way to deal with nuisance parameters. In a Bayesian framework, the parameters must be integrated or marginalized out. Unfortunately, this is usually very difficult. Fortunately, Laplace's method often provides a good approximation, in many cases being equivalent to classical maximum likelihood parameter estimation. Even these problems are not easy to solve, however, when dealing with complex, structured models. This is particularly true when it is necessary to estimate simultaneously both the information of interest and the parameters. AYIN is developing a number of different methods for dealing with nuisance parameters, corresponding to the diversity of modeling approaches.

3.3.2. Information extraction

Extracting the information of interest from any model involves making estimates based on various criteria, for example MAP, MPM, or MMSE. Computing these estimates often requires the solution of hard optimization problems. The complexity of many of the models to be developed within AYIN means that off-the-shelf algorithms and current techniques are often not capable of solving these problems. AYIN develops a diversity of algorithmic approaches adapted to the particular models developed.

4. Highlights of the Year

4.1. Highlights of the Year

- Josiane Zerubia is IEEE Signal Processing Society Distinguished Lecturer for 2016 and 2017, see (http://signalprocessingsociety.org/newsletter/2015/11/sps-announces-2016-class-of-distinguished-lecturers/)
- Josiane Zerubia received the Excellency Prize of UCA (Université Cote d'Azur) for her outstanding research work in December 2016.
- Nazre Batool who was an Inria post-doc in AYIN till May 2015 received the IEEE R8 Women in Engineering Clementina Saduwa 2016 award, see (http://www.femmesetsciences.fr/actualites/nazre-batool-prix-clementina-saduwa-2016/)
- Josiane Zerubia, in collaboration with Gabriele Moser from University of Genoa (Italy), edited a book of more than 400 pages on mathematical models for remotely sensed image processing [11] which was submitted to Springer Verlag in December 2016 and will be published early 2017. They also contributed to two chapters of this book.

5. New Software and Platforms

5.1. Consulting for Industry

Josiane Zerubia is a scientific consultant for the Galderma company (http://www.galderma.com/AboutGalderma/Worldwide-presence/R-D-Locations)

6. New Results

6.1. Fusion of multitemporal and multiresolution remote sensing data and application to natural disasters

Participants: Ihsen Hedhli, Josiane Zerubia [contact].

This work was carried out in collaboration with Prof. Gabriele Moser and Prof. Sebastiano Serpico from DITEN departement (http://www.dibe.unige.it/index.php?lang=en), University of Genoa, Italy.

In this work we address the problem of constructing statistical models of images using Hierarchical Hidden Markov modeling techniques for high resolution remotely sensed image classification of urban areas. The main difficulty is to develop a classifier that jointly utilizes the benefits of multi-band and multi-resolution input data while maintaining a good trade-off between accuracy and computation time. In this framework, Markov random field (MRF) models are widely used in classification problems since they provide a convenient and consistent way of integrating contextual information into the classification scheme. Furthermore, MRF models defined according to hierarchical structures exhibit good methodological and application-oriented properties including causality, thanks to the use of appropriate graphs such as a quadtree structure [1]. The input satellite images are inserted in a hierarchical structure on the basis of their spatial resolution. This approach is aimed at both exploiting multi-scale information, which is known to play a crucial role in high-resolution image analysis, and supporting contextual information at each scale. However, hierarchical MRFs on quad-trees rely on a causality concept captured by the factorization of the prior distribution in terms of causal transition probabilities [2]. In practice, this structure tends to generate "blocky" effects in the final classification map. Due to this disadvantage, a new hierarchical MRF based on a Symmetric Markov Mesh Random Field (SMMRF) is proposed in this work, to overcome these limitations from both mathematical and practical points of view, and to establish a causal and symmetrical model. This can be accomplished by scanning the lattice at each level of the hierarchical model based on the visiting scheme shown in Fig 1. Then, for each scale of the quad-tree, the causal SMMRF is integrated into the hierarchical structure. Accordingly, each node s at each scale level of the quad-tree, except at the root, is linked to one parent (in the upper level) and three neighbors (in the same level). For each pixel at the root level, there is no parent and only the neighbors remain. The shapes of the neighborhoods of the pixels at the top and left borders of each lattice, at each scale level of the pyramid, are obviously adapted to the image borders [8].

We applied the developed hierarchical classification approach to a multi-resolution dataset that consists of a panchromatic and a multi-spectral Pléiades images acquired over Port-au-Prince (Haiti). Experimental results with HR satellite imagery of a very high-resolution urban scene suggest that the method allows to effectively incorporate spatial information in the hierarchical classification process and provides higher accuracies than previous techniques. Indeed, it is confirmed experimentally (see Fig. 2) that MMRFs and their lattice models are corner-dependent, and that the proposed approach is effective in circumventing this drawback by using a Symmetric Markov Mesh Random Field. The proposed method, in the application to a challenging urban area classification problem, is able to combine the computational and modeling benefits of hierarchical and symmetric mesh MRF models, while preventing their individual artifacts.

6.2. Multitemporal change detection on image sequences with a False Discovery Rate approach

Participant: Josiane Zerubia [contact].

This work was carried out in collaboration with Dr. Vladimir Krylov, Prof. Gabriele Moser and Prof. Sebastiano Serpico from DITEN departement (http://www.dibe.unige.it/index.php?lang=en), University of Genoa, Italy.

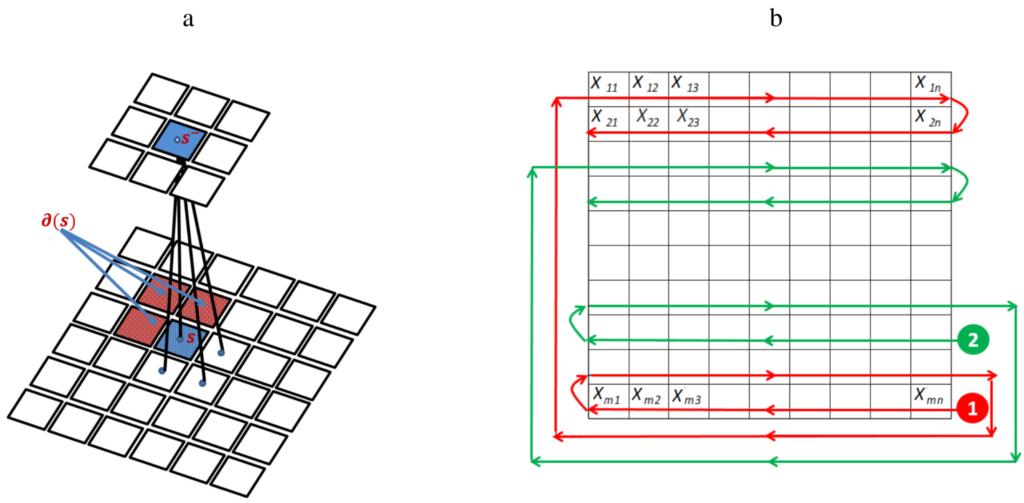

Figure 1. (a) Hybrid structure that combines a spatial grid using an SMMRF and a hierarchical MRF via a quad-tree. (b) Regular rectangular lattice S of size m x n: the "past" of site $s_{i,j}$ is the gray area, arrow lines show raster scan.

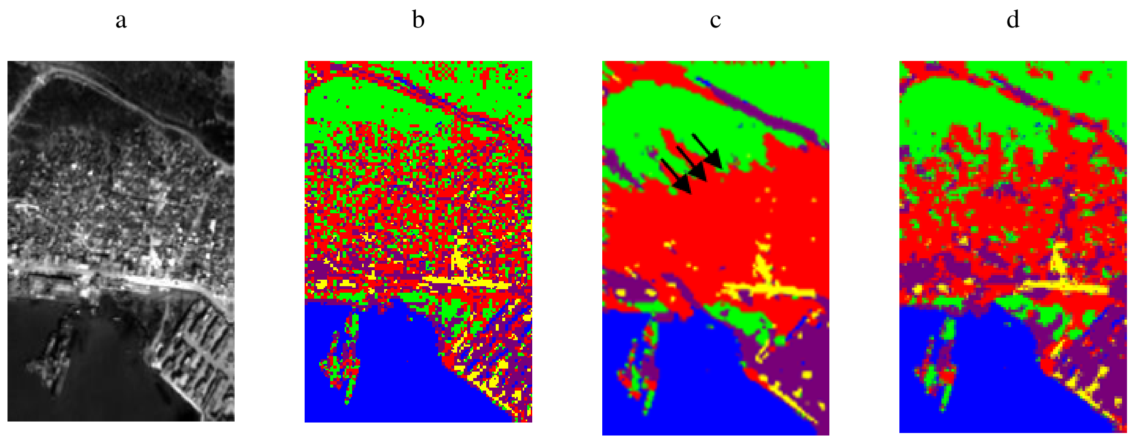

Figure 2. classification maps of optical (Pléiades) image (a) using the original Laferté method (b), the previous method in [2] (c) and the new proposed method (d).

Multitemporal change detection on image sequences is one of the fundamental image processing problems and multiple detection, monitoring and tracking applications rely on its accurate and timely performance. To address this problem we develop an approach that gives a unified statistical thresholding procedure to perform change detection based on statistical features that have a known distribution under the no-change hypothesis. The proposed False Discovery Rate (FDR) formulation is based on the control of the proportion of false alarms among all detections [3]. This efficient technique for large scale hypotheses testing allows to use the wide range of statistical tests developed in the state-of-the-art by adjusting to the dependence structure present in the images and the patch-based samples. The developed approach involves only a few parameters and is highly parallelizable. We propose several rank-based statistical features that report accurate experimental results and the corresponding detectors positively compare with benchmark techniques in three different applications. Further features can be easily constructed to elaborate application-specific change detectors.

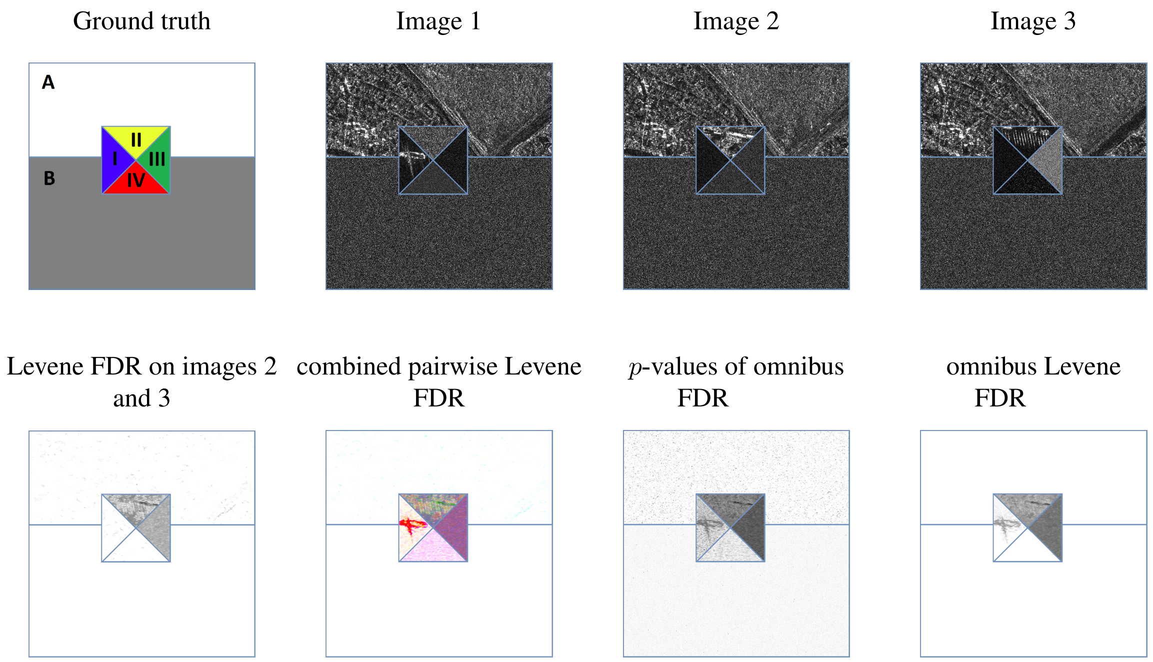

Figure 3. Semi-synthetic 3-image SAR sequence based on COSMO-SkyMed (©ASI) images of Haiti in 2011: (a) ground truth and (b)-(d) images, results of (e), (f) pairwise and (g), (h) omnibus Levene FDR-detection.

In Fig. 3 we demonstrate a typical result of the FDR-based change detector on a semi-synthetic 3-image synthetic aperture radar sequence based on COSMO-SkyMed (©ASI) images of Haiti (April, May and August 2011). In this experiments the Levene multisample statistic with a 9-by-9 local window is employed. A comparison of the omnibus test (formulating the hypothesis for all three images simultaneously) with pairwise tests, demonstrates that the latter are more sensitive to changes. This sensitivity can be a disadvantage as is the case with the detection noise in (e) and (f). The omnibus test on the other hand did not suffer from the same mistake due to a generally higher level of tolerance to pairwise fluctuations. Hence, from the SAR-change detection point of view, the results reported by omnibus version of Levene-statistic are considered more adequate.

6.3. Solving inverse problems related to FUV image processing for ICON mission

Participant: Josiane Zerubia [contact].

This work has been conducted in collaboration with Prof. Farzad Kamalabadi, Dr. Jianqi Qin and Dr. Mark Butala from Coordinated Science Laboratory (CSL, http://www.csl.illinois.edu/) at University of Illinois at Urbana Champaign (UIUC, http://illinois.edu/)

ICON (Ionospheric Connection Explorer) is a satellite which is part of the NASA Explorer missions (see http://icon.ssl.berkeley.edu/) and is planned to be launched in 2017 (see Fig. 4). The main goal of ICON is to study the area where terrestrial weather meets space weather in order to understand the behavior of our planet's upper atmosphere, including what causes disruptions in this region, such as those that can significantly affect radio transmissions.

There will be 4 instruments on board. One of them is the FUV: Far UltraViolet spectrographic imager. Prof Kamalabadi is responsible to process the FUV data from this instrument. During Josiane Zerubia's stay at CSL, UIUC, she worked with Prof. Farzad Kamalabadi team on defining a proper energy function using Bayesian theory (i.e. defining a data term + various priors for regularizing the solution) in order to be able to take into account the geometry of the information and also to deal with optical transmission function. This inverse problem is highly non linear. We will continue in the future to work on the problem of the error estimation (or bound derivation) as far as the estimation of distribution parameters is concerned.

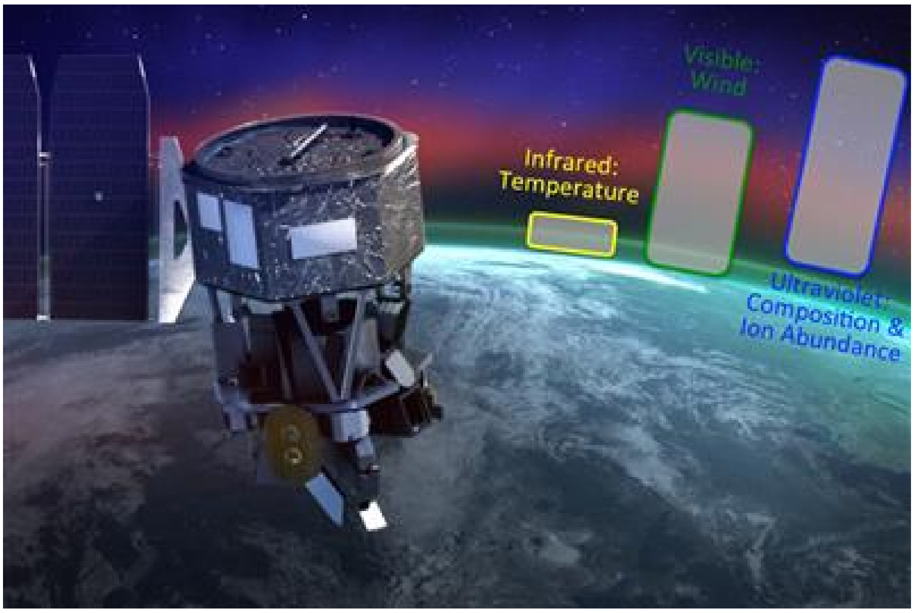

Figure 4. Ionospheric Connection Explorer satellite ©NASA.

6.4. Hyperspectral Image Processing for Detection and Grading of Skin Erythema

Participant: Josiane Zerubia [contact].

This work was carried out in collaboration with Ali Madooei (Simon Fraser University (https://www.sfu.ca/), Canada), Ramy Abdlaty (McMaster University (https://www.mcmaster.ca/), Canada), Lilian Doerwald-Munoz (Hamilton Health Sciences - General Hospital (http://www.hamiltonhealthsciences.ca/), Canada), Joseph Hayward (Hamilton Health Sciences - General Hospital, Canada), Mark Drew (Simon Fraser University, Canada) and Qiyin Fang (McMaster University, Canada).

This study focused on detection and grading of skin erythema using hyperspectral image processing. The ultimate objective is to build a system for monitoring radiation response in individuals using hyperspectral imaging technology and image processing. The present project was to investigate the possibility of monitoring the degree of skin erythema. To this aim, we proposed an image processing pipeline and conducted controlled experiments to demonstrate the efficacy of the proposed approach for (1) reproducing clinical assessments, and (2) outperforming RGB imaging data (see Fig. 5). We combined the problem of erythema detection and grading into a multi-class classification problem where each pixel is classified as one of the four erythema classes or a non-erythema class. We used a weighted LDA (linear discriminant analysis) classifier to deal with noisy labels. Moreover, we devised pre-processing steps to deal with noisy measurements. We evaluate the system against the clinical assessment of an experienced clinician. We also compare the performance to that of using digital photography (instead of hyperspectral images) [9]. The results from this preliminary study are encouraging and indicate that hyperspectral image data contain relevant information, and indeed outperform imaging photography. In future, we want to extend the technique to further detect other skin responses to radiation (such as dry/moist desquamation, skin necrosis, etc.) and also to experiment with real patients undergoing radiotherapy.

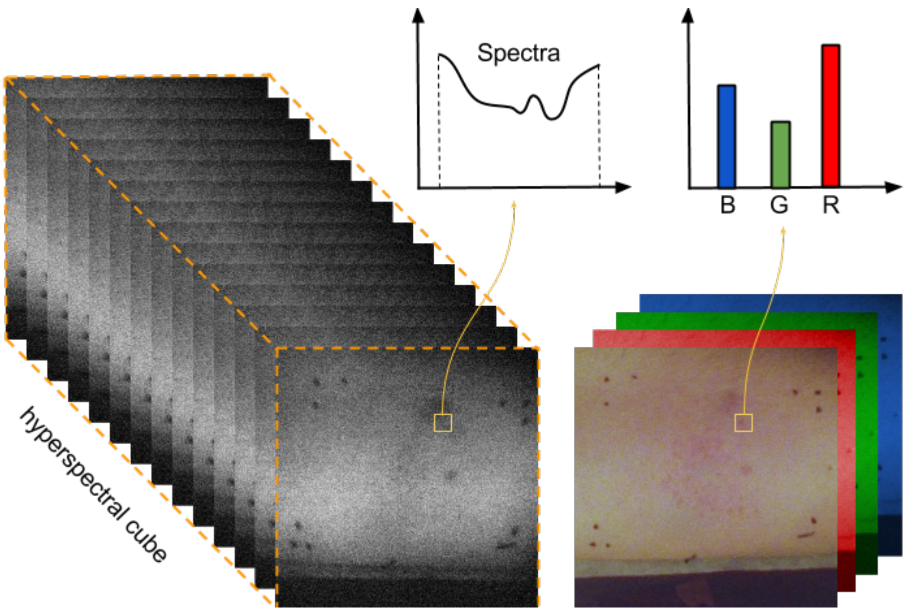

Figure 5. A schematic representation of hyperspectral vs. RGB image data. The image shows artificially induced erythema over the inside of the forearm of a volunteer.

7. Partnerships and Cooperations

7.1. Regional Initiatives

- Josiane Zerubia has been in contact with Dr. Sandrine Mathieu, image processing quality expert at Thales Alenia Space in Cannes (https://www.thalesgroup.com/en/worldwide/space) to discuss AYIN's research in remote sensing.

- Josiane Zerubia is part of the FAULTS-R-GEMS project funded by Academy 3 of Idex UCA-Jedi (http://univ-cotedazur.fr/english/idex-uca-jedi/academies-of-excellence), PI: Isabelle Manighetti of Geoazur (OCA, CNRS, UCA), in collaboration with Yuliya Tarabalka from TITANE Inria team, as well as members of UCA, Institut de Physique du Globe in Paris, Geoscience in Montpellier, ETH Zurich, CalTech, Arizona State University and UNAVCO consortium in the USA.

7.2. International Initiatives

7.2.1. Inria International Partners

- Josiane Zerubia has a strong collaboration with University of Genoa, Italy, for more than 20 years [11].
- Another collaboration in Canada with Mc Master University, Hamilton, started in 2012 [9], and has been extended to Juravinski Cancer Center (http://www.jcc.hhsc.ca/) in Hamilton and Simon Fraser University.

7.3. International Research Visitors

7.3.1. Visits of International Scientists

7.3.1.1. Research Stays Abroad

Josiane Zerubia was invited to spend 2 months, from late August to late October, at the Coordinated Science Laboratory (CSL, http://www.csl.illinois.edu/) of the University of Illinois at Urbana Champaign (UIUC) to work with Prof. Farzad Kamalabadi (https://www.ece.illinois.edu/directory/profile/farzadk) and his team on FUV image processing for ICON NASA mission.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. Member of the Organizing Committees

- Josiane Zerubia in collaboration with Farzad Kamalabadi from UIUC organized a special session at the Symposium URSI-France (http://ursi-france.telecom-paristech.fr/evenements/journees-scientifiques/2017.html) in Sophia Antipolis (February 2017).
- Josiane Zerubia is part of the organizing committee and will be co-Chair of the EARTHVISION workshop at CVPR'17 (http://cvpr2017.thecvf.com/) in Hawaii, USA, in July 2017.
- Josiane Zerubia is part of the organizing committee of the 50th GRETSI conference (http://gretsi.fr/colloque2017/2016/10/bienvenue-au-gretsi-2017/) which will take place in Juan-les-Pins, in September 2017.

8.1.2. Scientific Events Selection

8.1.2.1. Member of the Conference Program Committees

- Josiane Zerubia was part of the conference program committee of SYNASC'16 (http://synasc.ro/2016/) in Timisoara, Romania, in September 2016.
- Josiane Zerubia was part of the conference program committee of ISPRS/SPIE Remote Sensing'16 (http://spie.org/Documents/ConferencesExhibitions/ERS-ESD16-Final-lr.pdf) in Edinburgh, UK, in September 2016.

8.1.2.2. Reviewer

- Josiane Zerubia was a reviewer for the conferences IEEE ICASSP'16, IEEE ICIP'16, ISPRS-SPIE Remote Sensing'16, ECCV'16, IEEE CVPR'16, IAPR ICPR'16, IEEE EMBC'16, IEEE-EURASIP EUSIPCO'16 and SYNASC'16.

8.1.3. Journal

8.1.3.1. Member of the Editorial Boards

- Josiane Zerubia is an Associate Editor of the collection "Foundation and Trends in Signal Processing" (http://www.nowpublishers.com/SIG).
- Josiane Zerubia is a member of the Editorial Board of the "Revue Française de Photogrammétrie et de Télédétection of SFPT" (http://www.sfpt.fr/rfpt/).
- Josiane Zerubia is an Associate Editor of the electronic journal Earthzine (http://www.earthzine.org/).

8.1.3.2. Reviewer - Reviewing Activities

- Ihsen Hedhli was a reviewer for IEEE TGRS, TGRL and TIP journals and Elsevier Pattern Recognition Letters.

8.1.4. Invited Talks

- As IEEE SPS Distinguished Lecturer, Josiane Zerubia gave in 2016 ten invited talks: at DITEN Dept., University of Genoa, Italy, at the Faculty of Mathematics and Computer Science from the West University of Timisoara, Romania, at the Faculty of Electronics, Telecommunications & IT and the Faculty of Medical Engineering, University Politehnica of Bucharest, Romania, at the Georgia Tech Research Institute in Atlanta, USA, at the SenSIP Center, School of Electrical, Computer & Energy Engineering, Arizona State University, Tempe, USA, at both the Sine Seminars and the Remote Sensing Seminars, within the Coordinated Science Laboratory, University of Illinois at Urbana Champaign, USA, at the Signal and Communications laboratory in the Dept. of Engineering, University of Cambridge, UK, at the Faculty of Engineering, University of Bristol, UK, and finally a plenary talk at the international symposium ISIVC2016 in Tunis, organized by Sup'Com (see http://www.supcom.mincom.tn/Fr/Fr/Fr/actualites-de-l-ecole_7_280_D875#.WG0L9jU5ReR).

8.1.5. Leadership within the Scientific Community

- Josiane Zerubia is IEEE Fellow (http://www.ieee.org/membership_services/membership/fellows/index.html) since 2003 and IEEE SPS Distinguished Lecturer since 2016 (http://signalprocessingsociety.org/newsletter/2015/11/sps-announces-2016-class-of-distinguished-lecturers/).

8.1.6. Scientific Expertise

- Josiane Zerubia was a reviewer for the Israeli Ministry of Science, Technology and Space (http://most.gov.il/english/Pages/default.aspx)
- Josiane Zerubia is part of the Scientific Council of Academy 3 of UCA-Jedi (http://univ-cotedazur.fr/english/idex-uca-jedi/academies-of-excellence) dedicated to "Space, Environment, Risks and Resilience".

8.1.7. Research Administration

- Josiane Zerubia is part of the Board of Directors of the French Photogrammetry and Remote Sensing Society (http://www.sfpt.fr/sfpt/bureau/).
- Josiane Zerubia is a member of the Inria-SAM Center Committee since 2016.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

- Masters: Josiane Zerubia, Advanced Techniques in Signal and Image Processing, 30h eq. TD (20h of lectures), ISAE/SUPAERO, France. Josiane Zerubia is also director of this course (total: 30h of lectures and 10h of TD). This course was given to third-year students at ISAE/SUPAERO and was also validated by the M2 of Applied Mathematics at the University Toulouse III Paul Sabatier, France.
- Masters: Josiane Zerubia, Deconvolution and Denoising in Confocal Microscopy, 18h eq. TD (12h of lectures), M2 BCC, Université de Nice Sophia-Antipolis, France. Josiane Zerubia is also director of this course (total: 24h of lectures).
- Summer School (PhD and Post-doc level): Josiane Zerubia gave a presentation at the Summer School SSMIA'16 in Budapest, Romania.

8.2.2. Supervision

PhD (defended with best honors): Ihsen Hedhli, Change detection methods for multisensor and multiresolution remote sensing images for applications to environmental disaster management, University of Genoa and Université Nice Sophia Antipolis, started in January 2013, defended in March 2016, Gabriele Moser and Josiane Zerubia.

8.2.3. Juries

- Josiane Zerubia was a member of a PhD defense committee at University of Genoa, in Italy, in March 2016.

8.3. Popularization

- Josiane Zerubia presented Inria and Inria-SAM to Masters, PhDs and Post-docs of the following foreign universities during 2016: University of Genoa, West University of Timisoara, Georgia Tech, Arizona State University, University of Illinois at Urbana Champaign, University of Cambridge, University of Bristol.
- Josiane Zerubia was interviewed in August with two other French women scientists working in remote sensing by a journalist for Earthzine (webzine supported by IEEE and NASA) see https://earthzine.org/2016/10/13/the-three-musketeers-making-an-impact-in-french-remote-sensing-and-breaking-down-gender-barriers/
- In September, Josiane Zerubia actively participated to a debate about Women in Signal Processing at the IEEE International Conference ICIP'16 (http://2016.ieeeicip.org/) in Phoenix, USA
- Josiane Zerubia, with Gabriele Moser and Sebastiano Serpico from University of Genoa, wrote in December an article about natural disaster monitoring for ERCIM News, see http://ercim-news.ercim.eu/en108/special/natural-disaster-monitoring-multi-source-image-analysis-with-hierarchical-markov-models.

9. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] I. HEDHLI.*Hierarchical joint classification models for multi-resolution, multi-temporal and multi-sensor remote sensing images. Application to natural disasters*, Université Nice Sophia Antipolis, March 2016, https://tel.archives-ouvertes.fr/tel-01333880.

Articles in International Peer-Reviewed Journal

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Project-Team BIOCORE

Biological control of artificial ecosystems

IN PARTNERSHIP WITH:
CNRS

INRA

Université Pierre et Marie Curie (Paris 6)

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Modeling and Control for Life Sciences

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Project-Team BIOCORE

Creation of the Project-Team: 2011 January 01

Keywords:

Computer Science and Digital Science:

1.5.1. - Systems of systems
6.1.1. - Continuous Modeling (PDE, ODE)
6.1.3. - Discrete Modeling (multi-agent, people centered)
6.1.4. - Multiscale modeling
6.2.1. - Numerical analysis of PDE and ODE
6.2.6. - Optimization
7.2. - Discrete mathematics, combinatorics

Other Research Topics and Application Domains:

1.1.9. - Bioinformatics
1.1.10. - Mathematical biology
1.1.11. - Systems biology
1.1.12. - Synthetic biology
1.2. - Ecology
2.4.1. - Pharmaco kinetics and dynamics
3.1. - Sustainable development
3.1.1. - Resource management
3.4.1. - Natural risks
3.4.2. - Industrial risks and waste
3.4.3. - Pollution
4.3.1. - Biofuels

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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 UPMC-CNRS (Oceanographic Laboratory of Villefranche-sur-mer - LOV, UMR 7093/ Université P.M. Curie, 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

- Collaboration with IFREMER (Nantes), INRA (MISTEA Montpellier, BIOGER Grignon. IAM Nancy, Agrocampus Ouest, MaIAGE Jouy-en-en-Josas, BioEpAR Nantes), CIRAD Montpellier, Centre d'Océanologie de Marseille, LOCEAN (Paris), GIPSA Grenoble, IBIS, BANG, ANGE and MODEMIC Inria teams.
- Participation in the French groups ModStatSAP (Modélisation et Statistique en Santé des Animaux et des Plantes), GDR Invasions Biologiques and PROBBE (Processus biologiques et bioinspirés pour l'Énergie).
- Université Catholique de Louvain (Belgium), Université de Mons (Belgium), University of Stuttgart (Germany), Rutgers University (USA), 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).
- Participation to national programmes: ANR *Blanc* projects Gemco and FunFit, ANR *BioME* projects Facteur 4 and Purple Sun, ANR projects Funfit and Phycover, *Projet d'Investissement d'Avenir* RESET, UMT Fiorimed, and Labex SIGNALIFE.

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 [73]. 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) [2].

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 (compared to chemicals)... The use of biocontrol agents, which are, generically, natural enemies (predators, parasitoids or pathogens) of crop pests [6], 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 [85] must be extended from a theoretical point of view and validated experimentally.

4.5. Experimental Platforms

To test and validate our approach, we use experimental platforms developed by our partner teams; these are highly instrumented for accurately monitoring the state of biological species:

- At LOV: A photobioreactor (SEMPO) for experimental simulation of the Lagrangian dynamical environment of marine microalgae with computer controlled automata for high frequency measurement and on-line control. This photobioreactor is managed by Amélie Talec and Eric Pruvost.

- At LOV: the Full Spectrum platform is dedicated to experimental pilots for microalgae production. This 60 m2 greenhouse contains four instrumented raceways. The light received by the cultivation devices can be modified with spectral filters. The objective of the platform is to grow algae in outdoor conditions, with the natural fluctuations of light and temperature. Finally this pilot allows to test management strategies in conditions closer to industrial production.
- At LBE: Several pilot anaerobic digesters that are highly instrumented and computerized and the algotron, that is the coupling of a digester and a photobioreactor for microalgae production. Eric Latrille is our main contact for this platform at LBE.
- AT ISA: Experimental greenhouses of various sizes (from laboratory to semi-industrial size) and small scale devices for insect behavior testing. A device for microalgae growth in greenhouses has also been set up at ISA. Christine Poncet is our main contact regarding experimental setups at ISA.

Moreover, we may use the data given by several experimental devices at EPI IBIS/ Hans Geiselmann Laboratory (University J. Fourier, Grenoble) for microbial genomics.

5. Highlights of the Year

5.1. Highlights of the Year

- 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, which depends on the pest-natural enemies interaction. Since some natural enemies may exhibit positive predator density dependence in the predation interaction, we studied its impact on the optimal biological control introduction strategies [15].
- Optimal allocation of resources in a bacterium. We studied 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) [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.

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

6.2. Odin

Platform for advanced monitoring, control and optimisation of bioprocesses
KEYWORDS: Bioinformatics - Biotechnology
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: Melaine Gautier, Florian Guenn, Fabien Dilet, Olivier Calabro, Romain Primet, Serigne Sow, Olivier Bernard, Mathieu Lacage and Francesco Novellis
- 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 biological models

7.1.1.1. Mathematical study of semi-discrete models

Participants: Frédéric Grognard, Ludovic Mailleret, Pierre Bernhard, Elsa Rousseau, Nicolas Bajeux, Bapan Ghosh.

Semi-discrete models have shown their relevance in the modeling of biological phenomena whose nature presents abrupt changes over the course of their evolution [81]. 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. 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, or through the introduction of biological control agents in deterministic [15] or stochastic [43], [33] fashion. 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, where the crop is absent, as in the dynamics of plant pathogens [24].

7.1.1.2. Model reduction and sensitivity analysis

Participants: Suzanne Touzeau, Jean-Luc Gouzé, Stefano Casagranda, 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 [67]. A global sensitivity analysis was performed to check the method robustness against parameter uncertainty and variability. A more general method robust to initial conditions has been elaborated [31]. This work is part of Stefano Casagranda’s ongoing PhD thesis and is also a collaboration with Bayer (Sophia-Antipolis).

7.1.1.3. *Estimation and control*

Participants: Suzanne Touzeau, Natacha Go, Jean-Luc Gouzé.

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. So we developed a specific procedure based on sensitivity analysis, to select the parameters to be estimated, to define their ranges and to set the values of the remaining parameters [72]. We used this method to fit a within-host immunological model to a large data set of individual viremia profiles. Our aim was not to reproduce individual profiles, but to identify parameter sets compatible with the data. So we based our fitting criterion on viral indicators rather than the whole viremia dynamics and we defined realistic data-based ranges for these indicators. We used a genetic algorithm for the minimisation. This ongoing work is part of Natacha Go's post-doctorate, supported by the MIHMES project, in collaboration with the Roslin Institute, Edinburgh, UK. It benefits from the resources and support of NEF computation cluster.

Parameter identification in compartmental systems. In collaboration with F. Dayan (R&D Manager, Dassault Systèmes), we work on practical problems of identifiability of parameters in linear pharmacokinetic models.

7.1.2. Metabolic and genomic models

Participants: Jean-Luc Gouzé, Madalena Chaves, Olivier Bernard, Valentina Baldazzi, Stefano Casagranda, Francis Mairet, Sofia Almeida, Claudia Lopez Zazueta, Lucie Chambon, Ivan Egorov.

7.1.2.1. *Hybrid models analysis*

Attractor computation using interconnected Boolean networks Following the work in [94] and [68], we have generalized the method for computation of the asymptotic graph. In addition, we have extended this methodology for the case of Boolean networks with synchronous updates (collaboration with D. Figueiredo and M.A. Martins from the University of Aveiro, Portugal).

Periodic orbits in non monotonic negative feedback circuits We study 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. By circumscribing the smooth system by two piecewise linear ones, we show there exists an invariant toroidal region which contains a periodic orbit of the original smooth system [29]. This orbit is unique under some conditions on the parameters.

Piecewise linear representation of genetic regulatory networks The main goal was to develop a methodology for constructing piecewise linear and discrete models from a continuous model: given an initial partition of the state space, or grid, a piecewise constant vector field and diagram of transitions were computed based on the original ODE in the grid (M2 thesis of C. Kozia).

7.1.2.2. *Continuous models analysis*

A reduced model for the mammalian cell cycle This work focuses on identifying and analysing the main mechanisms underlying the cell cycle. A reduced two-dimensional model was proposed and calibrated against experimental data on cyclin B. As a validation, the model faithfully predicts the period of the cell cycle in response to an external growth factor input (experimental data on the periods is from F. Delaunay's lab). This work in collaboration with F. Delaunay (and part of the PhD thesis of Sofia Almeida) has been submitted to a journal.

Modeling the apoptotic signaling pathway 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 (collaboration with J. Roux, for the PhD thesis of Luis Pereira).

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. We also study other models of the global cellular machinery. This is part of the PhD thesis of Stefano Casagranda, and done in collaboration with Inria IBIS project-team, in particular with D. Ropers.

Reduction of metabolic networks. We develop a dynamical reduction reduction for metabolic networks through Elementary Flux Modes and Quasi Steady State Approximation. The aim is, in the spirit of [1], to obtain a system of lower dimensions, with some accumulative variables. This is part of the PhD thesis of Claudia Lopez Zazueta.

7.1.2.3. 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) [23]. We developed different versions of the problem, and consider a new problem where the aim is to optimize the production of a product (ANR project Reset).

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 [74].

7.1.2.4. Slow-Fast analysis of metabolic models

Metabolic modelling 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 [16], and show that Drum is a reasonable approximation, provided that growth rate stays low.

7.2. Fields of applications

7.2.1. Bioenergy

7.2.1.1. Modelling microalgae production

Participants: Olivier Bernard, Antoine Sciandra, Frédéric Grognard, Ghjuvan Grimaud, Quentin Béchet, David Demory, Anaïs Bacquet, Jean-Philippe Steyer, Francis Mairet.

Experimental developments

Experiments have been carried out to study the effects of nitrogen limitation on the lipid production in microalgae and support model development. These experiments have been carried out in the Lagrangian simulator, under constant or periodic light and temperature, varying the total amount of light dose in the day [11]. The response in terms of storage carbon (triglycerides and carbohydrates) has been measured and correlated to the environment fluctuations.

Other experiments were carried out to reproduce the light signal percept by a cell in a raceway pond [71], derived from hydrodynamical studies [79]. An electronic platform was developed to reproduce this high frequency light signal. The experiments show that the microalgae adapt their pigments to the average light that they have received [70]. Experiments with coloured light demonstrated that the growth rate results from the absorbed light, whatever its wavelength.

A new methodology to measure cell viability has been set up. This approach is very promising to distinguish between net and gross growth rate [66]. It was used in the models to assess the impact of temperature on growth and mortality [20], [30].

On top of this, we carried out pilot experiments with solar light. We tested the impact of coloured film mimicking possible photovoltaic material. The collected data were used to calibrate models integrating the light spectrum in Ambre Veisseix's master thesis.

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

Metabolism of carbon storage and lipid production

A macroscopic model for lipid production by oleaginous microalgae [7] has been previously proposed. This model describes the accumulation of neutral lipids (which can be turned into biofuel), carbohydrates and structural carbon [57], [56][16]. A metabolic model has been set up and validated for the microalgae *Isochrysis luthea*. A model was developed to represent heterotrophic growth on a mixture of acetate and butyrate [95]. A metabolic model was set up, on the basis of the DRUM framework [1], 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 in Anais Bacquet's master thesis.

Modelling the coupling between hydrodynamics and biology

The evolution of the biomass of microalgae in a raceway may be analyzed through an advection-diffusion-reaction Partial Differential Equations (PDE). First, the advection part corresponds to the transportation of the biomass through the raceway. Second, the diffusion coefficient allows to consider a Brownian motion for each particular trajectory of the particle. Finally, the reaction term corresponds to the biological dynamics. The optimization of the raceway was carried out by a vertical discretization of the raceway and an adjoint-based approach. In a similar way, the shape optimization was considered with the steady solutions of the Saint-Venant equations.

In collaboration with the Inria ANGE team, a model coupling the hydrodynamics of the raceway (based on a new multilayer discretisation of Navier-Stokes equations) with microalgae growth was developed [63]. This model is supported by the work of ANGE aiming at improving the discretization scheme to more finely represent the hydrodynamics of the raceway and more accurately reconstruct Lagrangian trajectories.

Modelling the photosynthesis response to fast fluctuating light

The impact of hydrodynamics on the light perceived by a single cell was studied thanks to fluid dynamics simulations of a raceway pond [78]. The light signals that a cell experiences at the Lagrangian scale, depending on the fluid velocity, were then estimated. A Droop-Han model was used to assess the impact of light fluctuation on photosynthesis. A new model accounting for photoacclimation was also proposed [28]. Single cell trajectories were simulated, and the effect on photosynthesis efficiency was assessed using models of photosynthesis. These results were compared to experimental measurements where the high frequency light was reproduced.

Modelling 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. A simpler model was developed and used to identify the optimal working mode of a process based on photosynthetic biofilm growing on a conveyer belt, in Jérome Grenier's internship.

Modeling microalgae production processes

The integration of different models developed within BIOCORE [61], [65], [7] was performed to represent the dynamics of microalgae growth and lipid production in raceway systems, on the basis of the dynamical model developed to describe microalgal growth under light and nitrogen limitations.

Using these approaches, we have developed a model which predicts lipid production in raceway systems under varying light, nutrients and temperature [36]. This model is used to predict lipid production in the perspective of large scale biofuel production [61].

In the framework of the ANR project Purple Sun, we developed a thermic model of a raceway pond within a greenhouse in order to estimate the culture temperature. We also included in the microalgae model the effect of light wavelength. This model has been calibrated on experimental data from LOV and has been used to support lighting strategy in order to optimize microalgal productivity (a patent on this process has been submitted).

Modelling thermal adaptation in microalgae

An extended statistical analysis was carried out on a database representing the temperature response of more than 200 microalgal species [12]. First the model proposed by [62] turned out to properly reproduce the temperature response. A model was then extracted to predict the observed link between the cardinal temperatures.

We have used Adaptive Dynamics theory to understand how temperature drives evolution in microalgae. For a constant temperature, we have shown that the optimal temperature trait tends to equal the environment temperature [12]. We now use this method at the scale of the global ocean, validating our approach with experimental data sets from 194 species [75], [76].

Modelling 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.

7.2.1.2. Control and Optimization of microalgae production

On-line monitoring

Interval observers give an interval estimation of the state variables, provided that intervals for the unknown quantities (initial conditions, parameters, inputs) are known [73], [86]. Interval observers were designed for the estimation of the microalgae growth and lipid production within a production process [61] and validated experimentally [83].

Optimization of the bioenergy production systems

Based on simple microalgae models, analytical optimization strategies were proposed. We assessed strategies for optimal operation in continuous mode using the detailed model for raceways [88]. We first solved numerically an optimal control problem on a finite time horizon. Then, we re-analysed the optimization problem and derived a simplified sub-optimal strategy. These approaches were extended to outdoor cultivation, considering a possible variable culture depth. Assuming known weather forecasts considerably improved the control efficiency [21].

We also propose a nonlinear adaptive controller for light-limited microalgae culture, which regulates the light absorption factor (defined by the ratio between the incident light and the light at the bottom of the reactor).

Interactions between species

We had formerly proposed an adaptive controller which regulates the light at the bottom of the reactor [84]. When applied for a culture with n species, the control law allows the selection of the strain with the maximum growth rate for a given range of light intensity. This is of particular interest for optimizing biomass production as species adapted to high light levels (with low photoinhibition) can be selected. We have also proposed a strategy based on light stresses in order to penalize the strains with a high pigment content and finally select microalgae with a low Chlorophyll content [64][39]. This characteristic is of particular interest for maximizing biomass production in dense culture. The strategy has been carried out at the LOV and eventually the productivity of *Tisochrysis lutea* was improved by 75%. A patent on this strategy has been submitted.
Strategies to improve the temperature response have also been proposed. First we modelled the adaptive dynamics for a population submitted to a variable temperature [12]. This was used at the LOV to design experiments with periodic temperature stresses during 200 days aiming at enlarging the thermal niche of *Tisochrysis lutea*. It resulted in an increase by 2 degrees of the thermal niche [64].
Finally, in a more theoretical framework, we studied how to select as fast as possible a given species in a chemostat with two species at the initial instant. Using the Pontryagin maximum principle, we have shown that the optimal strategy is to maintain the substrate concentration to the value maximizing the difference between the growth rates of two species [58]. We now try to extend this result for n species with mutations.

7.2.2. Biological depollution

7.2.2.1. Control and optimization of bioprocesses for depollution

Participants: Olivier Bernard, Francis Mairet, Jean-Luc Gouzé.

We have considered the problem of global stabilization of an unstable bioreactor model (e.g. for anaerobic digestion), when the measurements are discrete and in finite number ("quantized"). These measurements define regions in the state space, wherein a constant dilution rate is applied We show that this quantized control may lead to global stabilization: trajectories have to follow some transitions between the regions, until the final region where they converge toward the reference equilibrium [82].

Although bioprocesses involve an important biodiversity, the design of bioprocess control laws are generally based on single-species models. In [26], we have proposed to define and study the multispecies robustness of bioprocess control laws: given a control law designed for one species, what happens when two or more species are present? We have illustrated our approach with a control law which regulates substrate concentration using measurement of growth activity. Depending on the properties of the additional species, the control law can lead to the correct objective, but also to an undesired monospecies equilibrium point, coexistence, or even a failure point. Finally, we have shown that, for this case, the robustness can be improved by a saturation of the control.

7.2.2.2. Coupling microalgae to anaerobic digestion

Participants: Olivier Bernard, Antoine Sciandra, Jean-Philippe Steyer, Frédéric Grognard, Francis Mairet.

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 [93], [92].

We have proposed and analysed a three dimensional model which represent the coupling of a culture of microalgae limited by light and an anaerobic digester. We first prove the existence and attraction of periodic solutions. Applying Pontryagin's Maximum Principle, we have characterized optimal controls, including the computation of singular controls, in order to maximize methane production. Finally, we have determined numerically optimal trajectories by direct and indirect methods [59].

7.2.2.3. Life Cycle Assessment

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

In the sequel of the pioneering life cycle assessment (LCA) work of [80], we continued to identify the obstacles and limitations which should receive specific research efforts to make microalgae production environmentally sustainable.
The improvements due to technological breakthrough (leading to higher productivities) have been compared to the source of electricity. It turns out that the overall environmental balance can much more easily be improved when renewable electricity is produced on the plant [90]. As a consequence, a new paradigm to transform solar energy (in the large) into transportation biofuel is proposed, including a simultaneous energy production stage. This motivated the design of the purple sun ANR-project where electricity is produced by semi transparent photovoltaic panels [60] under which microalgae are growing. The LCA of such innovative processes where microalgae are grown under greenhouses has been carried out.

Finally, some work are aiming at normalising LCA for microalgae and proposing guidelines to make the LCA more easily comparable [69].

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 pests

Participants: Frédéric Grognard, Ludovic Mailleret, Suzanne Touzeau, Nicolas Bajeux.

Optimization of biological control agent introductions

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 [6] [89], unveiling the crucial influence of within-predator density dependent processes. Since some natural enemies may be more prone to exhibit positive density dependent dynamics rather than negative ones, we studied the impact of positive predator-predator interactions on the optimal biological control introduction strategies (PhD of Nicolas Bajeux, [15]). Current research aims to understand the influence of different forms of stochasticity in the introduction process or the population dynamics on the efficacy of the introduction program [43], [33]. This last part of N. Bajeux's PhD si performed in collaboration with Vincent Calcagno (ISA).

Characteristics of space and the behavior and population dynamics of parasitoids

We tested the influence of the spatial heterogeneity of resource (hosts) distribution on the movements and fitness of individual parasitoids on a laboratory and a wild strain of the same species of *Trichogramma.* We showed that the level of resource aggregation has not the same influence on the different strains of the parasitoid, pointing out a behavioral adaptation of the laboratory strain [44]. This work is part of Victor Burte PhD Thesis (ISA, 2015-) and is done in close collaboration with V. Calcagno (ISA).

Connected research on the influence of space on the establishment of biological control agents is also being pursued both through computer simulations and laboratory experiments on *Trichogramma* [50]. This was the topic of the PhD thesis of Thibaut Morel Journel (ISA, defended in December 2015) [87] and is the present topic of Marjorie Haond (ISA, 2015-). In particular, we showed both theoretically and experimentally how landscape connectivity [27] or habitat richness [45], [37], [46] shape the spatio-temporal dynamics of populations in spatially structured environments. This work is being performed in collaboration with Elodie Vercken (ISA) and Lionel Roques (BioSP, Avignon).

7.2.3.2. Controlling plant pathogens

Participants: Frédéric Grognard, Ludovic Mailleret, Suzanne Touzeau, Elsa Rousseau.

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 also conducted in INRA Avignon, followed by high-throughput sequencing (HTS) to identify the dynamics of virus strains competing within host plants. Different plant genotypes were chosen for their contrasted effects on genetic drift and selection they induce on virus populations. Those two evolutionary forces can play a substantial role on the durability of plant resistance. Therefore we fitted a mechanistic-statistical model to these HTS data in order to disentangle the relative role of genetic drift and selection during within-host virus evolution [41], [42]. A stochastic model was also produced to simulate the effect of drift on the virus epidemiological dynamics and on the durability of qualitative resistances [32], [40]. This was the topic of Elsa Rousseau's PhD thesis [14], and was done in collaboration with Frédéric Fabre (INRA Bordeaux) and Benoît Moury (INRA Avignon).

We also developed an epidemiological model describing the dynamics of root-knot nematodes in a protected vegetable cropping system, to design optimal management strategies of crop resistance. The model was fitted to experimental and field data. Preliminary results show that alternating susceptible and resistant crops not only increased the resistance durability, but reduced the disease intensity over time [47]. This research is the main topic of Samuel Nilusmas PhD thesis (ISA, 2016-).

We extended the epidemiological model describing the phoma stem canker of oilseed rape, which aims at assessing the durability of crop resistance in the field and design efficient deployment strategies. We introduced a spatial structure based on real landscapes, as well as plant rotation strategies based on surveys conducted among farmers and cooperatives. We also performed a sensitivity analysis, to guide the model calibration. This ongoing work is part of (i) the K-Masstec project, which also incorporates experimental and field studies in collaboration with BIOGER (INRA Grignon); (ii) the GESTER project, with close collaborations with various INRA partners. It benefits from the resources and support of NEF computation cluster.

Eco-evolutionary dynamics of plant pathogens in seasonal environments

Understanding better pathogen evolution also requires to understand how closely related plant parasites may coexist. Such coexistence is widespread and is hardly explained through resource specialization. We showed that, in agricultural systems in temperate environments, the seasonal character of agrosystems is an important force promoting evolutionary diversification of plant pathogens [77]. The plant parasites reproduction mode may also strongly interact with seasonality. In this context, we investigated the special case of oak powdery mildew, an oak disease which is actually caused by a complex of two different species, combining original plant epidemic data with the semi-discrete seasonal plant epidemic model we introduced a few years ago [24]. This work has been done in collaboration with Frédéric Hamelin (Agrocampus Ouest), Marie Laure Desprez Loustau and Frederic Fabre (INRA Bordeaux).

7.2.3.2.1. Optimality/games in population dynamics

Participants: Frédéric Grognard, Ludovic Mailleret, Pierre Bernhard, Ivan Egorov.

Optimal resource allocation

Mycelium growth and sporulation is considered for phytopathogenic fungi. For biotrophic fungi, a flow of resource is uptaken by the fungus without killing its host; in that case, the life history traits (latence-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. This work, in the framework of the ANR Funfit project, is done with Fabien Halkett of INRA Nancy.

Optimal foraging and residence times variations

We also investigated the problem in foraging theory of evaluating the expected harvest of an animal when conspecifics may arrive on the same patch of resource in a stochastic fashion, specificaly according to a Poisson process or a Bernoulli process [18].

With Marc Deschamps, similar questions were studied in theoretical economy in the context of a Cournot competition on a single market [17].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

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

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

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. National programmes

- **ANR-Purple Sun:** The objective of this project (ANR-13-BIME-004) is to study and optimize a new concept consisting in coupling the production of microalgae with photovoltaic panels. The main idea is to derive the excess of light energy to PV electricity production, in order to reduce the phenomena of photoinhibition and overwarming both reducing microalgal productivity.

- **ANR-Facteur 4:** The objective of this project to produce non OGM strain of microalgae with enhanced performance. BIOCORE is involved in the directed selection of microalgae with interesting properties from an industrial point of view. The theory of competition is used to give a competitive advantage to some species. This competitive advantage can be provided by an online closed loop controller.
- **ANR-Phycover:** The overall objective of the PHYCOVER project 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 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 (2013-2017) 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-GESTER:** “Management of crop resistances to diseases in agricultural landscapes as a response to new constraints on pesticide use”, ANR Agrobiosphère, 2011–2016. This project aims at producing allocation scenarios of resistant varieties at the scale of cultivated landscapes, that will allow to limit disease development while ensuring sustainable efficiency of genetic resistances. BIOCORE participates in this project via MaIAGE, INRA Jouy-en-Josas.
- **ANR-MIHMES:** “Multi-scale modelling, from animal Intra-Host to Metapopulation, of mechanisms of pathogen spread to Evaluate control Strategies”, ANR – Investissement d’avenir, action Bioinformatique (ANR-10-BINF-07) & Fond Européen de Développement Régional des Pays-de-la-Loire (FEDER), 2012–2017. This project aims at producing scientific knowledge and methods for the management of endemic infectious animal diseases and veterinary public health risks. BIOCORE participates in this project via MaIAGE, INRA Jouy-en-Josas. This project supports Natacha Go’s postdoctoral position.
- **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.
- **RESET:** The objective of this project is to control the growth of *E. coli* cells in a precise way, by arresting and restarting the gene expression machinery of the bacteria in an efficient manner directed at improving product yield and productivity. RESET is an “Investissements d’Avenir” project in Bioinformatics (managed by ANR) and it is coordinated by H. de Jong (Ibis, Inria)
- **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.

9.1.2. Inria funding

- **Inria Project Lab, Algae** *in silico***:** The Algae in silico Inria Project Lab, funded by Inria and coordinated by O. Bernard, focuses on the expertise and knowledge of biologists, applied mathematician and computer scientists to propose an innovative numerical model of microalgal culturing devices. The latest developments in metabolic modelling, hydrodynamic modelling 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.

9.1.3. INRA funding

- **Take Control:** This project, “Deployment strategies of plant quantitative resistance to take control of plant pathogen evolution,” is funded by the PRESUME call of the SMAcH INRA metaprogram (Sustainable Management of Crop Health). BIOCORE is a partner together with INRA PACA (Sophia Antipolis and Avignon) and INRA Toulouse (2013-2016). This project provides the major part of the funding for the experiments held for Elsa Rousseau’s thesis.
- **K-Masstec:** “Knowledge-driven design of management strategies for stem canker specific resistance genes”, INRA Metaprogramme SMaCH, PRESUME action, 2013–2016. The project aims at developing efficient strategies for the deployment of genetic resistance in the field, based on knowledge issued from the understanding of the molecular interaction between distinct avirulence genes, and mainly the discovery of non-conventional gene-for-gene interactions.

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 comitee 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 modelling 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. FP7 & H2020 Projects

SysBioDRez: Marie Curie International Incoming Fellowship FP7 (EC-PEOPLE) is a multidisciplinary CNRS-Inria project for the collaboration of Jeremie Roux (researcher) with both Paul Hofman (scientist in charge) and Jean-Luc Gouzé (partner lab), with the objective of linking in vitro quantitative dynamics to primary tumor samples profiling in order to determine the resistance probability of a specific combination of anti-cancer drugs in lung cancer, using computational methods (see [91]).

9.2.2. Collaborations with Major European Organizations

Imperial college, Department of Chemical engineering (UK),

Modelling and optimization of microalgal based processes.

Imperial College, Centre for Synthetic Biology and Innovation, Dept. of Bioengineering (UK):

Study of metabolic/genetic models

University of Aveiro, Portugal

Interconnected boolean networks

Roslin Institute, Edinburgh, UK

Epidemiology

University of Padova, Italy.

Modelling and control of microalgal production at industrial scale.

9.3. International Initiatives

9.3.1. Inria International Labs

Inria Chile

Associate Team involved in the International Lab:

9.3.1.1. GREENCORE

Title: Modelling and control for energy producing bioprocesses

International Partners (Institution - Laboratory - Researcher):

CIRIC (Chile) - Mélaine Gautier

PUCV (Chile) - Escuela de Ingenieria Bioquimica (EIB) - Gonzalo Ruiz Filippi

UTFSM (Chile) - Departamento de Matematica - Eduardo Cerpa

UFRO (Chile) - Chemical Engineering Department - David Jeison

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 UFRO) and software development (CIRIC).

9.3.1.2. Other IIL projects

BIOCORE is involved in the Bionature project from Inria Chile CIRIC (the Communication and Information Research and Innovation Center), in collaboration with four Chilean universities (Universidad de Chile, Universidad Tecnica Federico Santa Maria, Pontificia Universidad Catolica de Valparaiso, and Universidad de la Frontera). The Bionature project is devoted to natural resources management and the modeling and control of bioprocesses.

9.3.2. Inria International Partners

9.3.2.1. Informal International Partners

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

Universidad de la Frontera (CL), Modelling of CO_2 transfer in a microalgal absorption column.

GRIMCAPE, Université de Douala, Cameroon. Epidemiology.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

- Claude Aflalo (Ben Gurion University of the Neguev, Israel), 1 week;
- Eduardo Sontag (Rutgers University);
- Laurent Tournier (Inra Jouy-en-Josas), 1 week;
- Bapan Ghosh (National Institute of Technology Meghalaya, India), 1 month.

9.5. Project-team seminar

BIOCORE organized a 4-day seminar in September in La Colle-sur-Loup. On this occasion, every member of the project-team presented his/her recent results and brainstorming sessions were organized. Jacques-Alexandre Sepulchre (INLN, Univ. Nice) was invited as a guest speaker.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

J.-L. Gouzé organized with P. Brest, H. Barelli and F. Besse the Signalife Maths-Bio workshop held at the Inria Sophia Antipolis center, on November 25.

10.1.1.1. Members of the conference program committee

J.-L. Gouzé is a member of the program committee for the conference BIOMATH, held in Sofia (Bulgaria), and POSTA (Rome, Italy). He is in the scientific committees of several summer schools.

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

Valentina Baldazzi co-organised the HortiModel2016 international symposium on *Models for plant growth, environment control and farming management in protected cultivation*, Avignon, 16–22 September 2016.

10.1.1.2. Reviewers

All BIOCORE members have been reviewers for the major 2016 conferences in our field: CDC, IFAC NOLCOS,...

10.1.2. Journal

10.1.2.1. Members of the editorial board

M. Chaves is an Associated Editor of SIAM Journal on Applied Dynamical Systems (SIADS), since January 2015

10.1.2.2. Reviewers

All BIOCORE members have been reviewers for the major journals in our field: Automatica, IEEE Transactions on Automatic Control, Journal of Mathematical Biology, Mathematical Bisciences, New Phytologist,...

10.1.3. Invited talks

J.-L. Gouzé was invited to give the plenary introductory lecture at POSTA, the 5th International Symposium on Positive Systems, Università Campus Bio-Medico di Roma , Italy.

M. Chaves gave a talk at the workshop on “Asynchronous dynamics of logical models: assessing biologically relevant properties”, at CIRM, Marseille (November 2016).

O. Bernard was invited to give a conference on microalgae at Ecole Centrale de Paris (“Biotechnological challenge”) ‘Use of microorganisms for biofuel production” (December, 8th, 2016).

O. Bernard was invited to give a talk at the ALgoReso workshop related to the development of innovative photobioreactors (May, 12th, 2016).

O. Bernard was invited for a presentation at the Metabolism in Systems Biology (Lille, 24th of November, 2016) workshop organized by the BIOSS working group.

O. Bernard was invited for a talk at the Days of the SFR Condorcet (Namur, 5-6 july, 2016).

10.1.4. Scientific expertise

J.-L. Gouzé was in several evaluation committees or juries: Stic Amsud, Région Région Aquitaine- Limousin - Poitou Charentes, Université de Grenoble, Centrale-Supelec.

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

10.1.5. Research administration

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).

M. Chaves and J.-L. Gouzé were part of the committee for the selection of the 2016 Signalife PhD students.

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 as well as some project proposals (EuroMed 3+3), and ERCIM post-docs.

M. Chaves is a member of the CLHSCT (local committee for the safety of working conditions)

O. Bernard represents Inria at the ANCRE (Alliance Nationale de Coordination de la Recherche pour l’Energie), in the biomass committee. He is a member of the ADT (Technological Development Actions) at Inria.

S. Touzeau is an elected member of the scientific committee of the MIA department at INRA (2011–2016). She is a member of the steering committee of the metaprogramme SMaCH *Sustainable Management of Crop Health*, INRA (since 2016).

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 member of the steering committee of Academy 3, Space, Environment, Risk & Resilience of UCA-JEDI.

L. Mailleret is the head of the M2P2 team (Models and Methods for Plant Protection) of ISA.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Bachelor: F. Grognard (45.5h ETD) and L. Mailleret (26h ETD), “Equations différentielles ordinaires et systèmes dynamiques”, L3, 1st year Engineering in Modelling and Applied Mathematics, Polytech’Nice, Université of Nice Sophia Antipolis, France.

Bachelor: N. Bajeux (192h ETD) is ATER at IUT Nice Côte d'Azur of Université of Nice Sophia Antipolis, France.

Master: F. Grognard (33h ETD) and L. Mailleret (33h ETD), “Bio-Mathématiques”, M1, 2nd year Engineering in Modelling and Applied Mathematics (eq. M1), Polytech'Nice, Université of Nice Sophia Antipolis, France.

Master: J.-L. Gouzé (9h ETD), M. Chaves (9h ETD), “Discrete and continuous approaches to model gene regulatory networks”, Master of Science in Computational Biology (M2), University of Nice - Sophia Antipolis.

Master: J.-L. Gouzé (18h ETD), M. Chaves (12h ETD) “Modelling biological networks by ordinary differential equations”, 4th year students, Génie Biologie, Polytech'Nice, University of Nice - Sophia Antipolis.

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), “Modelling biotechnological processes”, M2, Ecole Centrale de Paris, France.

Master: S. Touzeau (30.75h ETD), “Analyse de données”, M1, 2nd engineering year in Génie Biologie, Polytech'Nice – Université Nice Sophia Antipolis, France.

Doctorat: M. Chaves gave courses at the Research School on “Modelling Complex Biological Systems in the Context of Genomics, advances in Systems and Synthetic Biology” (1.5h, Évry, March 2016) and the Summer School on “Modélisation formelle de réseaux de régulation biologique” (3h, Porquerolles, June 2016).

Doctorat: S. Touzeau (8h), “Mathematical modelling in animal and plant epidemiology”, CIMPA-Cameroun-CETIC research school *Mathematical and Computer Models in Epidemiology, Ecology and Agronomy*,Yaoundé, Cameroon, September 2016.

O. Bernard together with F. Mairet and Q. Béchet supervised two projects for engineering school students. The first project involved 6 students of Ecole Nationale Supérieure des Mines de Paris (last year of engineering school, 1 week ("Combining photovoltaic panels and microalgae") and the second project involved three groups of 4 students from the Ecole Centrale de Paris (first year of engineering school), 4 months, to design a process with microalgae growing on a biofilm.

10.2.2. Supervision

HDR: F. Mairet, "Control theory applied to microorganism growth: from physiological insights to bioprocess management", December 7th, 2016.

PhD : C. Combe, "Quantitative and qualitative effects of light on the Growth of microalgae in dense cultures ", May, 9th, 2016, UPMC. Supervisors: A. Sciandra, S. Rabouille and O. Bernard.

PhD : E. Rousseau, ”Impact of genetic drift and selection on the durability of plant resistance to viruses" ”, May 27th, 2016, Univ. Nice Sophia Antipolis. Supervisors: F. Grognard, L. Mailleret, B. Moury, and F. Fabre (INRA Avignon).

PhD : G. Grimaud, "Modeling of the effect of temperature on phytoplankton: from acclimation to adaptation", June, 14th, 2016 Univ. Nice Sophia Antipolis. Supervisors: O. Bernard, F. Mairet and S. Rabouille.

PhD in progress : D. Demory, "Impact of virus dynamics on microalgae mortality ", since September 2013, UPMC. Supervisors: A. Sciandra and O. Bernard.

PhD in progress : N. Bajeux, "Influence d'une densité dépendance dans les modèles impulsionnels de dynamiques des populations", since October 2013, Univ. Nice Sophia Antipolis. Supervisors: F. Grognard and L. Mailleret.

PhD in progress : S. Casagranda. “Analysis and control of cell growth models”, since November 2013, Univ. Nice Sophia Antipolis. Supervisors: J.-L. Gouzé and D. Ropers (Inria IBIS).

PhD in progress : S. Almeida. "Theoretical design of synthetic biological oscillators and their coupling", since October 2014, Univ. Nice Sophia Antipolis. Supervisors: M. Chaves and F. Delaunay (Univ. Nice, iBV).

PhD in progress : M. Caïa, "Characterization and modelling of a mixotrophic algae - bacteria ecosystem for waste recovery", since September 2015, University Montpellier. Supervisors: J.-P. Steyer and O. Bernard.

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 : C. Martinez von Dossow . "Modélisation et optimisation de consortia microalgues-bactéries", since February 2016, UPMC. Supervisors: O. Bernard, F. Mairet and A. Sciandra.

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, Univ. Nice Sophia Antipolis. Supervisors: M. Chaves and J. Roux (IRCAN, Nice).

PhD in progress : L. Chambon. “Control of models of genetic regulatory networks”. since October 2016, Univ. Nice Sophia Antipolis. Supervisor J.-L. Gouzé.

PhD in progress : C. Lopez-Zazueta. “Use of Perturbation Theory to optimize metabolic production of biofuels by microalgae.”, since January 2016, Univ. Nice Sophia Antipolis, supervisors O. Bernard and J.-L. Gouzé.

PhD in progress: S. Nilusmas, “Gestion durable des nématodes à galles en cultures maraîchères : modélisation et optimisation du déploiement des résistances et des pratiques agronomiques”, since December 2016, Univ. Nice Sophia Antipolis. Supervisors: S. Touzeau, C. Caporalino (ISA), V. Calcagno (ISA), P. Castagnone (ISA) and L. Mailleret.

Master theses and engineering internships supervision

M1: Ambre Vaisseix, "Effet de la température pour des cultures de microalgues sous serre", Université de Nantes

M1: Anais Bacquet, "Modélisation métabolique de Chlorella sorokiniana, en condition mixotrophe pour identifier des stratégies optimales de consommation de déchets organiques", Univ. Nice Sophia Antipolis.

Engineer: Jérome Grenier, "Développement et modélisation d’un système innovant de production de microalguessous forme de biofilm", Ecole Centrale de Paris

M2: Christina Kozia, "Dynamical representation and analysis of models of genetic regulatory networks", Univ. Nice Sophia Antipolis.

Engineer: Arthur Péré, "Évaluation in silico de la durabilité de résistances variétales avec interaction entre gènes par une approche de modélisation", INSA Lyon.

M2: Samuel Nilusmas, "Évolution de la virulence chez un nématode phytoparasite : déploiement optimal et robuste de plantes résistantes", Université Claude Bernard Lyon 1.

10.2.3. Juries

M. Chaves was reviewer for the PhD defense of Simona Catozzi "Retroactivity in signal transduction: a comparative study of forward and backward responses in signaling cascades", University of Nice Sophia Antipolis, December 15, 2016.

J.-L. Gouzé was reviewer for the PhD of Hafiz Ahmed “Modeling and synchronization of biological rhythms: from cells to oyster behavior”, University of Lille 1, September 22, 2016.

J.-L. Gouzé was reviewer for the PhD of Clément Aldebert, “Uncertainty in predictive ecology: consequence of choices in model construction ”, Univ Aix-Marseille, November 29, 2016.

J.-L. Gouzé was in the jury of the HDR of Francis Mairet, “ Control theory applied to microorganism growth: from physiological insights to bioprocess management ”, University of Nice Sophia Antipolis, December 7, 2016.

J.-L. Gouzé was in the jury of the PhD of Dominique Lamonica, “Capturer les interactions écologiques en microcosme sous pression chimique à travers le prisme de la modélisation”, Université Claude Bernard Lyon 1,April 8, 2016.

J.-L. Gouzé was in the jury of the PhD of Elsa Rousseau “Effect of genetic drift and selection on plant resistance durability to viruses”, University of Nice Sophia Antipolis, May 27, 2016. F. Grognard and L. Mailleret were invited members of this jury

O. Bernard was reviewer for the HDR of S. Tebbani "Contribution à l’étude des systèmes non linéaires incertains : application à la commande de systèmes biotechnologiques ", University of Paris-Sud, November 7th, 2016.

O. Bernard was reviewer for the PhD thesis of C. E. Robles Rodriguez " Modeling and optimization of bio-lipid production by oleaginous yeasts ", University of Toulouse, October 19th, 2016.

O. Bernard was in the PhD jury of J. Rumin "Non-GMO improvement of microalgae performances", University of Nantes, March, 16th, 2016.

O. Bernard was in the PhD jury of G. Grimaud, "Modeling of the effect of temperature on phytoplankton: from acclimation to adaptation", Univ. Nice, June 14th, 2016.

O. Bernard was in the PhD jury of C. Combe, "Quantitative and qualitative effects of light on the Growth of microalgae in dense cultures ", UPM, May 9th, 2016.

S. Touzeau is in the thesis committees of David Demory (UPMC, 2013–2016).

10.3. Popularization

The activities related to microalgae have generated many articles in national newspapers (Le Monde, Nice Matin, journal du CNRS,...) where ...), and broadcasts on national radio (Europe 1) and TV (France 2, France 3). Several articles were written by the team members explaining the hurdles and potential of microalgae.

M. Chaves was part of the jury for the PhD student contest "Ma thèse en 180 sec" (regional stage, April 2016, Nice).

Biocore, especially Stefano Casagranda and Lucie Chambon, was involved in the "Spring of Researchers" and in the "Fête de la Science".

P. Bernhard has given conferences in Lycée René Gosciny, in Drap on January 12th (Le nombre d’or: mythes et curiosités), in Lycée Alexandre Dumas, in Cavaillon on February 29th ("Game Theory") and in Lycée Costebelle, in Hyères on March 15th (Le nombre d’or: mythes et curiosités).

11. Bibliography

Major publications by the team in recent years

[1] C. Baroukh, R. Muñoz-Tamayo, J.-P. Steyer, O. Bernard. *DRUM: A New Framework for Metabolic Modeling under Non-Balanced Growth. Application to the Carbon Metabolism of Unicellular Microalgae*, in "PLoS ONE", August 2014, vol. 9, n^{o} 8, e104499 [*DOI :* 10.1371/journal.pone.0104499], https://hal.inria.fr/hal-01097327.

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[7] F. Mairet, O. Bernard, P. Masci, T. Lacour, A. Sciandra.*Modelling neutral lipid production by the microalga Isochrysis affinis galbana under nitrogen limitation*, in "Biores. Technol.", 2011, vol. 102, p. 142-149, http://dx.doi.org/10.1016/j.biortech.2010.06.138.

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Publications of the year

Doctoral Dissertations and Habilitation Theses

[11] C. Combe.*Quantitative and qualitative effects of light on the growth of microalgae in dense cultures and on the production of molecules of interest*, Université Pierre et Marie Curie - Paris VI, May 2016, https://tel.archives-ouvertes.fr/tel-01395588.

[12] G. M. Grimaud.*Modelling the temperature effect on phytoplankton : from acclimation to adaptation*, Université Nice Sophia Antipolis, June 2016, https://tel.archives-ouvertes.fr/tel-01383294.

[13] F. Mairet.*Control theory applied to microorganism growth: from physiological insights to bioprocess management*, Université de Nice Sophia Antipolis, December 2016, Habilitation à Diriger des Recherches, Ph. D. Thesis.

[14] E. Rousseau.*Impact of genetic drift and selection on the durability of plant resistance to viruses*, Université de Nice Sophia Antipolis, May 2016.

Articles in International Peer-Reviewed Journal

[15] N. BAJEUX, F. GROGNARD, L. MAILLERET.*Augmentative biocontrol when natural enemies are subject to Allee effects*, in "Journal of Mathematical Biology", 2016 [*DOI :* 10.1007/S00285-016-1063-8], https://hal.archives-ouvertes.fr/hal-01402250.

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Invited Conferences

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International Conferences with Proceedings

[33] N. BAJEUX, F. GROGNARD, L. MAILLERET, V. CALCAGNO.*Introduced populations in a stochastic world*, in "Models in population dynamics and ecology", Marseille, France, 2016, https://hal.archives-ouvertes.fr/hal-01402247.

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Team BIOVISION

Biologically plausible Integrative mOdels of the Visual system : towards synergIstic Solutions for visually-Impaired people and artificial visiON

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 Medecine

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Team BIOVISION

Creation of the Team: 2016 January 01

Keywords:

Computer Science and Digital Science:

5.3. - Image processing and analysis
5.4. - Computer vision
5.6. - Virtual reality, augmented reality
6.1.1. - Continuous Modeling (PDE, ODE)
6.1.4. - Multiscale modeling
6.1.5. - Multiphysics modeling
6.2.4. - Statistical methods

Other Research Topics and Application Domains:

1.1.10. - Mathematical biology
1.3.1. - Understanding and simulation of the brain and the nervous system
1.4. - Pathologies
2.1. - Well being
2.5.1. - Sensorimotor disabilities
9.4.2. - Mathematics
9.4.3. - Physics

1. Members

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Bruno Cessac [Team leader, Inria, Senior Researcher, HDR]
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PhD Students

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Kartheek Medathati [Inria, PhD Student, until December 2016]
Selma Souihel [Inria, PhD Student, from September 2016]

Post-Doctoral Fellows

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Daniela Pamplona [Inria, Post-Doctoral fellow until December 2016]

Administrative Assistant

Marie-Cecile Lafont [Inria, AI]

Others

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Selma Souihel [Inria grant, Internship , from March 2016 until September 2016]

2. Overall Objectives

2.1. Overall Objectives

Vision is a key function to sense the world and perform complex tasks, with a high sensitivity and a strong reliability, given the fact 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:

1. Axis 1 focuses on the development of high tech vision aid systems for low vision patients.
2. Axis 2 focuses on the precise 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. 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

The most popular class of vision aid systems for low vision patients is based on the idea of magnification. These aids are helpful for tasks such as reading but of course are not useful in other common daily tasks such as navigation.

Video goggles [0] are another kind of device where visual information is captured by a head-mounted camera, processed and then displayed on a near-the-eye display screen. So far, this technology did not encountered a big success essentially due to their narrow field of view. This situation could evolve with the fast progression of technology around virtual reality and augmented reality.

In BIOVISION we mainly focus on this technology to develop new vision aid systems that could take into account the pathologies of low vision patients but also on the tasks performed by the patients. We have three main goals:

1. We plan to focus on three tasks: reading, watching movies and navigating (indoor or outdoor), which are all important daily life activities for patients.
2. We aim at proposing new **scene enhancements** depending on **pathologies**.
3. We want to test them in **immersive** environments with low vision patients, taking into consideration **ergonomics**.

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.

[0] Video goggles are marketed by several companies such as, e.g., `eSight`, `Enhanced Vision` and `Lumus`

In BIOVISION we contribute to a better understanding of the visual system with three main goals:

1. We aim at proposing simplified mathematical models characterizing how the **retina** converts a visual scene into spike **population coding**, in **normal and under specific pathological conditions**.
2. We want to design an integrated numerical model of the visual stream, with a focus on motion integration, from retina to **visual cortex** area (e.g., the motion stream **V1-MT-MST**).
3. We plan to develop 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 will be to develop novel synergistic solutions to solve computer vision tasks based on bio-inspired mechanisms.

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 processing

An impressive range of techniques have been developed in the fields of image processing, computer vision and computer graphics to manipulate and interpret image content for a variety of applications. So far only a few of these techniques have been applied in the context of vision aid systems and even less have been carefully evaluated with patients. However it is worth noticing a recent gain of interest from the artificial vision side to low vision applications [0]. We investigate which techniques could bring a real interest for vision aid systems, how to combine them and how to make them adapted to patient needs, so that they can not only "see" an image but understand it more efficiently.

Some techniques have already been explored. Among the first, enhancing image content (equalization, gamma correction, tone mapping, edge enhancement, image decomposition, cartoonization) seems a natural type of processing to make. Some methods have already been tested with low vision patients [38], [54], [55] or even in retina prosthesis systems as a pre-processing [37]. For some visual impairement it can be useful to consider methods that help patients to focus on the most relevant information, using techniques such as scene retargeting [59], seam carving [40], [39], saliency-based enhancements [71], [82] or 3D-based enhancements when available [64]. All the work done on image understanding could also be extremely useful to help patients navigate in natural cluttered environments both in low vision condition or for prosthetics vision [58]. 3D information, obtained from stereo head systems or RGB-D cameras also bring useful information about the environment [62] and integrated systems combining different expertise are appearing [46].

Our goal will be to take the most of state-of-the-art computer vision methods, in combination with virtual and augmented reality devices (Sec. 3.2.2) to provide patients vision aid system that can adapt to their impairment and so that they can easily change the parameters of the processing in an intuitive way.

3.2.2. Virtual and augmented reality

Our goal is to develop vision-aid systems using virtual and augmented reality [87]. There is a rich continuum of devices between virtual reality (which is *a priori* simpler to use since there is no problem of mobility and environment is well defined), and augmented reality (where information has to be superimposed in real time on top of the real environment to enrich it). Between these two extremes, new hybrid see-through systems are available or under development such as light glasses where additional information can be locally displayed at the center or on the corner (e.g., Google glass improving it). We invest on these technologies which enable new kinds of interaction with visual content which could be very powerful when adapted to low vision patients who want to use their remaining sight. We investigate how low vision patients could take benefits from this technology in their daily life activities [47] [0].

[0] See, e.g., the Special issue on Assistive Computer Vision and Robotics - "Assistive Solutions for Mobility, Communication and HMI" from Computer Vision and Image Understanding (August 2016) or the International Workshop on Assistive Computer Vision and Robotics (ECCV 2016 Sattelite workshop)

We focus on three activities: reading, watching movies and navigating in real world (indoor and outdoor). In these three scenario, this technology should offer crucial advantages for people in low vision. For reading, this could help them solving the page navigation problem or the limitations of magnification encountered when standard CCTVs are used. When watching a movie, the possibility to explore a pre-processed visual scene presented with very high visual angle can help patients to follow the storyline more easily and this poses some interesting questions on the creation of content specifically for virtual reality headsets. Finally, in real scenarios, augmented reality offers promising perspectives to enrich the scene by highly visible visual cues to facilitate low vision patients navigation. Of course the choices of adaptive image processing techniques (see Sec. 3.2.1) will be crucial and this will be the add-on value of our work.

Another important aspect of this work that will progressively need attention is ergonomic which will have to take into account the other potential functional limitations of these patients in addition to low vision (e.g., limitations in mobility, hearing, or agility).

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 do not focus on mathematical proofs, instead insisting on the quality of the model in predicting, and, if possible 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 [4],[33], [22].

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 will be applied for large scale activity in the retina and in the cortex [7], [11],[15].

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 [60] used by numerous authors in the context of the retina (see, e.g., [73], [75], [57], [56], [78]). These papers were restricted to a statistical description without memory neither causality: the time correlations between successive times is not considered. A paradigmatic example of this is the Ising model, used to describe the retinal activity in, e.g., [73], [75]. However, maximum entropy extends to spatio-temporal correlations as we have shown in, e.g., [13], [5].

More generally, while maximum entropy models rely heavily on the questionable assumption of stationariy, the concept of Gibbs distribution does not need this hypothesis. Beside, it allows to handle models with large memory; it also provides a framework to model anticipation [16]. It includes as well existing models to explain retina statistics such as the Generalized Linear Model (GLM) [44].

[0] Note that wearing such headsets may not be easily accepted by patients who do not want to advertise their disability. More generally, this poses the general question of how users come to accept and use a technology. This question is debated in the Technology Acceptance Model (TAM) which postulates that two specific perceptions about technology determine one behavioral intention to use a technology: perceived ease of use and perceived usefulness (see, e.g., [50]).

4. Application Domains

4.1. High tech vision aid systems for low vision patients

Vision aid systems for low vision patients is an application domain with commercial products already existing. A variety of solutions are on the market and can be distinguished by their functioning (in virtual or augmented reality), the tasks targeted by the systems (e.g., face and object recognition, reading), the platform they use (dedicated platform or general existing one). Our goal is to propose competing solutions based on wide-spread and cheap platforms (e.g., mobile phone and cheap headset) to facilitate transfer to consumer market.

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

4.2.1. Cells characterization from their spike response

A prior step toward understanding how the retina extracts the information from a visual scene is the characterization of retinal ganglion cells receptive fields. The receptive field allows to classify retinal ganglion cells in sub-types such as direction sensitive cells. Each of these type extracts a local and definite piece of information from the visual scene, transmitted to the visual cortex. Hence receptive fields are somewhat the fundamental bricks of vision.

Current techniques of receptive fields estimation are based on Spike-Triggered Average [70]. However, this method heavily relies on the assumption that the static non linearity is convex (typically this is an exponential). Unfortunately, this violates a fundamental biophysical property of neurons: firing rate is bounded due to the refractory period. Additionally, this method is slow and of low precision.

We are working on more efficient techniques based on non-convex analysis, faster, more precise, and working for a non-convex (typically sigmoidal) non linearity. Additionnally we are also working on designing better stimuli for receptive fields estimations.

4.2.2. Understanding the role of spatio-temporal correlations in visual scene encoding

Retinal response to stimuli is related, on one hand, to spatio-temporal correlations of the stimulus [76], and, on the other hand to the intrinsic spatio-temporal correlations of the retinal activity induced by its vertical and lateral connectivity [81]. However, the role of spatio-temporal correlations in retinal coding is still controversial. With the current evolution of multi-electrode arrays recordings, it is possible to record from tens to thousands of neurons [42], [51], [63], [86], studying not only the correlations between few neurons, but also the correlations present in a whole population of retinal ganglion cells [73], [75], [77], [80]. The BIOVISION team has proposed a framework to study this correlation structure using Gibbs distributions (Sec. 3.2.4). Based upon the mathematical results presented in the papers [5] [45], we have developed algorithms to analyse and reproduce spatio-temporal correlations in neural assemblies containing up to a few hundreds of neurons [13], [69], [68].

We are now applying these methods for the analysis of retina data so as to better understand the role of spatio-temporal spike correlations in vision encoding.

4.2.3. Retinal waves

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 [83], [52], [74], [53]. 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 [48]. This could have deep consequences on therapy for several degenerative retinal diseases. The mechanism of their generation, in imature, or adult retinas, remains however incompletely understood [84].

We aim at proposing a dynamical model of retinal waves depending on a few canonical parameters (e.g. concentration of a pharmacological agent) controlling the arousal of retinal waves as well as their shape/intensity. We want, on one hand, to design a model sufficiently close to biophysics so that it can reproduce and predict experimental results, and, on the other hand, sufficiently general to provide a generic mechanisms of retinal waves arousal also describing their different types.

4.2.4. Trajectory anticipation, from retina to V1

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 des Neurosciences de la Timone and Institut de la Vision, and design a simulator of retinal output feeding V1. This study is a step toward understanding mechanisms of motion coding and anticipation with strong impact on our understanding of the visual system.

4.2.5. Simulating and analysing retina's response to visual stimuli

We want to design a retina simulator integrating the most recent advances on retina modeling. We will propose a user-friendly simulator, using parallel (multi-threads) programming, in order to simulate rapidly a large piece of the retina. This platform is further described in the section Software.

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

The Virtual Retina software allows large-scale simulations of biologically-plausible retinas, with customizable parameters. Virtual Retina has been shown to reproduce a wide range of experimental data from salamander, cat and primate retinas [14], and has been used in several theoretical studies [65], [66], [67], [41], [17]. It has recently been shown to predict spikes in a mouse retina more accurately than linear-nonlinear (LN) models [79]. The underlying model includes a non-separable spatio-temporal linear model of filtering in the Outer Plexiform Layer, a shunting feedback at the level of bipolar cells, and a spike generation process using noisy leaky integrate-and-fire neurons to model RGCs. All parameters for the different stages of the model are customizable so that the visual field can be paved with different RGC types.

FUNCTIONAL DESCRIPTION.

Virtual Retina is a simulation software that allows large-scale simulations of biologically-plausible retinas.

- Participants: Bruno Cessac, Maria-Jose Escobar, Pierre Kornprobst, Selim Kraria, Daniela Pamplona, Selma Souihel, Thierry Vieville and Adrien Wohrer.
- Contact: Pierre Kornprobst
- URL: https://enas.inria.fr/virtual-retina.html

5.2. ENAS: Event Neural Assembly Simulation

KEYWORDS: Neurosciences - Health - Physiology

SCIENTIFIC DESCRIPTION

As one gains more intuitions and results on the importance of concerted activity in spike trains, models are developed to extract potential canonical principles underlying spike coding. These methods shed a new light on spike train dynamics. However, they require time and expertise to be implemented efficiently, making them hard to use in a daily basis by neuroscientists or modelers. To bridge this gap, we developed the license free multiplatform software ENAS (https://enas.inria.fr) integrating tools for individual and collective spike analysis and simulation, with some specificities devoted to the retina. The core of ENAS is the statistical analysis of population codes. One of its main strength is to provide statistical analysis of spike trains using Maximum Entropy-Gibbs distributions taking into account both spatial and temporal correlations as constraints, allowing to introduce causality and memory in statistics. It also generates simulated population raster from an user-specified Gibbs distribution.

We hope that ENAS will become a useful tool for neuroscientists to analyse spike trains and we hope to improve it thanks to user feedback. Our goal is to progressively enrich it with the latest research results, in order to facilitate transfer of new methods to the community.

FUNCTIONAL DESCRIPTION. ENAS is developed joinly by the Biovision, CORTEX/Mnemosyne, and DREAM Inria teams, under CeCILL-C licence, APP logiciel ENAS : IDDN.FR.OO1.190004.000.S.P.2014.000.31235. It can be freely loaded. ENAS has a friendly Graphical User Interface that avoids any scripting or writing code from user. Most methods have been implemented to run in parallel to reduce the time and memory consumption.

- Participants: Bruno Cessac, Pierre Kornprobst, Selim Kraria, Hassan Nasser, Thierry Vieville, Daniela Pamplona, Geoffrey Portelli, Selma Souihel.
- Contact: Bruno Cessac
- URL: https://enas.inria.fr

5.3. The Enas–Virtual Retina platform

In 2016 we merged Enas and Virtual Retina to produce the Enas platform https://enas.inria.fr. The initial version of Virtual retina has been extended to include lateral connections in the Inner Plexiform Layer. We can then simulate the response of the retina to visual stimuli (movies), including the effect of lateral connectivity, analyse the collective spike response to this stimulus using Gibbs distributions, and reproduce a similar raster using learning methods shaping the connectivity in the Inner Plexiform Layer.

This work has been presented in [27] and submitted to Frontiers in Neuroinformatics [3].

6. New Results

6.1. High tech vision aid systems for low vision patients

This is a new axis in the team that we started this year. We do not have results yet available but one project has started to allow real-time enhancement of environments in Virtual Reality (equipement: Samsung S6 and Samsung VR headset). This is the internship work of Alberto Patino (grant: CONACYT) who is co-supervised by Pierre Kornprobst and Fabio Solari (University of Genoa, Italy). We plan to submit an abstract to Vision 2017 conference, the 12th International Conference by the International Society for Low Vision Research and Rehabilitation.

Another project is in preparation, involving Fabio Solari (University of Genoa, Italy) and other colleagues from Université Cote d'Azur. New results are expected in 2017.

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

6.2.1. *Cells characterization from their spike response*

6.2.1.1. A new nonconvex variational approach for sensory neurons receptive field estimation

Participants: Audric Drogoul, Gilles Aubert [UCA, Laboratoire Jean Alexandre Dieudonné, Nice, France], Bruno Cessac, Pierre Kornprobst.

Determining the receptive field of a visual sensory neuron is a first but crucial step to- wards the characterization of neurons response to local spatio-temporal stimuli. Existing methods are based on convex optimization methods neglecting biophysical constraints of neurons (bounded firing rate), and they are relatively poor in terms of accuracy and running time. We propose a new method to estimate receptive fields by a nonconvex variational approach, thus relaxing the simplifying and unrealistic assumption of convexity made by standard approaches. The method consists in studying a relaxed discrete energy minimized by a proximal alternating minimization algorithm. We compare our approach with the classical spike-triggered-average technique on simulated data, considering a typical retinal ganglion cell. Results show a high improvement in terms of accuracy and convergence with respect to the duration of the experiment.

This work was presented in [29], [21] and has been submitted, see [24] .

6.2.1.2. Pan-retinal characterization of Light Responses from Ganglion Cells in the Developing Mouse Retina

Participants: Gerrit Hilgen [Institute of Neuroscience, Medical School, Newcastle University, Newcastle UK], Sarah Pirmoradian [ANC - Institute for Adaptive and Neural Computation, Edimburgh, UK], Daniela Pamplona, Pierre Kornprobst, Bruno Cessac, Matthias Hennig Pirmoradian [ANC - Institute for Adaptive and Neural Computation, Edimburgh, UK], Evelyne Sernagor [Institute of Neuroscience, Medical School, Newcastle University, Newcastle, UK].

We have investigated the ontogeny of light-driven responses in mouse retinal ganglion cells (RGCs). Using a large-scale, high-density multielectrode array, we recorded from hundreds to thousands of RGCs simultaneously at pan-retinal level, including dorsal and ventral locations. Responses to different contrasts not only revealed a complex developmental profile for ON, OFF and ON-OFF RGC types, but also unveiled differences between dorsal and ventral RGCs. At eye-opening, dorsal RGCs of all types were more responsive to light, perhaps indicating an environmental priority to nest viewing for pre-weaning pups. The developmental profile of ON and OFF RGCs exhibited antagonistic behavior, with the strongest ON responses shortly after eye-opening, followed by an increase in the strength of OFF responses later on. Further, we found that with maturation receptive field (RF) center sizes decrease, responses to light get stronger, and centers become more circular while seeing differences in all of them between RGC types. These findings show that retinal functionality is not spatially homogeneous, likely reflecting ecological requirements that favour the early development of dorsal retina, and reflecting different roles in vision in the mature animal.

This work is under revision, submitted to EScience [25]

6.2.2. *Understanding the role of spatio-temporal correlations in visual scene encoding*

6.2.2.1. Spike train analysis and Gibbs distributions

Participants: Bruno Cessac, Rodrigo Cofré [Département de Physique Théorique, Université de Genève].

Spikes in sensory neurons are conveyed collectively to the cortex using correlated binary patterns (in space and time) which constitute “the neural code”. Since patterns occur irregularly it is appropriate to characterize them using probabilistic descriptions or statistical models. Two major approaches attempt to characterize the spike train statistics: The Maximum Entropy Principle (MaxEnt) and Neuronal Network modeling (N.N). Remarkably, both approaches are related via the concept of Gibbs distributions. MaxEnt models are restricted to time-invariant Gibbs distributions, via the underlying assumption of stationarity, but this concept extends to non-stationary statistics (not defined via entropy), allowing to handle as well statistics of N.N models and GLM with non-stationary dynamics. We show in this poster that, stationary N.N, GLMmodels and MaxEnt models are equivalent via an explicit mapping. This allows us, in particular, to interpret the so-called "effective interactions" of MaxEnt models in terms of “real connections” models.

This work was presented in the Bernstein Conference 2016 [28] and will be soon submitted to Journal of Statistical Physics.

6.2.2.2. Dimensionality Reduction in spatio-temporal MaxEnt models and analysis of Retinal Ganglion Cell Spiking Activity in experiments

Participants: Rubén Herzog [CINV - Centro Interdisciplinario de Neurociencia de Valparaíso], Maria-Jose Escobar [Univ Tecnico Federico Santa María], Adrian Palacios [CINV - Centro Interdisciplinario de Neurociencia de Valparaíso], 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 model 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 [1]. To resolve this issue we have considered spatio-temporal MaxEnt model formerly developed e.g. by Vasquez et al. [2]. 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 handle 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.

This work has been presented in the Bernstein 2016 conference [31] and has been submitted to Plos Comp Bio.

6.2.2.3. On the mathematical consequences of binning spike trains

Participants: Bruno Cessac, Arnaud Le Ny [LAMA - Laboratoire d'Analyse et de Mathématiques Appliquées], Eva Loecherbach [AGM - Laboratoire d'Analyse, Géométrie et Modélisation and Département de Mathématiques, [Cergy-Pontoise].

We initiate a mathematical analysis of hidden effects induced by binning spike trains of neurons. Assuming that the original spike train has been generated by a discrete Markov process, we show that binning generates a stochastic process which is not Markovian any more, but is instead a Variable Length Markov Chain (VLMC) with unbounded memory. We also show that the law of the binned raster is a Gibbs measure in the DLR (Dobrushin-Lanford-Ruelle) sense coined in mathematical statistical mechanics. This allows the derivation of several important consequences on statistical properties of binned spike trains. In particular, we introduce the DLR framework as a natural setting to mathematically formalize anticipation, i.e. to tell "how good" our nervous system is at making predictions. In a probabilistic sense, this corresponds to condition a process by its future and we discuss how binning may affect our conclusions on this ability. We finally comment what could be the consequences of binning in the detection of spurious phase transitions or in the detection of wrong evidences of criticality.

This work has been published in Neural Computation, Massachusetts Institute of Technology Press (MIT Press), 2016 [16].

6.2.3. Retinal waves

6.2.3.1. Mathematical and experimental studies on retinal waves

Participants: Dora Karvouniari, Lionel Gil [INLN -Institut Non Linéaire de Nice Sophia-Antipolis], Olivier Marre [Institut de la Vision], Serge Picaud [Institut de la Vision], Bruno Cessac.

We reproduce the spontaneous intrinsic cell-autonomous rhythmic bursting in Starbust Amacrine Cells (SACs) and the slow After Hyperpolarisation Current (sAHP), which modulates the refractory process inbetween two consecutive bursts, observed experimentally in [85]. We describe the dynamical influence of cholinergic synapses, ensuring the level of SAC synchrony necessary for the emergence of waves. We obtain: a) a plausible generic mechanism generating spontaneous retinal waves in development, without any need for external stimulation as opposed to existing models and b) a mathematical characterization of retinal waves. Especially, a biophysical parameter controls the wave arousal and the corresponding shape. The model is accurate enough to reproduce existing experiments, but also to propose new ones.

This work has been presented in the workshop "Modelling the early visual system" [32], 2nd International Conference on Mathematical Neuroscience (ICMNS) [22], the AREADNE conference [34], the Bernstein conference [33]. Two papers are in preparation.

6.2.4. Trajectory anticipation, from retina to V1

This work is just starting. The main work has been done by Selma Souihel in her Master II instership supervised by Bruno Cessac [36]. The aim of the internship is to use and update the software VirtualRetina and Enas in order to reproduce the activity of the retina in response to the stimulus of a moving bar, observed By Mr Berry & al. A form of anticipation of the movement has been demonstrated experimentally by its authors in salamander, rabbit and goldfish retinas. This anticipation can be explained, in the case of a simple trajectory, by the gain control mechanism specific to the ganglion cells, implemented by Virtual-Retina-Enas.

6.2.5. Simulating and analysing retina's response to visual stimuli

6.2.5.1. ENAS: A new software for spike train analysis and simulation

Participants: Bruno Cessac, Pierre Kornprobst, Selim Kraria, Hassan Nasser, Daniela Pamplona, Geoffrey Portelli, Thierry Vieville [Mnemosyne - Mnemonic Synergy LaBRI - Laboratoire Bordelais de Recherche en Informatique, IMN - Institut des Maladies Neurodégénératives, [Bordeaux].

This work, presenting the Enas-Virtual Retina platform has been presented in [27] and submitted to Frontiers in Neuroinformatics [3].

6.2.5.2. Rank order coding: a retinal information decoding strategy revealed by large-scale multielectrode array retinal recordings

Participants: Geoffrey Portelli, John M. Barrett [Institute of Neuroscience, Medical School, Newcastle University, Newcastle UK], Gerrit Hilgen [Institute of Neuroscience, Medical School, Newcastle University, Newcastle UK], Timothée Masquelier [CERCO, Toulouse, France], Alessandro Maccione [NetS3 Lab - Neuro-Engineering & bio-arTificial Synergic SystemS Laboratory, Genova, Italy], Stefano Di Marco [NetS3 Lab - NeuroEngineering & bio-arTificial Synergic SystemS Laboratory, Genova, Italy], Luca Berdondini [NetS3 Lab - NeuroEngineering & bio-arTificial Synergic SystemS Laboratory, Genova, Italy], Pierre Kornprobst, Evelyne Sernagor [Institute of Neuroscience, Medical School, Newcastle University, Newcastle, UK].

How a population of retinal ganglion cells (RGCs) encodes the visual scene remains an open question. Going beyond individual RGC coding strategies, results in salamander suggest that the relative latencies of an RGC pair encodes spatial information. Thus a population code based on this concerted spiking could be a powerful mechanism to transmit visual information rapidly and efficiently. Here, we tested this hypothesis in mouse by recording simultaneous light-evoked responses from hundreds of RGCs, at pan-retinal level, using a new generation of large-scale, high density multielectrode array consisting of 4096 electrodes. Interestingly, we did not find any RGCs exhibiting a clear latency tuning to the stimuli, suggesting that in mouse, individual RGC pairs may not provide sufficient information. We show that a significant amount of information is encoded synergistically in the concerted spiking of large RGC populations. Thus, the RGC population response described with relative activities, or ranks, provides more relevant information than classical independent spike count- or latency- based codes. In particular, we report for the first time that when considering the relative activities across the whole population, the wave of first stimulus-evoked spikes (WFS) is an accurate indicator of stimulus content. We show that this coding strategy co-exists with classical neural codes, and that it is more efficient and faster. Overall, these novel observations suggest that already at the level of the retina, concerted spiking provides a reliable and fast strategy to rapidly transmit new visual scenes.

This work has been published in eNeuro [20].

6.2.5.3. Microsaccades enable efficient synchrony-based coding in the retina: a simulation study.

Participants: Timothée Masquelier [CERCO, Toulouse, France], Geoffrey Portelli, Pierre Kornprobst.

It is now reasonably well established that microsaccades (MS) enhance visual perception, although the underlying neuronal mechanisms are unclear. Here, using numerical simulations, we show that MSs enable efficient synchrony-based coding among the primate retinal ganglion cells (RGC). First, using a jerking contrast edge as stimulus, we demonstrate a qualitative change in the RGC responses: synchronous firing, with a precision in the 10 ms range, only occurs at high speed and high contrast. MSs appear to be sufficiently fast to be able reach the synchronous regime. Conversely, the other kinds of fixational eye movements known as tremor and drift both hardly synchronize RGCs because of a too weak amplitude and a too slow speed respectively. Then, under natural image stimulation, we find that each MS causes certain RGCs to fire synchronously, namely those whose receptive fields contain contrast edges after the MS. The emitted synchronous spike volley thus rapidly transmits the most salient edges of the stimulus, which often constitute the most crucial information. We demonstrate that the readout could be done rapidly by simple coincidence-detector neurons without knowledge of the MS landing time, and that the required connectivity could emerge spontaneously with spike timing-dependent plasticity.

This work has been published in Scientific Reports [17].

6.2.6. Mean-Field models in neuroscience

6.2.6.1. Perspectives on Multi-Level Dynamics

Participants: Fatihcan Atay [MPI-MIS - Max Planck Institute for Mathematics in the Sciences], Sven Banisch [MPI-MIS - Max Planck Institute for Mathematics in the Sciences], Philippe Blanchard [University of Bielefeld-Departement of physics], Bruno Cessac, Eckehard Olbrich [MPI-MIS - Max Planck Institute for Mathematics in the Sciences], Dimitri Volchenkov [University of Bielefeld, Departement of physics].

As Physics did in previous centuries, there is currently a common dream of extracting generic laws of nature in economics, sociology, neuroscience, by focalising the description of phenomena to a minimal set of variables and parameters, linked together by causal equations of evolution whose structure may reveal hidden principles. This requires a huge reduction of dimensionality (number of degrees of freedom) and a change in the level of description. Beyond the mere necessity of developing accurate techniques affording this reduction, there is the question of the correspondence between the initial system and the reduced one. In this paper, we offer a perspective towards a common framework for discussing and understanding multi-level systems exhibiting structures at various spatial and temporal levels. We propose a common foundation and illustrate it with examples from different fields. We also point out the difficulties in constructing such a general setting and its limitations.

This work has been published in The interdisciplinary journal of Discontinuity, Nonlinearity, and Complexity, 2016, 5 [15].

6.2.7. Motion perception

6.2.7.1. The relative contribution of noise and adaptation to competition during tri-stable motion perception

Participants: Andrew Isaac Meso [Institut de Neurosciences de la Timone, Team InVibe, France], James Rankin [Center for Neural Science, New York UniversityNew York, NY], Pierre Kornprobst, Olivier Faugeras [Université Côte d'Azur, Inria, MathNeuro team, France], Guillaume S. Masson [Institut de Neurosciences de la Timone, Team InVibe, France].

Animals exploit antagonistic interactions for sensory processing and these can cause oscillations between competing states. Ambiguous sensory inputs yield such perceptual multistability. Despite numerous empirical studies using binocular rivalry or plaid pattern motion, the driving mechanisms behind the spontaneous transitions between alternatives remain unclear. In the current work, we used a tristable barber pole motion stimulus combining empirical and modeling approaches to elucidate the contributions of noise and adaptation to underlying competition. We first robustly characterized the coupling between perceptual reports of transitions and continuously recorded eye direction, identifying a critical window of 480 ms before button presses, within which both measures were most strongly correlated. Second, we identified a novel nonmonotonic relationship between stimulus contrast and average perceptual switching rate with an initially rising rate before a gentle reduction at higher contrasts. A neural fields model of the underlying dynamics introduced in previous theoretical work and incorporating noise and adaptation mechanisms was adapted, extended, and empirically validated. Noise and adaptation contributions were confirmed to dominate at the lower and higher contrasts, respectively. Model simulations, with two free parameters controlling adaptation dynamics and direction thresholds, captured the measured mean transition rates for participants. We verified the shift from noise-dominated toward adaptation-driven in both the eye direction distributions and intertransition duration statistics. This work combines modeling and empirical evidence to demonstrate the signal-strength–dependent interplay between noise and adaptation during tristability. We propose that the findings generalize beyond the barber pole stimulus case to ambiguous perception in continuous feature spaces.

This work is a a continuation of former paper [72], [12] and has been published in Journal of Vision [19].

6.2.7.2. Understanding the impact of recurrent interactions on MT population tuning: a simulation study.

Participants: Kartheek Medathati, Andrew Isaac Meso [Institut de Neurosciences de la Timone, Team InVibe, France], Guillaume S. Masson [Institut de Neurosciences de la Timone, Team InVibe, France], Pierre Kornprobst, James Rankin [Center for Neural Science, New York University, USA].

In sensory systems, different computational rules are often evident in different neuronal subpopulations. Most previous models of motion estimation by MT cells explain their specific tuning functions by having multiple feedforward inputs, largely ignoring the role of recurrent connectivity, a hallmark of cortical circuits. Therefore they fail to explain the dynamics of these tuning functions and the fact that different behaviour can be achieved by a single subpopulation when varying the spatiotemporal properties of the input. Here, using numerical simulations, we focus on a ring network that models visual motion processing at the level of MT cells. We show how excitatory and inhibitory recurrent connections shape motion direction tuning, thus resulting in different computational rules such as vector averaging, winner-take-all or bimodal representations. In particular, depending on the inhibition regime the ring network can switch from motion integration to motion segmentation, being able to compute either a single pattern motion or to superpose multiple inputs as in motion transparency. Such feature space centre-surround recurrent mechanisms may be widely applicable to explain context-modulation of sensory processing.

This work has been presented at AREADNE conference [35] and a paper is in preparation.

6.2.8. Bio-Inspired Computer Vision

6.2.8.1. Bio-Inspired Computer Vision: Towards a Synergistic Approach of Artificial and Biological Vision

Participants: Pierre Kornprobst, Guillaume S. Masson [Institut de Neurosciences de la Timone, Team InVibe], Kartheek Medathati [correspondent], Heiko Neumann [Ulm University, Germany].

Studies in biological vision have always been a great source of inspiration for design of computer vision algorithms. In the past, several successful methods were designed with varying degrees of correspondence with biological vision studies, ranging from purely functional inspiration to methods that utilise models that were primarily developed for explaining biological observations. Even though it seems well recognised that computational models of biological vision can help in design of computer vision algorithms, it is a non-trivial exercise for a computer vision researcher to mine relevant information from biological vision literature as very few studies in biology are organised at a task level.

In [26], we aim to bridge this gap by providing a computer vision task centric presentation of models primarily originating in biological vision studies. Not only we revisit some of the main features of biological vision and discuss the foundations of existing computational studies modelling biological vision, but also consider three classical computer vision tasks from a biological perspective: image sensing, segmentation and optical flow. Using this task-centric approach, we discuss well-known biological functional principles and compare them with approaches taken by computer vision. Based on this comparative analysis of computer and biological vision, we present some recent models in biological vision and highlight a few models that we think are promising for future investigations in computer vision. To this extent, this paper provides new insights and a starting point for investigators interested in the design of biology-based computer vision algorithms and pave a way for much needed interaction between the two communities leading to the development of synergistic models of artificial and biological vision.

This work has been published in Computer Vision and Image Understanding Journal (CVIU) [9].

6.2.8.2. Retina-inspired tone mapping

Participants: Marco Benzi, Maria-Jose Escobar [Universidad Técnica Federico Santa María, Valparaíso, Chile], Adrien Bousseau [Inria, GraphDeco project-team], Pierre Kornprobst [correspondent].

Real-world radiance values span several orders of magnitudes which have to be processed by biological and artificial systems in order to maintain high visual sensitivity.

In biological systems, process starts at the retina level, where adaptation is absolutely crucial since retinas must maintain high contrast sensitivity over a very broad range of luminance, from starlight to direct sunlight. Adaptation is both global through neuromodulatory feedback loops and local through adaptive gain control mechanisms so that retinal networks can be adapted to the whole scene luminance level while maintaining high contrast sensitivity in different regions of the image, despite their considerable differences in luminance. Adaptation is present at different levels, e.g., at the photoreceptor level where sensitivity is a function of the recent mean intensity, and at the bipolar level where slow and fast contrast adaptation mechanisms are found. These multiple adaptational mechanisms act together, with lighting conditions dictating which mechanisms dominate.

In artificial systems, the process of compressing the range of intensities in High-Dynamic Range (HDR) images is know as tone mapping. It is a necessary step to properly visualize captured natural scenes as common displays are Low-Dynamic Range, spanning up to two orders of magnitude. There is a large body of literature in this area on static images, with approaches which combine luminance adaptation (using empirical laws such as the Naka-Rushton equation) and local contrast enhancement sometimes closely inspired from retinal principles [43], [61]. Recent developments concern video-tone mapping where a few approaches have been developed [49].

In this work, we investigate if the Virtual Retina simulator [14] could serve as a goof basis to develop a new tone mapping operator for videos. One strength of this simulator is its model of fast contrast gain control which has been validated on experimental data. However this model was not designed to deal with color and HDR images. This requires some pre- and post-processing but also changes in the Virtual Retina to account for other adaptation phenomena. Preliminary encouraging results have been obtained and we plan to continue that project in 2017.

7. Partnerships and Cooperations

7.1. National Initiatives

7.1.1. ANR

7.1.1.1. Trajectory

Title: Encoding and predicting motion trajectories in early visual networks

Programm: ANR

Duration: October 2015 - September 2020

Coordinator: Invibe Team, Institut des Neurosciences de la Timone, Frédéric Chavane,

Partners:

AMU INT Aix-Marseille, Université Institut de Neurosciences de la Timone

INSERM IDV INSERM Institut de la Vision

USM UV U Santa Maria & U Valparaiso

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.

7.2. European Initiatives

7.2.1. FP7 & H2020 Projects

7.2.1.1. RENVISION

Title: Retina-inspired ENcoding for advanced VISION tasks

Programm: FP7

Duration: March 2013 - February 2016

Coordinator: Instituto Italiano di Tecnologia_Pattern Analysis and Computer vision) Vittorio Murino

Partners:

PAVIS,NET3 Fondazione Istituto Italiano di Tecnologia (Italy)

Institute for Adaptive and Neural Computation, The University of Edinburgh (UK)

Institute of Neuroscience, University of Newcastle Upon Tyne (UK)

Inria contact: Bruno Cessac

The retina is a sophisticated distributed processing unit of the central nervous system encoding visual stimuli in a highly parallel, adaptive and computationally efficient way. Recent studies show that rather than being a simple spatiotemporal filter that encodes visual information, the retina performs sophisticated non-linear computations extracting specific spatio-temporal stimulus features in a highly selective manner (e.g. motion selectivity). Understanding the neurobiological principles beyond retinal functionality is essential to develop successful artificial computer vision architectures. RENVISION's goal is, therefore, twofold: i) to achieve a comprehensive understanding of how the retina encodes visual information through the different cellular layers; ii) to use such insights to develop a retina-inspired computational approach to high-level computer vision tasks. To this aim, exploiting the recent advances in high-resolution light microscopy 3D imaging and high-density multielectrode array technologies, RENVISION will be in an unprecedented position to investigate pan-retinal signal processing at high spatio-temporal resolution, integrating these two technologies in a novel experimental setup. This will allow for simultaneous recording from the entire population of ganglion cells and functional imaging of inner retinal layers at near-cellular resolution, combined with 3D structural imaging of the whole inner retina. The combined analysis of these complex datasets will require the development of novel multimodal analysis methods. Resting on these neuroscientific and computational grounds, RENVISION will generate new knowledge on retinal processing. It will provide advanced pattern recognition and machine learning technologies to ICTs by shedding a new light on how the output of retinal processing (natural or modelled) allows solving complex vision tasks such as automated scene categorization and human action recognition.

7.3. International Initiatives

7.3.1. Informal International Partners

- Maria-Jose Escobar, University Santa-Maria, Valparaiso;
- Adrian Palacios, Centro de Neurociencia, Valparaiso

7.4. International Research Visitors

7.4.1. Visits of International Scientists

7.4.1.1. Internships

- Marco Benzi (grant: Stage Master Transverse Biovision–GraphDeco), Retina-inspired tone mapping. Supervisors: Pierre Kornprobst and Adrien Rousseau (GraphDeco), in collaboration with Maria-Jose Escobar (Universidad Técnica Federico Santa María, Valparaíso, Chile)

- Alberto Patino (grant: CONACYT), Studying image transforms at neuronal level and in Virtual Reality. Supervisors: Pierre Kornprobst (Biovision) and Fabio Solari (University of Genoa, Italy)

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. Member of the Organizing Committees

- Bruno Cessac: "Neural Network Dynamics in Health and Disease", 12-14 October 2016, Institut de Neurosciences de la Timone (INT), Marseille, France, http://www.gdr-neuralnet.cnrs.fr/en.
- Bruno Cessac: "Neurostim2016", http://neurostim2016.inria.fr/ 22 November 2016.

8.1.2. Scientific Events Selection

8.1.2.1. Member of the Conference Program Committees

- Pierre Kornprobst was a member of the program committee of the 24th European Signal Processing Conference (EUSIPCO 2016).

8.1.2.2. Reviewer

Pierre Kornprobst has been a reviewer for SIGGRPAH 2016.

8.1.3. Journal

8.1.3.1. Member of the Editorial Boards

Pierre Kornprobst is associate editor for the Computer Vision and Image Understanding Journal (CVIU).

8.1.4. Invited Talks

- Bruno Cessac, Toulon, March 2016.
- Bruno Cessac, Theoretical Physics lab, Geneve, March 2016.

8.1.5. Research Administration

- Pierre Kornprobst is an elected member of the Conseil Académique d'Université Côte d'Azur (UCA).
- Pierre Kornprobst leads the project UCAGate to provide UCA a new tool aiming at (i) giving a clear view of skills and competences of UCA for internal and external users, (ii) facilitate the emergence of new transdisciplinary synergies between UCA partners, (iii) provide UCA tools to show the transformation effect from the IDEX for the next evaluation. A first prototype is expected in February 2017.
- Pierre Kornprobst is member of the editorial committee of the Sophia Antipolis internal letter SAM & YOU.
- Pierre Kornprobst has been appointed by Inria Direction representative of the administration in the advisory committee of Inria contractual doctoral candidates[0] (on July 16, for two years).

[0]Représentant de l'administration suppléant au sein de la Commission consultative des doctorants contractuels d'Inria

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Licence : Theodora Karvouniari, "Transmissions numériquese , 1ere année de l' IUT, Departement Réseaux et Telecommunications, 64h/ an, 50 students.

Master 2: Bruno Cessac, *Neuronal dynamics*, 36 hours, Master 2 of Computational Biology and Biomedicine, Université Nice Sophia Antipolis, France.

8.2.2. Supervision

- 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: Theodora Karvouniari, "Retinal waves in the retina: theory and experiments". Started in October 2014. Supervisor, B. Cessac.
- PhD defended: Kartheek Medathati, "Towards synergistic models of motion information processing in biological and artificial vision", co-supervised by Pierre Kornprobst and Guillaume S. Masson (Institut de Neurosciences de la Timone, Marseille, France), December 13, 2016.

8.2.3. Juries

Bruno Cessac, member of the Jury's thesis: "Vers des modèles synergiques de l'estimation du mouvement en vision biologique et artificielle", by Kartheek Medathati.

Bruno Cessac, member of the Jury's thesis: "Structuration temporelle de la mémoire de travail dans les réseaux de neurones récurrents" by Guillaume Rodriguez.

8.3. Popularization

- Rencontre avec le public à la suite de la projection du film "La nuit qu'on suppose" de Benjamin d'Aoust, Médiathèque d'Antibes, 16 Janvier 2016.
- Bruno Cessac. Cafe In Sophia. La rétine, fonctionnement et thérapie, 28 Janvier 2016.

9. Bibliography

Major publications by the team in recent years

[1] B. CESSAC.*A discrete time neural network model with spiking neurons II. Dynamics with noise*, in "J. Math. Biol.", 2011, vol. 62, p. 863-900.

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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 Medecine

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Team CAMIN

Creation of the Team: 2016 January 01

Keywords:

Computer Science and Digital Science:

1.2.6. - Sensor networks
1.3. - Distributed Systems
2.3. - Embedded and cyber-physical systems
2.5.2. - Component-based Design
4.4. - Security of equipment and software
4.5. - Formal methods for security
5.1.4. - Brain-computer interfaces, physiological computing
6.1.1. - Continuous Modeling (PDE, ODE)
6.3.2. - Data assimilation
6.4.1. - Deterministic control

Other Research Topics and Application Domains:

1.3.1. - Understanding and simulation of the brain and the nervous system
1.4. - Pathologies
2.2.1. - Cardiovascular and respiratory diseases
2.2.2. - Nervous system and endocrinology
2.2.6. - Neurodegenerative diseases
2.5.1. - Sensorimotor disabilities
2.5.3. - Assistance for elderly

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2. Overall Objectives

2.1. Overall Objectives

CAMIN team research 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 (fig.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 being to increase neurological recuperation by activating muscle contractions and stimulating both efferent and afferent pathways. Our work in this area naturally led us to take an increasing interest in brain organization and plasticity, as well as central nervous system (brain, spinal cord) responses to ES. When the objective of FES is a permanent assistive aid, invasive solutions can be deployed. We pilot several animal studies to investigate neurophysiological responses to ES and validate models. We also apply some of our technological developments in the context of human per-operative surgery, including motor and sensory ES.

CAMIN research 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.

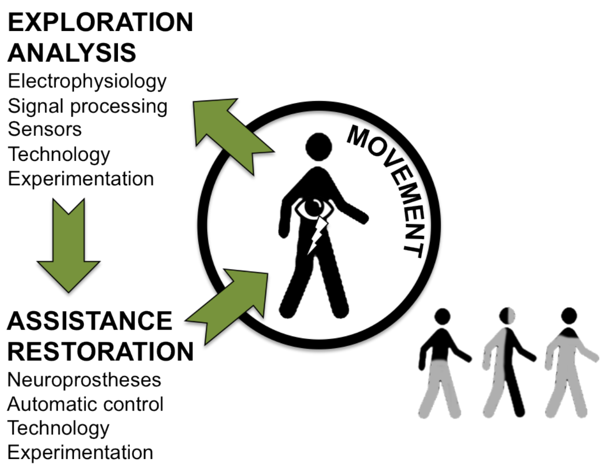


Figure 1. Overview of CAMIN*'s general scientific approach.*

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).

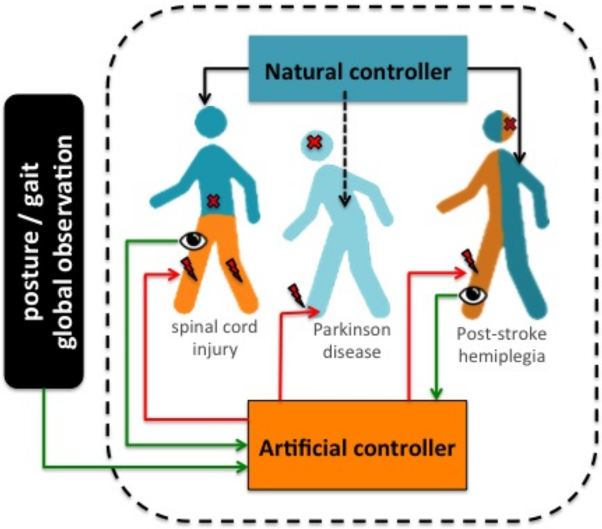


Figure 2. FES assistance should take into account the coexistence of artificial and natural controllers. Artificial controllers should integrate both global (posture/gait) and local (limb/joint) observations.

Real-time adaptation of the stimulation patterns is an important challenge in most of the clinical applications we consider. The modulation of ES parameters in the presence of fatigue or to adapt to context needs for adaptive controllers processing information on movement execution and environmental changes. A minimum number of sensors with minimal impact on patient motion is necessary.

4. Application Domains

4.1. Non invasive stimulation (external FES)

Both triggered open-loop and closed-loop FES controllers that we are developing for movement involve several sensors and stimulators whose activities must be precisely coordinated by the controller. For instance, the stimulation controller is fed back by various sensors, such as limb joint angles, IMUs providing accelerations, and electrophysiological signals like EMG. These signals are then used by feedback controllers to accurately control the artificially actuated limbs by means of stimulators. This distributed architecture is often deployed on a wireless network since it distinctively complies with mobility constraints, leading to good acceptance from human users. The quality of service (QoS) of this network influences the controlled system properties and the quality of control (QoC). The control performance and robustness of this system can be very far from expectations if implementation-induced disturbances are not taken into account. Thus, the overall performance of a real-time control system must be assessed not only with respect to deadlines (as in classical scheduling analysis) but also by considering other criteria such as time-varying delays and jitter. Hence, research on the joint design of control, computation and communication has to be carried out and applied [49] to the particular case of FES control loops distributed over imperfect links and low power nodes. In addition to the elaboration or adaptation of algorithms, specific tools must be further developed to assess the effectiveness of the new control algorithms and to support their implementation. In particular, realistic simulations remain a precious tool ahead of real experiments to ensure that the implementation meets the functional and safety requirements without danger. This is, for example, the case of the hybrid simulation framework of our distributed FES system currently under development [6]. Understanding and modeling the influence of an implementation (support system) on QoC is a challenging objective in a distributed control design process, but it is mandatory to guarantee the system's safety and effectiveness.

4.2. Invasive stimulation (implanted FES)

Invasive FES means that the selectivity issue has to be dealt with, both from theoretical and technological points of view. To take advantage of spatial and topological nerve organization, invasive stimulation must be able to focus the current in specific nerve areas to elicit subgroups of muscles, while avoiding undesired functional effects (i.e., undesired fiber recruitment). Although multipolar electrodes are available, it is still challenging to find the optimal electrode configuration to reach the given 3D current spreading (i.e., selective stimulus). Indeed, this is not intuitive and modeling is mandatory. On the other hand, implantable stimulators must provide for both dynamical electrode configuration and a complex stimulation profile.

Selectively activating part of the nerve requires an active contact configuration (anode, cathode, high impedance), distribution of the current over the selected contacts, and accurate control of the overall total injected current, both from amplitude and time dimensions. To meet these needs, the neurostimulator has been designed based on a 2-stage device [50]. The first stage is the output stage based on a dedicated analog ASIC (application-specific integrated circuit) that is able to drive 12 channels of stimulation in absolute synchronization, with a programmable and controlled current distribution over selected contacts. The latest ASIC version we designed is CORAIL (circuit fabrication by November 2016): this analog/digital integrated circuit ensures current distribution but also such features as the storage of multiple electrode configurations and the possibility to internally combine poles. The second stage consists of a digital architecture embedded in an FPGA containing a dedicated processor for programming complex stimulation profiles, a monitoring module ensuring the respect of safety constraints stemming from both target tissue protection and electrode integrity preservation (in terms of quantity of injected charge limits), and a protocol stack for remote programming and online control of stimulation parameters. This complex digital system was formally developed using HILECOP §6.1.1.

5. Highlights of the Year

5.1. Highlights of the Year

International Functional Electrical Stimulation Society Conference organization

In 2016, CAMIN organized the 20th International Functional Electrical Stimulation Society Conference. 135 participants attended the event. Papers are referenced in Pubmed and published in European Journal of Translationnal Myology. A special issue with a selection of best articles will be published in 2017 in Artificial Organs Journal. http://ifess2016.inria.fr/

Participation into Cybathlon competition

We have participated in the first international competition Cybathlon held in Kloten, Switzerland in October 2016. After more than one year of physical and technical preparation, our team, Freewheels, was present with one complete paraplegic pilot in the FES cycling discipline. http://freewheels.inria.fr/

Figure 3. Flyer of IFESS 2016 conference

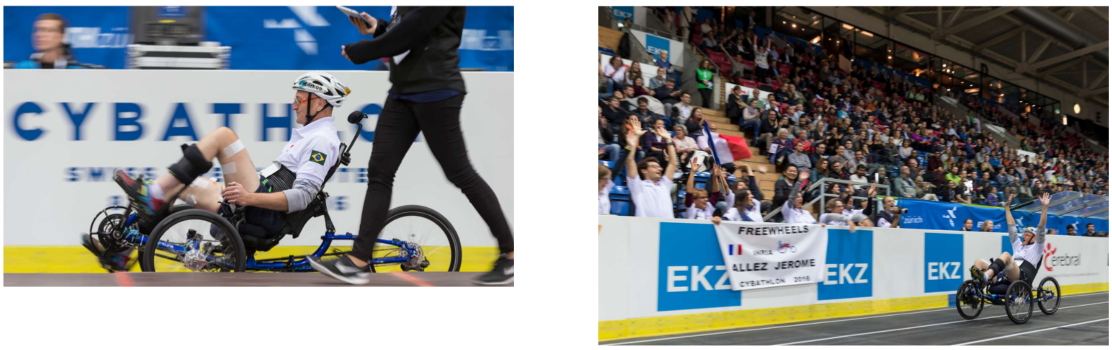


Figure 4. Freewheels team at Cybathlon 2016

6. New Software and Platforms

6.1. Software and platforms

6.1.1. HILECOP

Participants: Baptiste Colombani, David Andreu, Thierry Gil [LIRMM], Robin Passama [LIRMM].

High Level hardware Component Programming
FUNCTIONAL DESCRIPTION: Our SENIS (Stimulation Electrique Neurale dIStribuee) based FES architecture relies on distributed stimulation units (DSU) which are interconnected by means of a 2-wire based network. A DSU is a complex digital system since its embeds among others a dedicated processor (micro-machine with a specific reduced instruction set), a monitoring module and a 3-layer protocol stack. To face the complexity of the units digital part and to ease its prototyping on programmable digital devices (e.g. FPGA), we developed an approach for high level hardware component programming (HILECOP). To support the modularity and the reusability of sub-parts of complex hardware systems, the HILECOP methodology is based on components. An HILECOP component has: a Petri Net (PN) based behavior (fig.5), a set of functions whose execution is controlled by the PN, and a set of variables and signals. Its interface contains places and transitions from which its PN model can be inter-connected as well as signals it exports or imports. The interconnection of those components, from a behavioral point out view, consists in the interconnection of places and/or transitions according to well-defined mechanisms: interconnection by means of oriented arcs or by means of the "merging" operator (existing for both places and transitions).

The Eclipse-based version of HILECOP (registered at the french Agence de Protection des Programmes (APP)) has been refactored: for instance, the application ECore model, a new Eclipse E4 architecture and a set of new features (new link types and new views to connect components) have been developed.

Undergoing work concerns the integration, in the HILECOP tool, of the formalism evolutions that allow behavior agregation as well as exception handling, both for analysis and implementation sides.

Specification of GALS systems (Globally Asynchronous Locally Synchronous) is also an ongoing work, the aim being to take into account deployment properties like connecting different clocks to HILECOP components within a same FPGA, or on a set of interconnected FPGAs (and thus interconnecting them by means of asynchronous signals).

6.1.2. PersoBalance: A Personalized Balance Assessment in Home Rehabilitation

Participants: Maxime Tournier, Alejandro Gonzalez, Philippe Fraisse, Mitsuhiro Hayashibe.

In 2014-2015, the team demonstrated the feasibility of a personalized balance assessment system using low-end sensors for home rehabilitation. The corresponding software (PersoBalance) performs an identification of inertial parameters for a subject using a depth camera and a connected balance board (in this case, a Nintendo Wii BalanceBoard) through a dedicated Kalman filter as the subject assumes various body postures. When the inertial parameters are estimated, the software is then able to compute a stability index for the subject based on criteria found in robotics and biomechanics literature. This year, in order to exploit the newer, more accurate and more robust sensors such as the Microsoft Kinect v2, a new version of the PersoBalance software was engineered. While the core method remainsthe same, several improvement have been made regarding efficiency, user interface and extensibility. The new system is faster, more accurate and robust. It automatically registers the balance board during identification, and features improved graphical feedback during both identification and stability estimation phases. New stability measures were added, and support for online inverse dynamics is on the way. Most of the new version uses a scripting language (Python) except for time-critical algorithm, making the software easily extensible without recompilation. It is supported by Inria ADT PersoBalance2. Currently the software is being adapted to embedded computers in order to provide monitoring data in the City4Age project.

PersoBalance is registered with the Agency for the Protection of Programs (APP) and deposited at the BNF (Bibliotheque Nationale de France). Its registration number is Antepedia Deposit 20150710154654.

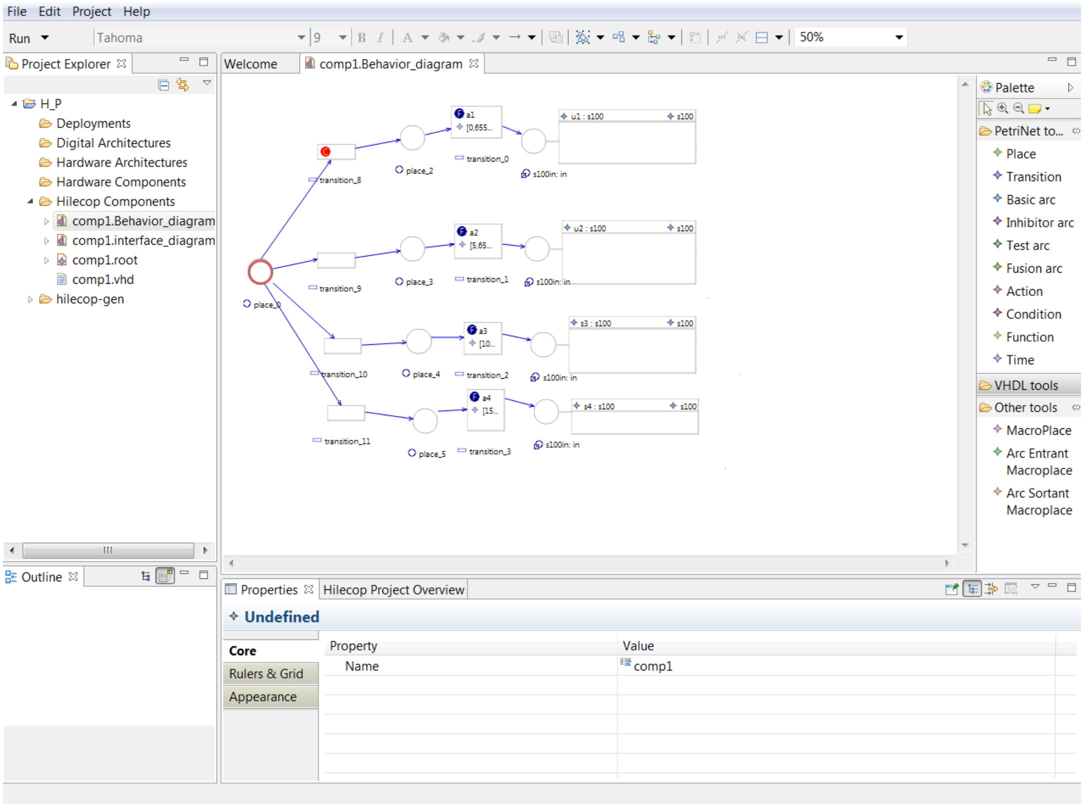


Figure 5. HILECOP screenshot

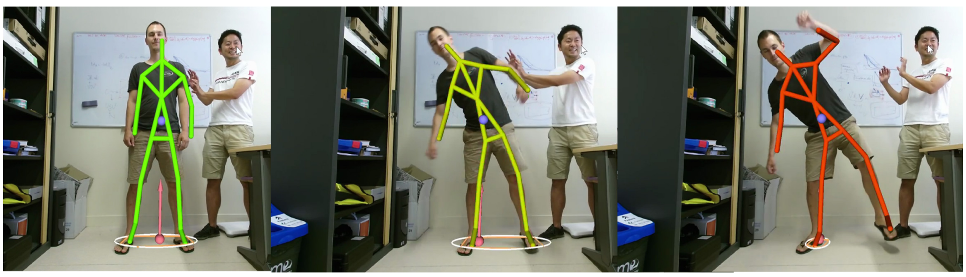


Figure 6. PersoBalance: Online stability estimation, from left to right: as a subject undergoes an unexpected external push, the system automatically estimates the ground reaction forces (pink arrow) and computes a stability index from the position of the ZRAM point relative to the support polygon (white/orange). The skeleton colour changes from green to red as the stability index decreases.

6.1.3. Sensbiotk

Participants: Christine Azevedo Coste, Roger Pissard-Gibollet, Benoît Sijobert.

Sensbiotk is a toolbox in Python for the calibration, the acquisition, the analysis and visualization of motion capture Inertial Measurement Units (IMU). Motion and Gait parameter reconstruction algorithms are also available.

http://sensbio.github.io/sensbiotk/

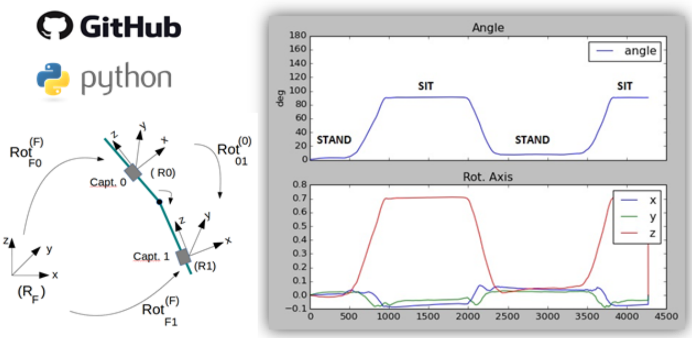


Figure 7. Sensbiotk toolbox for the calibration, the acquisition, the analysis and visualization of motion capture Inertial Measurement Units (IMU)

6.1.4. MOS2SENS

Participants: Mélissa Dali, Olivier Rossel, David Guiraud.

From Model Optimization and Simulation To Selective Electrical Neural Stimulation: it allows to manipulate 3D modeling of nerve and cuff electrodes taking into account anisotropy and the most advanced HH models of the myelinated axons. Based on optimized computing scheme, it allows to predict the acivation areas induced by a complex 3D spreading of the current over a multicontact electrodes. Moreover, the tool allows for performing optimization of the needed current to target a specific cross section of the nerve. Version 1.0 (IDDN.FR.001.490036.000.S.P.2014.000.31230) has been relaesed on december 2014 and v2.0 will be realeased January 2017. The last version includes full interface with OpenMEEG and COMSOL, and many other enhancements concerning both the model itself and the computation scheme.

6.1.5. STIMEP: An advanced real-time stimulation system based on a distributed architecture

Participants: Arthur Hiairrassary, David Andreu, David Guiraud, Olivier Rossel, Thomas Guiho.

The STIMEP has been developed within the EPIONE project (see section 9.3.1) which aims at assessing the use of invasive stimulation to relieve phantom pain. This innovative wearable stimulator allows to safely manipulate sensory afferent signals of an amputee through 4 TIME-4H intra fascicular electrodes, for a total of 56 channels.

The STIMEP is also designed to be controlled in real-time by a hand-prosthesis to generate feedback sensations; it permits as well a complex impedance follow-up.

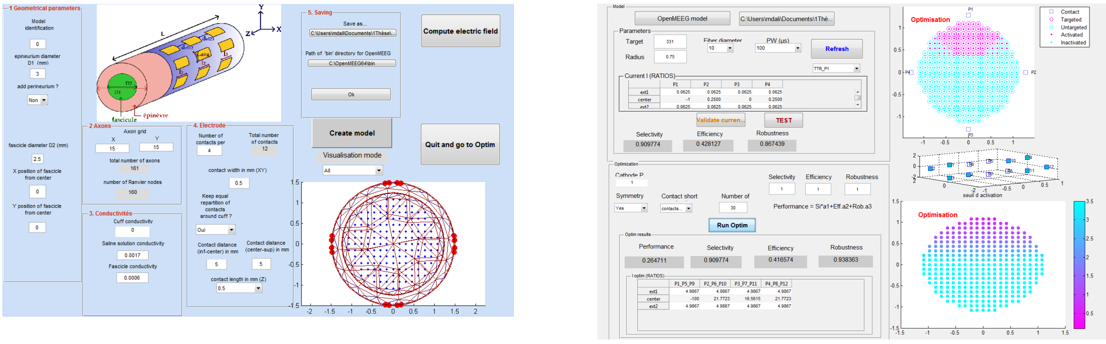


Figure 8. Graphical interface of software MOS2SENS, left: modeling multicontact CUFF electrode, right: optimization for spatial selectivity

The STIMEP is based on a distributed architecture and embeds:

- 1 x controller implemented on μC/OS-II RTOS exchanging data with a PC (USB) or an external device (SPI),
- 4 x neural stimulators with efficient modulation mechanisms to drive up to 4 multicontact electrodes simultaneously and independently,
- 6 x fully configurable procedures (formally modeled by Petri nets):
  - Contacts check, thresholds search, sensations characterization, therapy,
  - Real-time modulation of frequency, intensity and pulse-width,
  - Complex impedance measurement.
- 2 x smart and independent synchronization outputs,
- User and technical logs of relevant information.

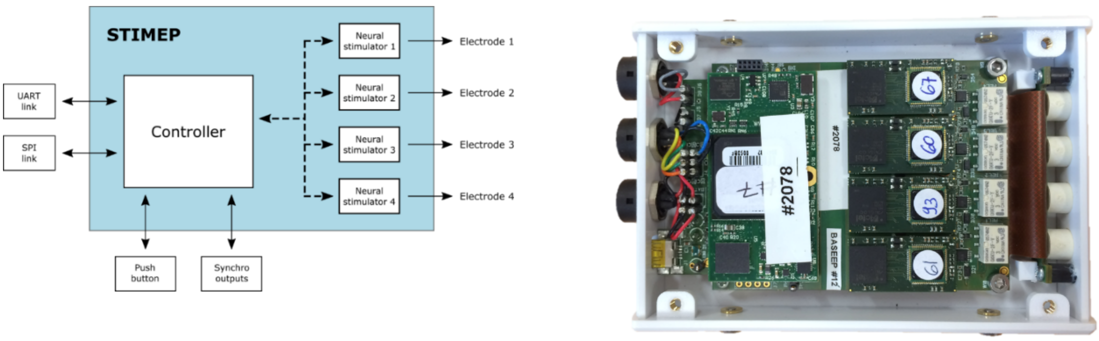


Figure 9. The STIMEP (STIMulator EPione)

The STIMEP is currently used in human trials and drives simultaneously 4 multicontact intrafascicular electrodes with real time control of the intensity, pulse-width and frequency of the stimulation to remove phantom pain and elicit very accurate sensation feedback.

7. New Results

7.1. Movement analysis and interpretation

7.1.1. *Inertial Sensor based Analysis of Gait for Children with Cerebral Palsy*

Participants: Christine Azevedo Coste, Benoît Sijobert, Jessica Rose [Stanford University].

Analysis of walking abnormalities is important for clinical diagnosis, to guide treatments, and to assess treatment outcomes for gait disorders particularly in children with cerebral palsy (CP). Motion capture, the current gold standard, enables practitioners to perform gait analyses with high accuracy in the laboratory. However, the motion capture technology used is constrained to a small space, the clinical environment may not be relevant to community mobility. This research collaboration investigated the development of a mobile systems using light-weight inertial measurement units (IMU). These sensor-based systems have potential to provide a more efficient, mobile alternative for movement analysis and can offer real-time feedback to patients for more effective rehabilitation. This interdisciplinary collaboration with Professor Jessica Rose, from the Department of Orthopedic Surgery at Stanford University aims to quantitatively assess walking problems associated with CP and related neurological conditions. Despite their small size, ease-of-use, robust design and low-cost, there are numerous recognized technical issues that make the use of IMUs relatively complex moreover in children. Through a series of experiments we leveraged our complementary skills to propose an IMU sensor system and software to extract meaningful gait parameters for rehabilitation of children with CP. A feasibility study was achieved at the Lucile Packard Children's Hospital Motion & Gait Lab in order to solve technical issues and refine calculations validated based on walking patterns recorded by Laboratory-based 3D motion capture data.

7.1.2. *Automatic Human Movement Assessment with Switching Linear Dynamic System: Motion Segmentation and Motor Performance*

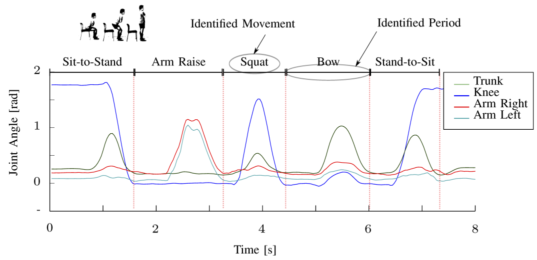
Participants: Baptista Roberto [Universidade de Brasilia, Brasil], Bo Antonio P.l. [Universidade de Brasilia, Brasil], Mitsuhiro Hayashibe.

Performance assessment of human movement is critical in diagnosis and motor-control rehabilitation. Recent developments in portable sensor technology enable clinicians to measure spatiotemporal aspects to aid in the neurological assessment. However, the extraction of quantitative information from such measurements is usually done manually through visual inspection.

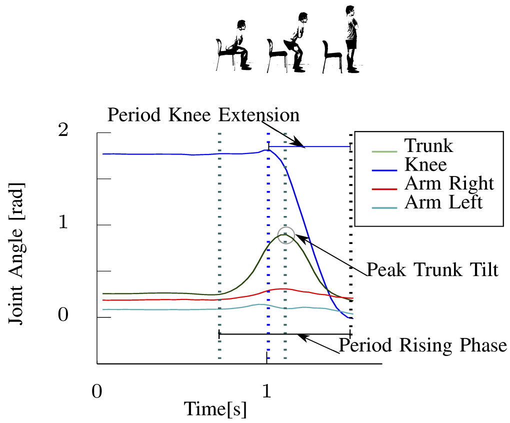
This work presents a novel framework for automatic human movement assessment that executes segmentation and motor performance parameter extraction in time-series of measurements from a sequence of human movements. We use the elements of a Switching Linear Dynamic System model as building blocks to translate formal definitions and procedures from human movement analysis. Our approach provides a method for users with no expertise in signal processing to create models for movements using labeled dataset and latter use it for automatic assessment.

Preliminary tests were carried out involving six healthy adult subjects that executed common movements in functional tests and rehabilitation exercise sessions, such as sit-to-stand and lateral elevation of the arms. Also five elderly subjects, two of which with limited mobility, that executed the sit-to-stand movement. The proposed method worked on random motion sequences for the dual purpose of movement segmentation (accuracy of 72-100%) and motor performance assessment (mean error of 0-12%).

The results of this work have been accepted for publication in the journal IEEE Transactions in Neural Systems and Rehabilitation Engineering.



Movement sequence segmentation and movement type recognition



Motor performance parameters extraction

Figure 10. Dual purpose of the proposed approach: movement segmentation and movement assessment.

7.1.3. Inertial Sensor based Analysis of Gait for Post-stroke individuals

Participants: Christine Azevedo Coste, Benoît Sijobert, Jérôme Froger [CHU Nîmes], François Feuvrier [CHU Nîmes].

Walking impairment after stroke can be addressed through the use of drop foot stimulators (DFS). In these systems, electrical stimulation is applied to activate the common peroneal nerve and elicit ankle dorsiflexion during the swing phase of gait. DFS are generally piloted by a heel switch positioned in the shoe of the affected side with stimulation being triggered ON by heel rise of the affected foot and triggered OFF by heel strike.

Using inertial sensors for modulating FES intensity could provide a more optimized delivery of stimulation and could also enable to regulate dorsiflexion in the presence of disturbances, such as fatigue or stairs. It could also increase the number of potential users of the technology, allowing subjects walking without heel strikes to be stimulated at a correct timing. Meanwhile, pathological post-stroke gait requires the investigation of complex inertial sensors based algorithms for being able to compute different useful gait parameters for later triggering stimulation.

Numerous constraints related to these clinical context, pathology and usability have to be taken into account for providing a reliable patient oriented solution. In this work, we aim to compare accuracy and feasibility of using a minimum amount of inertial sensors instead of the gold standard camera based motion capture, for assessing joint angles and other gait events such as stride length or dorsiflexion speed at heel on. A maximum of 30 subjects will be included in this experimental protocol. Equipped with motion capture targets on which an inertial sensor is set (Figure 11), subjects have to perform an experimental path on a gait carpet. EMG recordings are also performed to monitor and evaluate fatigue. In further works, algorithms from inertial data developed through these study will enable us to evolve toward close loop control, putting together inertial sensors and programmable stimulator in real time ([39]).

7.2. Modeling and identification of the sensory-motor system

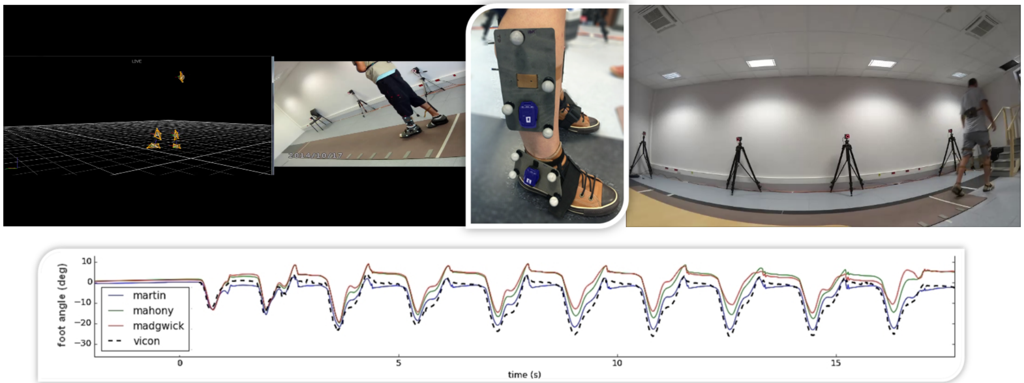


Figure 11. Gait analysis after stroke

7.2.1. Neuroplasticity and recovery in remote (sub)cortical structures following wide-awake surgery of infiltrative low-grade gliomas: investigation of fMRI and EEG signals by standard and nonlinear methods

Participants: Anthony Boyer, Jérémy Deverdun [CHU Montpellier], Hugues Duffau [CHU Montpellier], Emmanuelle Le Bars [CHU Montpellier], Sofiane Ramdani [LIRMM], David Guiraud, Nicolas Menjot de Champfleur [CHU Montpellier], François Bonnetblanc.

Wide-awake surgery of brain tumour is used to optimize the resection of tumoral tissue. Postoperatively, patients show mild and temporary neurological deficits despite massive cerebral resections. Reasons for these impairments along with the compensation mechanisms operating within the cortex and subcortical structures are barely understood. The objective of this project is to reveal the remote effects of the tumour and its resection, to determine their nature measuring changes induced in functional Magnetic Resonance Imagery (fMRI) and electroencephalographic signals using standard and nonlinear methods.

In a first attempt to better understand the direct consequences of wide-awake surgery we focused on the thalamus insofar as, topologically, it is the largest input source and output target of the cortex. It plays a major role in corticosubcortical and corticocortical interactions and is expected to be heavily impacted by the tumour removal while being essential to the recovery process. Studying the thalamus, based on its very particular anatomical properties, could provide essential indications regarding the behaviour of cortical and subcortical centers.

We carried out Amplitude of Low-Frequency fluctuations and Regional Homogeneity analyses on resting state fMRI data before and after the tumour removal, including an original 24h postoperative acquisition. We intended to assess possible changes in spontaneous neuronal activity over time, characterizing different facets of slow-wave hemodynamic fluctuations. We particularly sought evidences of disrupted and atypical neuronal activity emerging within deafferented thalamic subterritories.

This work revealed significant alterations of neuronal activity within distinct thalamic territories, in accordance with its neuro-anatomo-functional organization. We showed a transient decrease of neuronal activity intensity and homogeneity within the ipsilesional thalamus directly related with the anatomical dee- and deafferentation induced by the neurosurgery and a concomitant increase of neuronal activity and temporal synchrony in homologous regions of the contralesional thalamus, leading to a significant interhemispheric imbalance during the immediate postoperative period. Evidences of diaschisis-like phenomenon primarily affecting higher order thalamic nuclei of the ipsilesional thalamus and the extensive involvement of the contralesional thalamus in the postoperative period promote the thesis of transient diaschisis-induced contralesional compensation for patients who underwent wide-awake surgery (Figure 12).

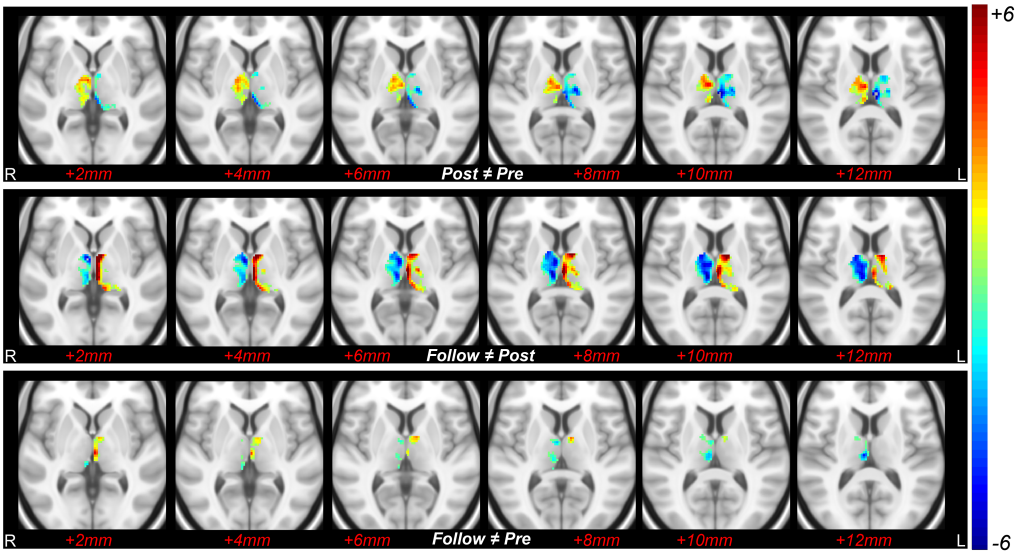


Figure 12. Voxelwise differences in ALFF score over time: ALFF maps were grouped depending on the acquisition date 1_Pre (-48h), 2_Post (+24h), 3_Follow (+3 months) and between-groups contrasts were generated as voxel-wise two-sample t-tests in order to highlight significant differences in scores over time (Post $\neq$ Pre, Follow $\neq$ Post and Follow $\neq$ Pre). Neuroradiological convention.

7.2.2. Understanding the effects of direct electrical stimulation of the brain during wide awake surgery

Participants: Marion Vincent, François Bonnetblanc, David Guiraud, Hugues Duffau, Mitsuhiro Hayashibe, Olivier Rossel.

Real-time functional mapping of the brain combined with direct electrical stimulation (DES) has been widely recommended for the awake neurosurgery of slow-growing and infiltrative brain tumors, to guide the resection [53]. Intra-operative DES is generally applied at 60 Hz in Europe (50 Hz in some other countries) (biphasic stimuli, single pulse duration 1 ms, intensity from 2 to 6 mA under local anesthesia, and during 1 to 5 s). By generating transient perturbations, it allows the real-time identification of both cortical areas and sub-cortical white matter pathways that are essential for the function. Its use lowers the probability of resecting essential functional areas near or within the tumor. However, the electrophysiological effects of DES remain poorly understood, locally and at a more remote distance [36], [9].

The investigation of this topic requires the recording of evoked potential. DES can be used to probe the spatio-temporal connectivity and dynamics of short- or long-range networks in vivo and in real time when combined with electrophysiological recordings (e.g. electroencephalography (EEG) or electroencephalography (ECoG)). This approach has been used for pre-surgical planning of drug-resistant epileptic patients by using an ECoG grid implanted at the surface of the grey matter. Matsumoto et al. [55] sought to measure in vivo connectivity with DES (rather than studying its propagation) but observed that a low-frequency cortical application of DES (1 Hz, constant current, and alternating rectangular wave pulses of 0.3 ms, with an intensity around 10-12 mA) induces 'cortico-cortical' evoked potentials (CCEPs) around 10-50 ms after stimulation. These properties are incompatible with the detection of EPs during awake brain surgery, when DES is classically applied at 60 Hz due to stimulation artefacts. Conversely, 100 ms (i.e. a frequency of 10 Hz) seems to be a sufficient time-window that facilitates real-time averaging to detect these CCEPs for further on-line analysis of brain connectivity during the surgery.

In addition, in the studies mentioned above, ECoG signals were recorded in a classical common mode (CM) configuration, i.e. the signal was measured between each channel of interest and a reference electrode. Also, in all this literature, CCEPs were measured by averaging a large set of trials together. This off-line averaging actually prevents the use of ECoG recording to monitor the evoked potentials on-line. Recently, by lowering the DES frequency to 10 Hz and by using a differential recording mode (DM) for ECoG signals, in which the signal is measured between two adjacent electrodes, we were able to record for the first time on-line CCEPs easily with a standard current amplitude of stimulation (2 ms) and without averaging the data [41] (Figure 13.

Recording ECoG in a DM enabled increasing the focality and the signal to noise ratio of the raw data. Ongoing experiments on new patients corroborate the reproducibility of this protocol. This unusual way of recording ECoG could improve the spatial resolution of the recordings in the three dimensions (in surface and in depth). Moreover, this method was used under general anesthesia but could also be performed on-line during the awake surgery. It would enable the investigation of the connectivity and to probe directly rapid plastic changes of cortical excitability.

7.2.3. A study on the effect of electrical stimulation as a user stimuli for motor imagery classification in Brain-Machine Interface

Participants: Saugat Bhattacharyya, Maureen Clerc, Mitsuhiro Hayashibe.

Functional Electrical Stimulation (FES) provides a neuroprosthetic interface to non-recovered muscle groups by stimulating the affected region of the human body. FES in combination with Brain-machine interfacing (BMI) has a wide scope in rehabilitation because this system directly links the cerebral motor intention of the users with its corresponding peripheral muscle activations. In this paper, we report the preliminary results of the effect of electrical stimulation during a motor imagery training task on healthy subjects and its comparison with visual stimuli.

The experiment designed for this work is divided into three sessions: only visual, only FES and both visual-FES stimuli. The sessions consist of instructing the subjects through a sequence of repetitive stimuli to execute the corresponding motor imagery task, which in our case, is left and right hand movement. The FES session is similar to the visual one except in place of the arrows, stimulation is directly induced in the fore-arm of the hand of interest, without providing any visual information. In the Visual-FES session, both the combined stimulations are time-synchronized to each other. After acquisition, the incoming raw EEG signal is band-pass filtered at 8-30 Hz. Then, common spatial filters (CSP) is applied to extract features relevant to left- and right-motor hand movement EEG signals. CSP is a spatial filter widely used in BMI because the spatial patterns contain highly discriminative features between two classes. In this study, we prepare the feature vectors using 6 spatial filters which is then transferred as inputs to a linear discriminant analysis (LDA) classifier. Finally, the classifier detects the corresponding motor intention of the subject, i.e., left and right motor movement. A block diagram of our experimental setup during Visual-FES session is illustrated in Fig. 14.

Classification results shows a significant rise in accuracy for 2 (of 3) subjects which suggest a positive influence of FES during motor imagery training of the subjects. It was noted that both the subjects had no previous experience on BMI, then they were not familiar with generating motor imagery with visual stimuli. Visual stimuli are the widely accepted form of motor training but the subject requires constant training to reach an optimal result. Based on the results of this study, we can infer that electrical stimulation can also be used for motor training and it can potentially provide better performance as it can make natural proprioceptive feedback related to motor performance than visual stimuli which requires user’s recognition regarding the visual cue.

7.2.4. A Study on the Effect of Electrical Stimulation During Motor Imagery Learning in Brain-Computer Interfacing

Participants: Saugat Bhattacharyya, Maureen Clerc, Mitsuhiro Hayashibe.

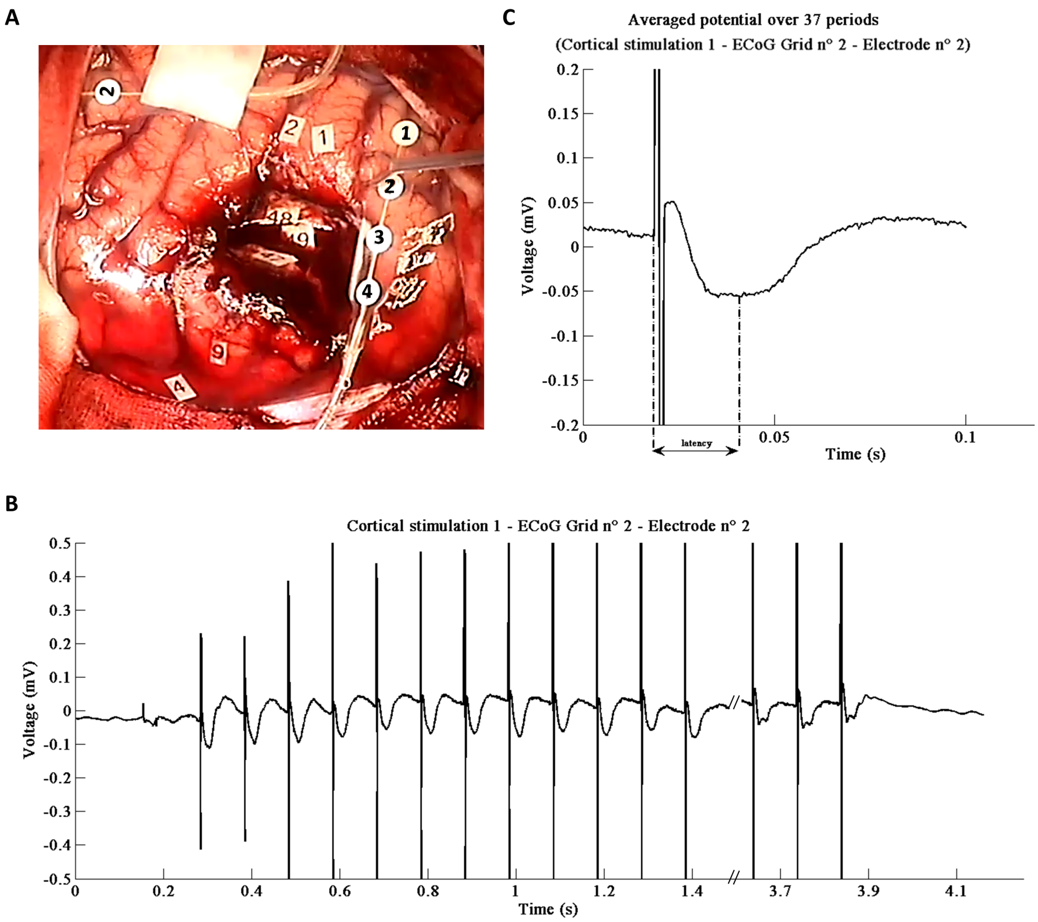


Figure 13. A: DES is applied cortically near the second electrode of the ECoG strip 2 during 3.7 s. B: Magnified view of the ECoG signal corresponding to the stimulation (with the 104 gain). CCEPs can be observed after each stimulation artefact. The last CCEPs are distorted due to the amplifier response. When the amplified signal exceeds the [-5 ; +5] volts range, an oscillation appears. C: Mean CCEP over 37 stimuli, with a latency of 23.7 ± 0.78 ms

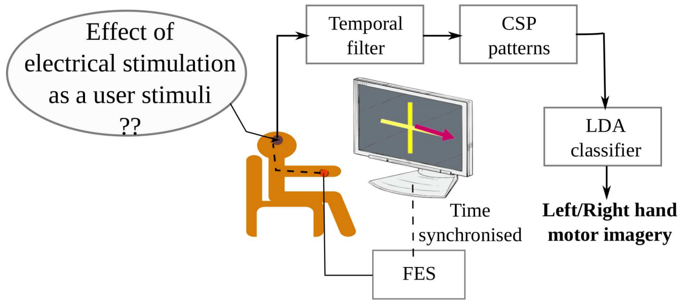


Figure 14. Block diagram of our experimental setup during motor imagery sessions where user stimuli is with conventional visual stimuli, electrical stimulation stimuli or the combined, respectively.

Functional Electrical Stimulation (FES) stimulates the affected region of the human body thus providing a neuroprosthetic interface to non-recovered muscle groups. FES in combination with Brain-computer interfacing (BCI) has a wide scope in rehabilitation because this system can directly link the cerebral motor intention of the users with its corresponding peripheral mucle activations. Such a rehabilitative system would contribute to improve the cortical and peripheral learning and thus, improve the recovery time of the patients.

To date, in BCI experiments feedback is commonly provided to the subject by means of a visual medium. On observing the feedback, the subject would attempt to perform his task. It is an interesting notion if one includes electrical stimulation to help in augmenting the performance of the motor task at hand. Thus, in this paper, we report the preliminary results of the effect of electrical stimulation on the learning of the subject during a motor imagery training task on healthy subjects. Through this study, we aim at employing FES as a proprioceptive feedback to the subject to improve the learning of the subject both in terms of accuracy and time.

In this experiment the participants performed four motor tasks: left hand movement, right hand movement, left foot movement and right foot movement across 6 separate sessions. A session provides instructions to the participant through a sequence of visual cues to execute one of the four motor tasks and each visual cue is termed as '*trial*'. Further, for data analysis, each trial are separated into time windows, termed as *epochs*. Each session consists of a feedback session provided visually to the participant at each trial, quantified by the hyperplane distance of the decoder. Before the start of the experiment, the participants undergo a training session for decoder training and to acclimatize to the tasks. Common Spatial Patterns is employed as features which is given as inputs to the Linear Discriminant decoder. The decoder designed in this work is a 2-level hierarchy. The first level classifies between left and right motor imagery and the second level discriminates between hand and foot motor imagery. In 3 of the 6 sessions, surface electrical stimulation (ES) is transmitted to the subject during the feedback period to aid the participant in performing the task. Thus, in this paper, we named the ES induced sessions as FES sessions and the sessions with only visual feedback as VIS sessions.

We report the learning during FES and VIS session feedback for each trial. For this purpose, we measure the distance of the feature vector from the hyperlane for each epoch updated at every 0.125 seconds. We took this parameter to study the feedback effect because the larger the distance from the hyperplane, the higher is the confidence of the classifier to detect the right output. The average feedback curve for all the correctly classified trials of both FES (in blue) and VIS (in red) are shown in Fig. 15. From the curves we assume that greater the slope of the curve, faster is the learning demonstrated by the subject. Subject 1 demonstrates an increasing learning effect (greater slope) for FES feedback for all the limbs, except Right foot as compared to the VIS feedback. The figures for Subject 2 illustrates a more prominent learning effect during FES feedback and it is clearly differentiable for VIS feedback even though Subject 1 showcased a higher increase in accuracy across trials than Subject 2. It is also noted from the figures of both the subjects that VIS feedback has a frequent increasing and decreasing trend of the curve. Subject 3 had a decrease in accuracy during FES feedback as compared to the VIS feedback which can be validated from the figure that the discriminability between the FES and VIS feedback are not as prominent in comparison to the other subjects. We can infer from these results that the electrical stimulation had a positive influence during motor task learning and with an increase in sessions one can assume ES to provide a faster learning. The steady increase of learning during FES sessions can be attributed to the fact that the subjects reported to be more motivated to perform the tasks when an ES was provided and they felt the inclusion of ES helped in their imagination. On the other hand, during VIS sessions the subjects reported to lose motivation in-between the tasks.

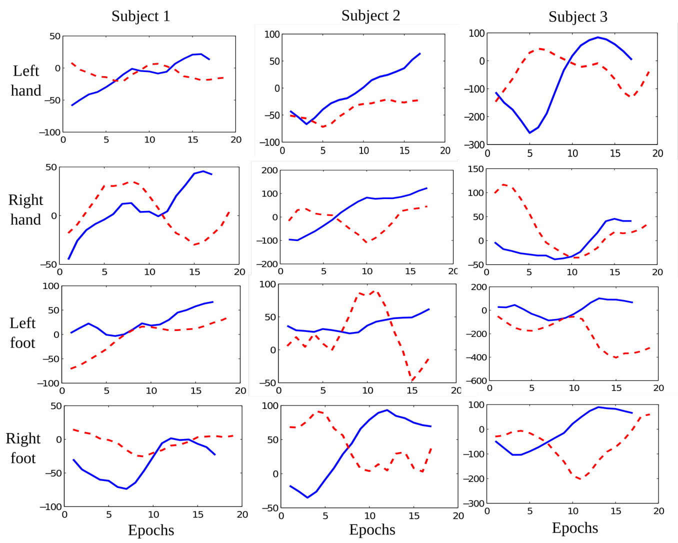


Figure 15. The learning curve of the 3 subjects for the motor imagery correctly classified tasks during FES sessions (in blue –) and VIS sessions (in red –) based on the average hyperplane distance.

7.2.5. NIRS-EEG joint imaging during transcranial direct current stimulation

Participants: Mehak Sood [IIT Hyderabad, India], Pierre Besson [Euromov, UM], Makii Muthalib [Euromov, UM], Utkarsh Jindal [IIT Hyderabad, India], Stéphane Perrey [Euromov, UM], Anirban Dutta, Mitsuhiro Hayashibe.

Transcranial direct current stimulation (tDCS) has been shown to perturb both cortical neural activity and hemodynamics during (online) and after the stimulation, however mechanisms of these tDCS-induced online and after-effects are not known. Here, online resting-state spontaneous brain activation may be relevant to monitor tDCS neuromodulatory effects that can be measured using electroencephalography (EEG) in conjunction with near-infrared spectroscopy (NIRS). We present a Kalman Filter based online parameter estimation of an autoregressive (ARX) model to track the transient coupling relation between the changes in EEG power spectrum and NIRS signals during anodal tDCS (2 mA, 10 min) using a 4x1 ring high-definition montage. Our online ARX parameter estimation technique using the cross-correlation between EEG band-power (0.5-11.25 Hz) and NIRS oxy-hemoglobin signal in the low frequency range was shown in 5 healthy subjects to be sensitive to detect transient EEG-NIRS coupling changes in resting-state spontaneous brain activation during anodal tDCS. Conventional sliding window cross-correlation calculations suffer a fundamental problem in computing the phase relationship as the signal in the window is considered time-invariant and the choice of the window length and step size are subjective. Here, Kalman Filter based method allowed online ARX parameter estimation using time-varying signals that could capture transients in the coupling relationship between EEG and NIRS signals. Our new online ARX model based tracking method allows continuous assessment of the transient coupling between the electrophysiological (EEG) and the hemodynamic (NIRS) signals representing resting-state spontaneous brain activation during anodal tDCS. It is supported by Franco-Indian Inria-DST project funding and by the LabEx NUMEV (ANR-10-LABX-20).

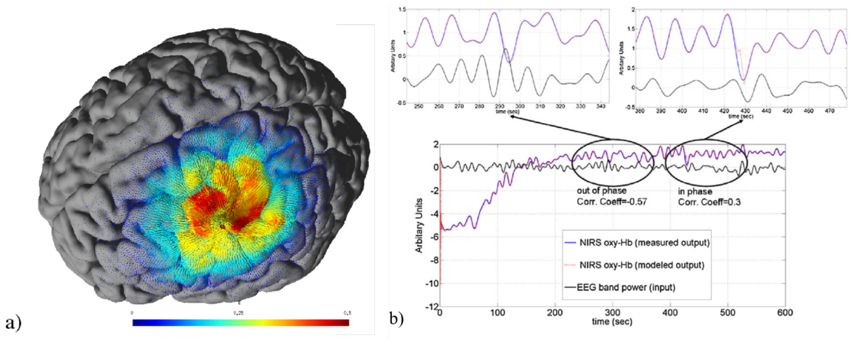


Figure 16. a) Electric field (V/m) estimated at the gray matter surface due to 2 mA anodal HD-tDCS. b) An illustrative example showing the NIRS oxy-Hb signal that was measured (in blue) as well as the predicted NIRS oxy-Hb signal using the ARX online tracking method (in dotted red).

7.2.6. Is EMG a good signal to assess fatigure under FES in different stimulation modes?.

Participants: Willy Fagart, Robin Candau [EUROMOV], Anthony Gelys [Propara Center], Mitsuhiro Hayashibe, David Guiraud.

The study that we have undertaken aims to analyse the neuromuscular fatigue in 3 paralysed subjects with spinal cord injury and to find if there is a link between the torque and the EMG signal. 6 series of 8 trains of stimulation (30 Hz, 400μs, 3 on / 2 off, in maximal intensity) were used to lead a muscular fatigue on the soleus muscle. At the beginning and the end of every series of stimulation, we measured the intermediate state of fatigue by evoking muscular twitch (1Hz, 400 μs and of maximal intensity) on the 2 legs. The temporal component and frequency of electromyographic activity were analyzed. These values were correlated with the torque. At the end of the protocol of stimulation, the torque decreased on 5 legs on 6 (ranging from -39 % to -20 %, p<0,05). A polynomial of degres 2 relation was found between the torque and the peak to peak value of the EMG signal. Nevertheless this relation does not remain reliable in a clinical context with regard to the variability of the data. This variability represents the processes of potentiation of the electric and mechanical answer as well as the expression of the mechanisms which contribute to the muscular fatigue.

7.2.7. EleVANT project: a diagnostic evaluation of acute stroke by near infrared spectroscopy and transcranial direct current stimulation coupling.

Participants: Victor Vagné, Vincent Costalat, David Guiraud, Emmanuelle Le Bars, Stéphane Perrey [EUROMOV], Olivier Rossel, Mitsuhiro Hayashibe.

Cerebral infarctions can now be treated with new techniques using intravenous thrombolysis and mechanical clearance. Their proven efficacy is directly correlated to the time lapse between the start of symptoms and initiation of treatment. Currently, a definitive diagnosis can only be made once the patient has realized a radiological imaging (CT scan or MRI) on a medical centre equipped with these expensive devices, thus enabling the medical team to initiate the appropriate treatment. Transit times during the pre-hospitalisation phase before diagnosis are therefore often longer and have the greatest negative impact on the patient's prognosis. The association of NIRS and tDCS enables recording modifications in cortical tissue oxygenation induced

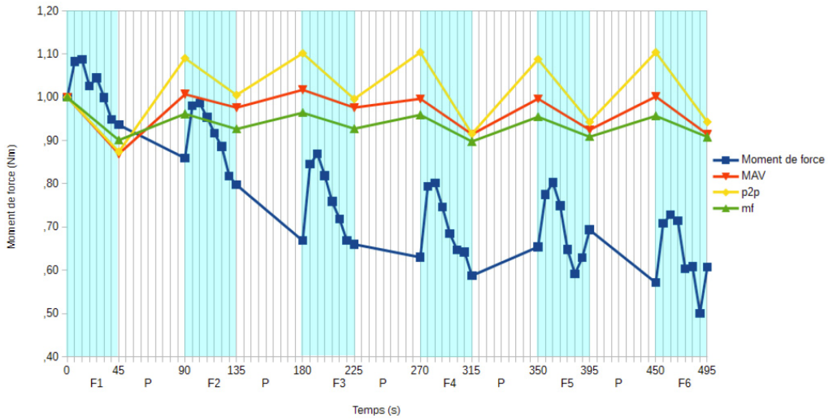


Figure 17. Correlation of different EMG features and torque during (Fn phases) and between (P phases) train of stimulations. Fatigue can be oberved and followed by EMG parameters.

by electrostimulation. A case-control study demonstrated the capacity of near infra-red spectroscopy (NIRS), combined with transcranial direct current stimulation (tDCS) to diagnose established cerebral ischaemia. According to this study, the affected hemisphere with impaired circulation showed significantly less change in cerebral hemoglobin oxygenation than the healthy side in response to anodal tDCS. This preliminary study showed the feasibility of identifying the lesioned hemisphere in subacute stroke patient. In collaboration with Gui de Chauliac Hospital, I2FH and Euromov, the EleVANT project is aiming to prospectively evaluate the NIRS-tDCS technique in the 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. A first NIRS-tDCS helmet prototype was developed to gather our Oxymon NIRS and Starstim tDCS devices, allowing good optodes-scalp and electrodes-scalp contact, while reducing both movement artifact and set-up time. This helmet was improved steps by steps as tests were done to attempt several parameters (among others electrodes location, amplitude and time of stimulation). A 4 NIRS optodes and 2 electrodes montage was retained to test and validate the proof of principle. Preliminary results are encouraging and need further investigation to be strongly validated.

Otherwise, as effects of anodal tDCS on hemodynamic response remain discussed, we'll proceed in parallel with the establishment of MRI protocols to attempt a validation of these effects.

7.3. Synthesis and Control of Human Functions

7.3.1. FES-assisted cycling in SCI individuals

Participants: Christine Azevedo Coste, Benoît Sijobert, Charles Fattal, Anne Daubigney [COS Divio, Dijon], Jérôme Parent, Antonio Padilha Bo [University Brasilia], Emerson Facin Martins [University Brasilia], Lucas Fonseca [University Brasilia], Juliana Guimaraes [University Brasilia].

During more than one year we have prepared one complete paraplegic patient to participate into FES-cycling discipline at Cybathlon 2016. A research protocol was associated to this physical preparation and several variables have been monitored during the training in order to evaluate performances, physical and psychological state. We have also developped a FES tricycle dedicated to the competition. We have modified a commercial trike and a commercial electrostimulator in order to have a mid cost system, adapted to complete paraplegia, easy to transport and compatible with safe transfers between wheelchair and trike seat. Our pilot reached the objectives: participating into the race, being qualified and cycle 750m in less than 8mn. He has been able during his training to cycle 1km200 in 13mn (fig.19).

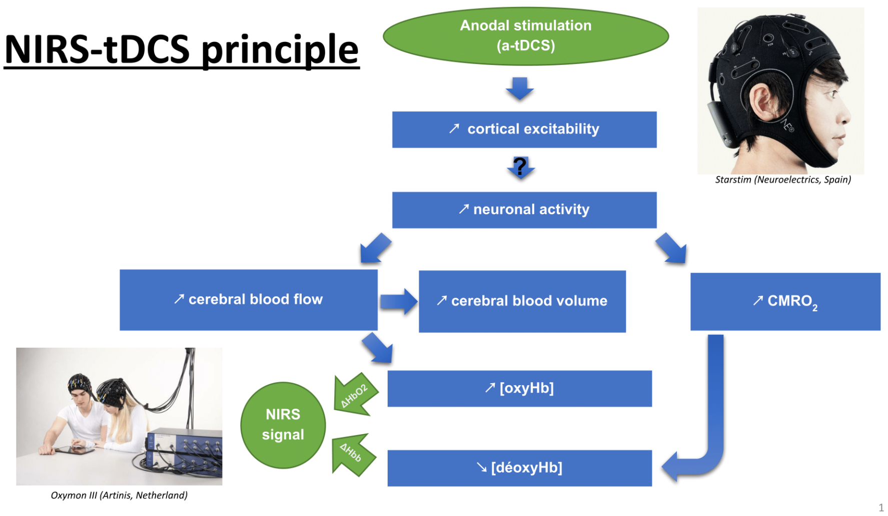


Figure 18.

In parallel, within CACAO associate team context, our Brazilian partner has trained several pilots using a similar training protocol [24], [22].

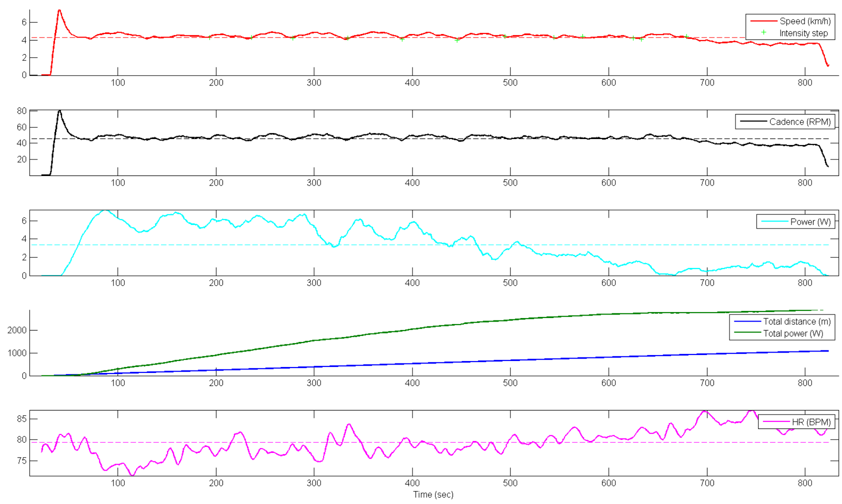


Figure 19. Best cycling performance. From top to bottom: speed (km/h), cadence (RPM), power (W), total distance (m) vs power (W), heart rate (BPM).

7.3.2. FES-assisted transfer in SCI individuals

Participants: Christine Azevedo Coste, Charles Fattal, Emerson Facin Martins [University Brasilia], Lucas Fonseca [University Brasilia], Ana Claudia Lopes [University Brasilia], Roberto Baptista [University Brasilia], Claudia Ochoa [University Brasilia].

One of the research axes investigated in CACAO associate team with Brasilia University is the assistance of seat to seat transfers in spinal cord injured (SCI) individuals. We have initated a research protocol to evaluate the feasibility to reduce arm efforts during pivot transfers by using feet support provided by lower limb muscles stimulation. 2 complete paraplegic patients were included for pilot experiments. Transfer is a key ability and allows greater interaction with the environment and social participation. Conversely, paraplegics have great risk of pain and injury in the upper limbs due to joint overloads during activities of daily living, like transfer. Preliminary results were promising [30]. Further inclusions will be achieved to confirm these preliminary observations.

7.3.3. New cueing modality for Parkinson Disease

Participants: Christine Azevedo Coste, Benoît Sijobert, Christian Geny [CHU Montpellier].

Parkinson's Disease (PD) is the second most common neurodegenerative disorder in the world. It is often related to gait impairments and to a high risk of falls. Among different consequences of this disease, the Freezing of Gait (FOG) is defined as an episodic inability to generate an effective stepping. Subjects report the feeling of having their feet "glued to the ground". Numerous studies used auditory or visual stimulus to prevent FOG to happen.

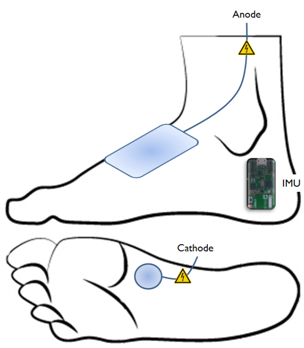


Figure 20. New cueing modality for Parkinson Disease. Electrodes and inertial sensor localization.

In our study, we aimed to investigate the effect of a sensitive cueing on gait disorders in subjects suffering from PD for improving gait and for reducing FOG occurrence. 13 participants with PD were equipped with an electrical stimulator and an inertial measurement unit (IMU) located under the lateral malleolus on the sagittal plane. Electrodes were positioned under the arch of the foot (Fig. 20) and electrical stimulation (ES) parameters adjusted to deliver a sensitive signal. Based on previous studies we achieved using IMU in Parkinson's Disease [52], [51], [56], in this protocol online IMU signal was processed in order to trigger ES at heel off detection (Fig. 21). Starting from a quiet standing posture, subjects were asked to walk at their preferred speed on a path including 5m straight line, u-turn and walk around tasks. 3 situations were considered: no stimulation baseline pre-condition, ES condition, no stimulation baseline post-condition. In ES condition the time to execute the different tasks was globally decreased in all the subjects. In "freezer" subjects, the time to complete the entire path was reduced by 19%. Freezing of Gait (FOG) episodes occurrence was decreased by 12% compared to baseline conditions. This preliminary work showed a positive global effect on gait and FOG in PD of a somatosensory cueing based on sensitive electrical stimulation [32].

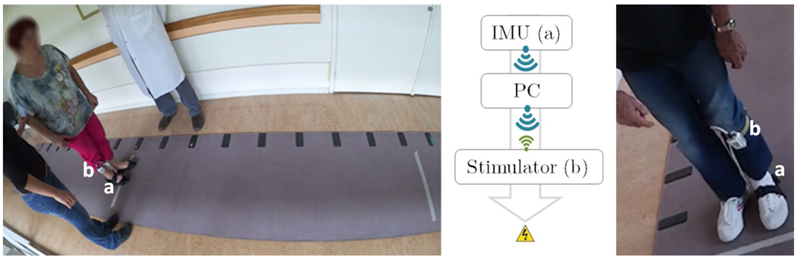


Figure 21. New cueing modality for Parkinson Disease. Experimental setup description.

7.3.4. Selective neural electrical stimulation of the upper limb nerves

Participants: Christine Azevedo Coste, David Guiraud, Wafa Tigra, Jacques Teissier [Clinique Beausoleil], Bertrand Coulet [CHU Montpellier], Charles Fattal, Anthony Gelis [Clinique PROPARA].

We have experimented a new approach of selective neural electrical stimulation of the upper limb nerves of two tetraplegic patients. Median and radial nerves are stimulated via a multipolar cuff electrode to elicit movements of wrist and hand in acute conditions during a surgical intervention. Various configurations corresponding to various combinations of a 12- poles cuff electrode contacts are tested. Video recording and electromyographic (EMG) signals recorded via sterile surface electrodes are used to evaluate the selectivity of each stimulation configuration in terms of activated muscles. We succeed to elicit graduated extension of wrist and fingers and graduated wrist flexion. We have also experimented a new human-machine interface to, at term trigger this electrical stimulation by individuals with tetraplegia. We investigated the feasibility of piloting an assistive device by processing supra-lesional muscle responses online. The ability to voluntarily contract a set of selected muscles was assessed in five spinal cord-injured subjects through electromyographic (EMG) analysis. Two subjects were also asked to use the EMG interface to control palmar and lateral grasping of a robot hand (Fig. 22). The use of different muscles and control modalities was also assessed. All patients are able to contract some of the evaluated muscles, preferential mode of pilot is patient dependent (Fig. 23).

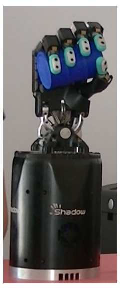


Figure 22. Closure posture of the Shadow robotic hand in the palmar grasp situation.

7.3.5. Spinal cord stimulation investigation

Participants: Christine Azevedo Coste, David Guiraud, Thomas Guiho, Charles Fattal, Luc Bauchet [CHU Montpellier].

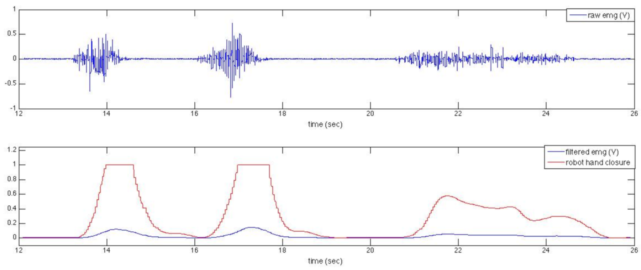


Figure 23. Robot hand trajectories generated from EMG recording for proportional mode. Top: raw EMG, bottom filtered EMG (blue) and hand trajectory (red). 0: hand is open, 1: hand is closed.

Spinal cord injury results in the loss of movement and sensory sensations but also in the disruption of some organ functions. Nearly all spinal cord injured subjects lose bladder control and are prone to kidney failure if they do not apply intermittent (self-) catheterization. Electrical stimulation of the sacral spinal roots with an implantable neuroprosthesis is one option besides self-catheterization to become continent and control micturition. However, many persons do not ask for this neuroprosthetic device (Brindley-Finetech implant) since deafferentation and loss of sensory functions and reflexes are serious side effects and since alternative treatments are available to patients (drugs, botulinus toxin. . . .). This PhD work aimed at investigating various techniques for spinal cord electrical stimulation in order to address dysfunctions in spinal cord injured individuals on lesion levels that have an impact on lower limb movements and bladder, bowel and sexual functions. Orderly recruitment of fibers at the spinal cord level should eventually lead to orderly recruitment of the detrusor muscle without activation of the bladder sphincter. Thereby, low pressure voiding, for example, should be obtained but is currently impossible with existing active implantable medical devices. A new large animal model – the domestic pig – was investigated to overcome size effects of rodent models and be able to translate results and technology more easily to human. [23].

7.4. Neuroprostheses and technology

7.4.1. Fast simulation and optimization tool to explore selective neural stimulation

Participants: Mélissa Dali, Olivier Rossel, David Guiraud.

In functional electrical stimulation, selective stimulation of axons is desirable to activate a specific target, in particular muscular function. This implies to simulate a fascicule without activating neighboring ones i.e. to be spatially selective. Spatial selectivity is achieved by the use of multicontact cuff electrodes over which the stimulation current is distributed. Because of the large number of parameters involved, numerical simulations provide a way to find and optimize electrode configuration. The present work offers a computation effective scheme and associated tool chain capable of simulating electrode-nerve interface and finds the best spread of current to achieve spatial selectivity. The software is protected to « Agence de Protection des Programmes « (APP), with the name MOS2SENS and identification IDDN.FR.001.490036.000.S.P.2014.000.31230 [21]

7.4.2. Numerical simulation of multipolar configuration

Participants: Mélissa Dali, Olivier Rossel, David Guiraud.

In the context of functional electrical stimulation of peripheral nerves, the control of a specific motor or sensory functions may need selective stimulation to target the desired effect without others. In implanted stimulation, spatial selectivity is obtained using multipolar CUFF electrodes with specific spread of the current over each contact. Furthermore, electrical stimulation recruits large fibers before small ones, whereas the targeted

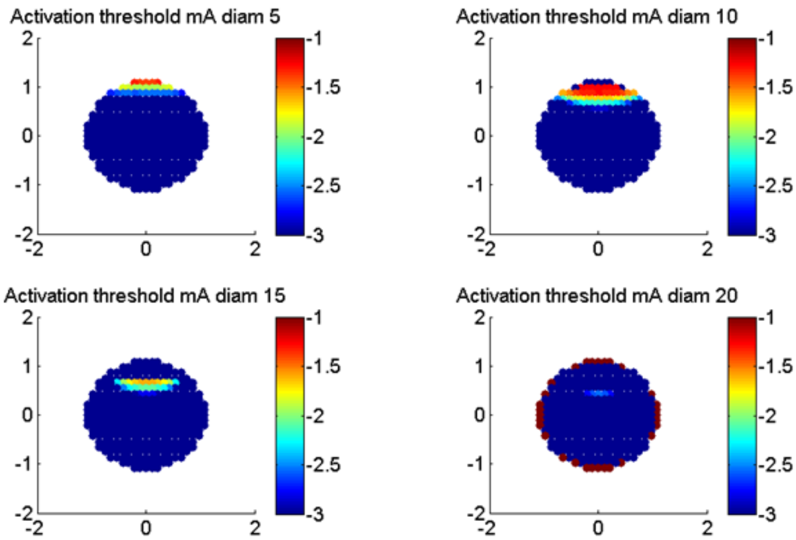


Figure 24. Spatially reverse recruitment order for fiber from 5µm to 20µm diameter obtained by multipolar configuration and prepulse technique

function could be elicited by a specific fiber type i.e. fiber diameter. In our work, numerical simulations were used to investigate the combination of multipolar configuration and prepulses, in order to obtain spatially reverse recruitment order. Multipolar stimulation provides efficient spatial selectivity, whereas subthreshold prepulses were used to reverse recruitment order with a reasonable increase of the injected charges. We compared several selective configurations combined with prepulses to show that some are able to guarantee both the spatial selectivity while one fiber's diameter can be preferentially activated [42].

7.4.3. Formal validation for critical embedded systems

Participants: Ibrahim Merzoug, Karen Godary-Dejean, David Andreu.

The works addressed here fall under the domain of formal modelling, semantics and verification methods (model checking). We focus on the analysis part of the HILECOP methodology, integrating the specific execution constraints (non-functional properties) into the validation process to guarantee the validation results. Indeed, the state space that is analyzed is that of the model of the system. It is clear that, if we want to obtain confident validation results, this analyzed state space must include all the possible behaviors of the real system, i.e., when it is executed.

One solution has been studied in the PhD thesis of H. Leroux [54], which lays the foundations of translation rules from the designed model to the analyzed model integrating both implementation and execution constraints. These transformations rules allow analyzing the resulting model with classical Petri nets analysis tools (as the Tina toolbox, and to guarantee the inclusion of the real states and traces into the analyzed state space.

A well-known drawback of such approach is that model checking is a technique that achieves properties verification through an exhaustive analysis of the state graph of the system model. The main limitation of this technique is the state space explosion problem because of its intrinsic exhaustivity. In a first part of the thesis (2015-2016), we proposed a compact state graph, called the Reduced Graph (see figure 25), which preserves all sequences of transitions firing as well as minimal and maximal duration of each sequence. To do so, we extend the partial order semantics to define temporal parallelism relations. According to covering steps approach, we compute our reduced graph reducing transitions interleaving, while keeping potential parallelism information.

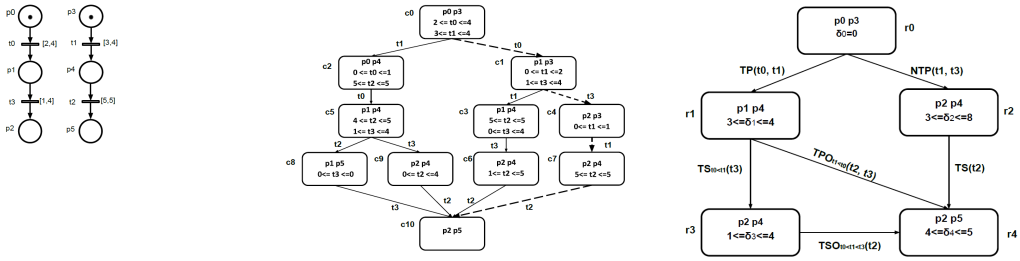


Figure 25. a Time Petri net, its classical State Class Graph and our Reduced Graph

But using classical analysis tools forces to analyze an over-set of the real behaviors, which limits the analytical capacities. In particular, the classical semantics of Petri nets considers an asynchronous execution, while in our context they are synchronously executed on FPGA with real parallelism and clock synchronization. Thus, we propose a new states graph which takes into account all the implementation and execution constraints related to the target hardware (non-functional properties): the Synchronous Behaviour Graph (SBG). We formally defined the graph and its semantics, illustrating this method on a simple example (see Figure 26). Then, we apply our method on a real industrial model, which is the execution engine embedded in our neurostimulator.

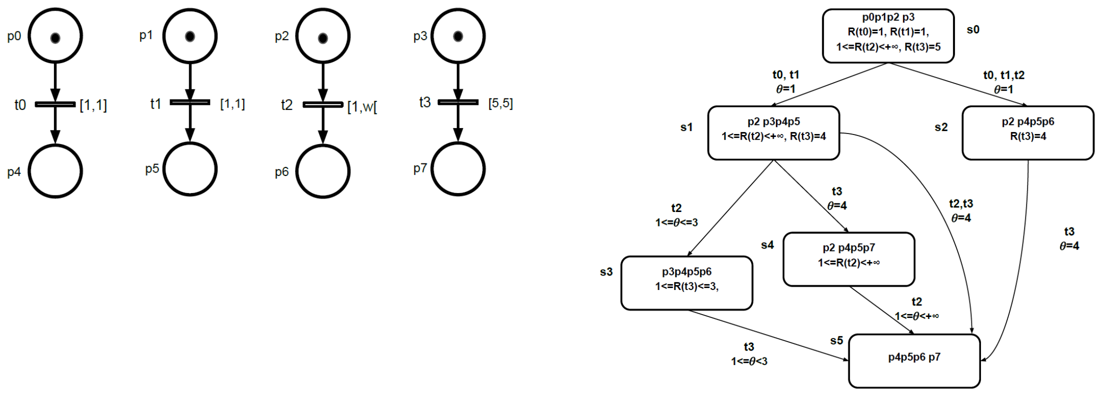


Figure 26. a Time Petri net and its Synchronous Behaviour Graph.

7.4.4. Control and scheduling co-design for stimulation systems

Participants: Daniel Simon, Zineddine Djellouli, David Andreu.

Functional Electrical Stimulation (FES) is used in therapy for rehabilitation or substitution for disabled people. They are control systems using electrodes to interface a digital control system with livings. Hence the whole system gathers continuous-time (muscles and nerves) and discrete-time (controllers and communication links) components. During the design process, realistic simulation remains a precious tool ahead of real experiments to check without danger that the implementation matches the functional and safety requirements [14]. To this aim a real-time open hybrid simulation software has been developed. It is dedicated to the analysis of FES systems deployed over distributed execution resources and wireless links. The simulation tool is especially devoted to the joint design and analysis of control loops and real-time features [6].

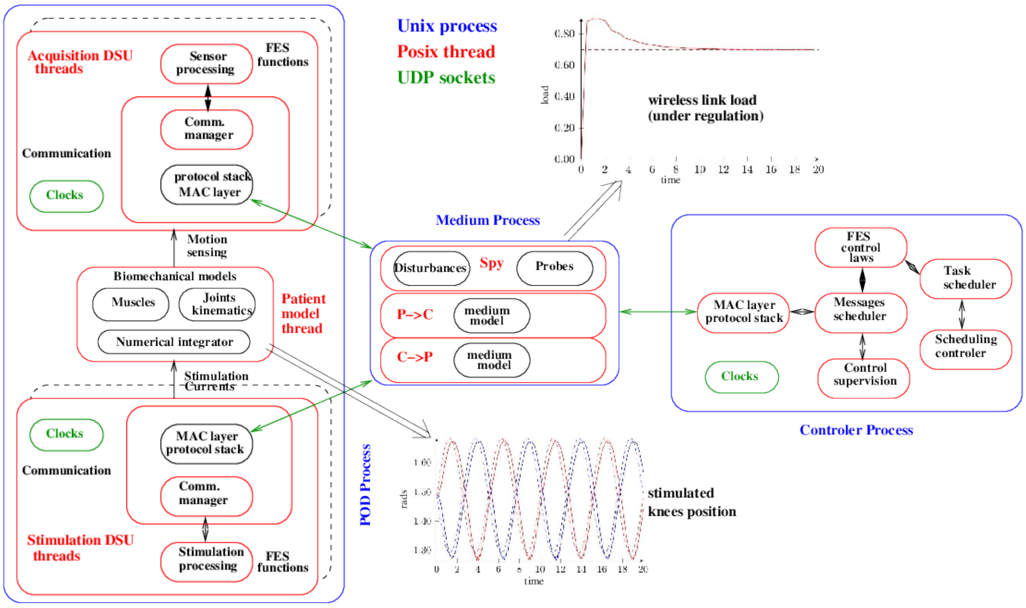


Figure 27. Real-time hybrid simulation architecture

Such simulator can be used for the design, testing and preliminary validation of new technologies and implementation. For example, it has been used to evaluate extensions of the STIMAP wireless communication protocol to optimize the network bandwidth when using multiple stimulation sites and control loops. Thanks to the hybrid nature of the simulation tool, the effect of the enhanced protocol can be directly observed on the controller output (e.g., concurrent controllers running to control several joints).

Another use is for the evaluation of closed-loop controllers acting on the execution resources of the distributed system. This approach provides adaptability and robustness, allowing for the design of fault-tolerant systems against varying and uncertain operating conditions [48]. It is especially usefull for embedded systems where these resources are scarce and fragile, as for the limited bandwith of wireless links between controllers and stimulation probes. Hence, a simple PI controller has been applied to the (m,k)-firm scheduling policy of control messages sent over the wireless link between the control device and the stimulation probes. It has been observed that such simple scheduling controller is able to jointly regulate both the communication load and the joints control quality.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

FUI MMCD (Multifunctions Modular Cockpit Display) [2014-2017] Labels : Pegase, ASTech
The MMCD project (Multi Functions Modular Cockpit Display) aims at designing a mechatronic architecture that is modular, certifiable and evolutive in terms of embedded GPU. This project will contribue to Avionics 2020 by developping a mock-up of new cockpit display system, allowing easy to manage GPU evolution.

Our contribution concerns formal design and prototyping of embedded supervisory functions, using the HILECOP methodology and tool.

8.2. Bilateral Grants with Industry

CIFRE phd financial support with Axonic (PhD grant), Wafa Tigra, 2013-2016, restoration of grasping using FES and selective stimulation

9. Partnerships and Cooperations

9.1. Regional Initiatives

- LABEX NUMEV (postdoc):

  Participants: Mitsuhiro Hayashibe, Denis Mottet (EUROMOV).

  A 1-year postdoc was funded by the NUMEV Labex on "Control of Arm Synergies After a Stroke (CASAS)".
- LABEX NUMEV (PhD grants co-fundings): Participants: Christine Azevedo, David Andreu, Benoit Sijobert.
  Participants: Sofiane Ramdani, François Bonnetblanc, Anthony Boyer.

9.2. National Initiatives

- BCI-LIFT: an Inria Project-Lab Participants : Mitsuhiro Hayashibe, Saugat Bhattacharyya.

  BCI-LIFT is a large-scale 4-year research initiative (2015-2018) which aim 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. We work on BCI-FES study for promoting motor learning.
- ADT PersoBalance2

  Participants : Mitsuhiro Hayashibe, Philippe Fraisse.

  A half-year engineer was funded by Inria ADT on "Personalized Balance Assessment in Home Rehabilitation, version2 (PersoBalance2)".

9.2.1. Excellence intitiative, PSPC

- Project INTENSE 2012-2018
- Leader: LIVANOVA
- Partners: LTSI, INRA Rennes, CEA LETI, HEGP, CHU Rennes, MXM-Axonic, 3D+
- the aim of the project is to treat severe obesity and cardiac failure through Vagus Nerve Stimulation (VNS). Our contirubution concerned the development of innovative hardware and software architecture to allow for selective stimulation. We developped the models that were used to optimize the settings of the stimulators taking into account the geometry of the 12-pole neural electrode. The selectivity and the efficacy of the stimulation were also improved through the study of original stiumulus waveforms. As a whole the idea was to further enhance the therapy while limiting the side effects that VNS my induce.
- the cardiac application stops end of august due to internal decisions at LIVANOVA but the obesity application continues to be investigated.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

Program: FP7

Project acronym: EPIONE

Project title: Natural sensory feedback for phantom limb pain modulation and therapy

Duration: 2013-2017

Coordinator: AAU (Aalborg, Denmark)

Other partners: Ecole polytechnique fédérale de Lausanne (EPFL), IUPUI (Indianapolis, USA), Lund University (LUNDS UNIVERSITET), MXM (Vallauris, France), Novosense AB (NS), IMTEK (Freiburg, Germany), UAB (Barcelona, Spain), Aalborg Hospital, Universita Cattolica del Sacro Cuore (UCSC), Centre hospitalier Universitaire Vaudois (CHUV)

Abstract: http://project-epione.eu/. The aim of the project is to treat phantom limb pain. CAMIN is only involved in the invasive approach using intrafascicular electrodes. We developed certified software with EPFL and AAU, co-supervised animal tests and data processing with UAB, provide support to clinical trials with IMTEK and UCSC and developped a new stimulator with MXM.

9.4. International Initiatives

9.4.1. Inria Associate Teams Not Involved in an Inria International Labs

9.4.1.1. NEUROPHYS4NEUROREHAB

Title: Development of neurophysiological test setup for customizing and monitoring patient-specific non-invasive electrical stimulation-facilitated neurorehabilitation.

International Partners (Institution - Laboratory - Researcher):

IITH (India) - Centre for VLSI and Embedded Systems Technology - Shubhajit Roy Chowdhury

IIT Gandhinagar (India) - Department of Electrical Engineering- Uttama Lahiri

Start year: 2014

See also: https://team.inria.fr/nphys4nrehab/

Stroke presents with heterogeneous patient-specific impairments in motor, sensory, tone, visual, perceptual, cognition, aphasia, apraxia, coordination, and equilibrium where the functional limitations following stroke are varied, including gait dysfunction, fall risk, limited activities of daily living, difficulties in swallowing, reduced upper extremity function, altered communication, besides others. These heterogeneous patient-specific impairments make planning of the neurorehabilitation therapy challenging. Here, it may be important to stratify the stroke survivors for restorative neurorehabilitation based on the prognosis and the ability of the stroke survivor to undergo therapy depending on their cardiovascular and neuromuscular capacity besides psychological factors such as motivation where the therapy needs to be tailored to individual health condition. The WHO International Classification of Functioning (ICF) model recommends intervention at multiple levels (e.g., impairment, activity, participation) where environment and personal factors can play an important role in resource-limited India. In fact, deconditioned chronic stroke survivor will need to recondition their cardiovascular endurance, metabolic fitness, and muscle conditions with a gradual increase in the intensity (number of hours per day) and frequency (number of days per week) of therapy, providing a higher level as they improve their function. Towards that overarching goal in a low-resource setting, we propose development of neurophysiological screening and monitoring tools using low-cost sensors.

9.4.1.2. CACAO

Title: Lower limb electrical stimulation for function restoration

International Partner (Institution - Laboratory - Researcher):

UNB (Brazil) - NTAAI - FACHIN-MARTINS Emerson

UNB (Brazil) - LARA - Padilha-Bo Antonio

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 will join our efforts and specific expertise to develop approaches of lower limb function restoration in spinal cord injured individuals. Two main applications will be addressed: 1) Functional Electrical Stimulation (FES) to assist SCI individuals to perform pivot transfers and 2) FES-assisted cycling (we already jointly prepared and participated to CYBATHLON'16). 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. We will take care in evaluating both functional and psychological effects of our solutions and to constrain technical choices to be acceptable by final user. CACAO project will be a good opportunity to combine "bioengineer" (DEMAR) and "physiology/rehabilitation" (NTAAI) visions and knowledges towards solutions for clinical applications.

9.5. International Research Visitors

9.5.1. Visits to International Teams

9.5.1.1. France-Stanford program

The Executive Committee of the France-Stanford Center for Interdisciplinary Studies supported our collaboration (§7.1.1) with Prof. Jessica Rose (Department of Orthopaedic Surgery, Stanford University). As part of the collaboration, Professor Rose presented a keynote lecture on Artificial Walking Technologies for Neuromuscular stimulation-assisted Gait for children with cerebral palsy at the International Functional Electrical Stimulation Society (IFESS) conference hosted by CAMIN. In July, a Benoît Sijobert spent 2 weeks in July 2016 to setup the experiment and Christine Azevedo Coste 1 week to run experiments.

9.5.1.2. Asgard program

From may 5 to may 13, François Bonnetblanc visited The Endestad Brain Imaging Group, the Institute of Basic Medical Sciences, Akershus universitetssykehus HF, Sunnaas Sykehus HF, UiO Department of Psychology, and the Norwegian School of Sport Sciences in Norway thanks to the Asgard programme. (http://www.france.no/if/oslo/cooperation/sciences/programmes-sciences/asgard/)

A shared project about the closed-loop stimulation of urinal control of pigs has been proposed with the Institute of Basic Medical Sciences in the framework of Aurora (followup of Adgard).

9.5.1.3. Research Stays Abroad

Christine Azevedo Coste spent 2,5 months (November 2015-February 2016) at Brasilia University as an invited researcher in collaboration within Emerson FACHIN-MARTINS responsible of the NTAAI (Nucléo de Tecnologia Assistiva, Acessibilidade e Inovacão) initiative.
Brazilian program: Science without borders (Ciencías sem fronteiras) CAPES. She spent 10 days in May 2016 together with Charles FATTAL to perform experiments.

Mitsuhiro Hayashibe was invited to participate to JSPS Program: Program for Advancing Strategic International Networks to Accelerate the Circulation of Talented Researchers. (PI Prof. Hitoshi Hirata, Dep. of Med. Nagoya Univ.)(Feb. 2016)

Mitsuhiro Hayashibe was visiting Researcher at EPFL, BIOROB supported by Swiss National Science Foundation (Sep.-Oct. 2016)

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

Christine Azevedo Coste was general chair of IFESS conference. http://ifess2016.inria.fr
M. Hayashibe is Co-Chair of IEEE Technical Committee on Human Movement Understanding at Robotics and Automation Society with E. Demircan (Univ. of Tokyo), D. Kulic (Univ. of Waterloo) and D. Oetomo (Univ. of Melbourne). https://sites.google.com/site/ieeehmu/

10.1.1.2. Member of the Organizing Committees

François Bonnetblanc, Mitsuhiro Hayashibe were membres of the IFESS organizing committee;

We organized the third European Computational Motor Control Summer School, June 26- July 2, 2016, Montpellier (Nicolas Schweighofer, Denis Mottet, Mitsuhiro Hayashibe) and Mitsuhiro Hayashibe organized Hands-on seminar for Friday July 1st. Motor Synergies. (AM : Andrea D'Avella, PM: Mitsuhiro Hayashibe)

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

- David Guiraud was associate editor of Theme 6 (rehabilitation Engineering) at IEEE EMBC conference
- David Guiraud was member of the IFESS program committee
- François Bonnetblanc was member of the IFESS program committee
- David Andreu was member of the IFESS program committee
- Mitsuhiro Hayashibe was member of the IFESS program committee
- Daniel Simon, ETFA 2016 and ICINCO 2016
- Mitsuhiro Hayashibe was Associate Editor of IEEE ICRA'17 (International Conference on Robotics and Automation) in charge of handling reviews on 6 papers in Nov.2016.

10.1.2.2. Reviewer

- Christine Azevedo was reviewer for IFESS and Engineering in Medicine and Biology Conference conferences
- David Guiraud was reviewer for IFESS, IEEE EMBC conferences
- François Bonnetblanc was reviewer for the IFESS and IEEE EMBC conferences;
- Daniel Simon was reviewer for the ETFA, ICINCO and MED conferences;
- Karen Godary-Dejean was reviewer for the IROS conference

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

M. Hayashibe is member of the Editorial Board of the International Journal of Advanced Robotic Systems, in Rehabilitation Robotics. David Guiraud is member of the editorial board of Journal of Neural Engineering (JNE) M. Hayashibe is member of the Editorial Board of ROBOMECH Journal.

10.1.3.2. Reviewer - Reviewing Activities

- François Bonnetblanc was reviewer for Cerebral Cortex, Neuropsychologia, and for the Journal of Neurophysiology;
- David Guiraud was reviewer for IEEE TNSRE, IEEE TBME, JNE, MEP, IEEE TBIOCAS, JNER, IEEE TCSC, journals
- Christine Azevedo was reviewer for Gait and Posture, IEE Transactions on Robotics (TRO), Artificial Organs, IEEE Journal of Biomedical and Health Informatics, IEEE Transactions on Biomedical Engineering (TBME) and IEEE Transactions on Neural Systems and Rehabilitation Engineering (TNSRE) Journals

10.1.4. Invited Talks

Mitsuhiro Hayashibe gave 2 talks on "Personalized Neuroprosthetics" and " Synergetic Learning Control" for LSRO and BIOROB labs, EPFL respectively at October 2016 (Lausanne, Switzerland).
Mitsuhiro Hayashibe gave a talk on "Synergetic Learning Control Paradigm - Computational Motor Control Principle" at Workshop Human Motor Control and Learning (EUROMOV, Montpellier) on November 21th 2016. In this workshop, Prof. Mark L. Latash (Pennsylvania State University, USA) and Dr. Yen-Hsun Wu were also invited.
Christine Azevedo gave a talk on "Neuroprosthetics in functional assistance: from observation to artificial control of movement" at EUROMOV, Montpellier on November 10th 2016.
Christine Azevedo gave a lecture at the International Symposieum on Electrical Stimulation Applied to Assistive technologies at Brasilia University in May 2016
Christine Azevedo gave a lecture at Genoploys center in June 16th ithin RUREKA cycle of conferences

10.1.5. Leadership within the Scientific Community

Christine Azevedo Coste is member of the board of International Functional Electrical Stimulation Society.

10.1.6. Scientific Expertise

Karen Godary-Dejean is member of COSTI «Acquisition de données traitement et visualisation de données numériques – Mécatronique » at Transfert LR, and member of the tranfer commission at LIRMM.

10.1.7. Research Administration

Christine Azevedo Coste is member of Inria Evaluation Committee.
She is involved in the working group for DEFROST and CHROMA Inria teams creation.
David Guiraud is involved in the working group for BIOVISION Inria team creation.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

- Master : Christine Azevedo, Ethics consideration in bioengineering research, 3h, M1, Master STIC SANTÉ, Montpellier University, France
- Master: Mitsuhiro Hayashibe, Neuroprotheses I and II (module coordinator), EMG and EEG signal processing and other rehabilitation modeling issues, 12h, Master STIC pour la Sante, Univ. de Montpellier, France;
- Master: Karen Godary-Dejean, computer engineering: embedded network, real time, DES (Discrete event system) modeling and control, dependability, formal validation, 230h, Polytech Montpellier.
- Master: David Guiraud, FES and Neuroprosthesis, M2 SMH, 12h, M1 and M2 Stic Santé 6h
- Master : D. Andreu, Software engineering, real time OS, discrete event systems, control architectures, networks, neuro-prosthesis, 200h, master and engineers degrees, Polytech Montpellier, France;

The team is leading 2 modules in Master Stic-Santé in Montpellier: Neuroprosthesis I (HMSN216) and II and (HMESN321). The objective is to initiate students to techniques used for the design of neuroprotheses in order to compensate for sensory motor deficiencies. This course aims at: investigating uses and needs for basic medical systems, as well as active and implantable ones and teaching of theoretical tools required for theirs understanding, settings and their conception (command, signal processing of physiological and physical signals, physical interfacing between living and artificial systems, bases in neurophysiology). Students will have to learn the following skills: electro- and neurophysiology bases required to understand active medical implantable systems, bases in signal processing, bases in embedded informatics and electronics, knowledge about sensory-motor functions and their deficiencies, bases on simulations and closed loop control for living and artificial systems.

10.2.2. Supervision

PhD defended on December 14th 2016 : Wafa Tigra, Assistance à la préhension par stimulation électrique fonctionnelle chez le patient tétraplégique, 01/10/2013, Christine Azevedo Coste, David Guiraud,

PhD defended on December 9th 2016 : Thomas Guiho, Évaluation de l'efficience de la stimulation électrique médullaire en vue de la restauration des fonctions urinaires et intestinales chez le patient lésé médullaire, 01/10/2013, David Guiraud, Christine Azevedo Coste

PhD in progress : Antony Boyer, Neuroplasticité et récupération dans les structures corticales et sous corticales distantes suite à une chirurgie éveillée des gliomes infiltrants de bas grades, 01/09/2016, François Bonnetblanc and Sofiane Ramdani.

PhD in progress : Marion Vincent, Mesures des potentiels évoqués par la stimulation électrique directe lors de la chirurgie éveillée des gliomes infiltrants de bas grades vers une compréhension des effets électrophysiologiques, 01/12/2013, François Bonnetblanc, David Guiraud and Hugues Duffau.

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 : Ibrahim Merzoug, Validation formelle pour les systèmes embarqués critiques, Since Oct. 2014, K. Godary-Dejean and D. Andreu.

PhD in progress : Mélissa Dali, modèles de génération et de propagation de potentiel d'action neurla en condition de stimulation sélective multipolaire, since october 2014, David Guiraud and Olivier Rossel (up to july 2016).

PhD in progress : Benoît Sijobert, Stimulation électro-fonctionnelle pour l'assistance aux mouvements des membres inférieurs dans les situations de déficiences sensori-motrices, Since Dec. 2015, Christine Azevedo Coste and D. Andreu.

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)

10.2.3. Juries

Daniel Simon was reviewer and member of the PhD jury of Wael Zouaoui (LAAS Toulouse, january 15, 2016).

Karen Godary-Dejean was member of the PhD jury of Louis Marie Givel,École Centrale de Nantes, december 16, 2016.

David Guiraud was reviewer of 2 PhD thesis at UTC and Univ. Of Toulon.

David Guiraud was member of the selection committee, CNU61, for an assistant professor position at the university of Nantes.

Christine Azevedo was member of the selection committee, Inria, Young graduate scientist ("CR2") in Paris.

David Andreu was reviewer and member of the PhD jury of Nicolas Gobillot, INPT Toulouse, april 29, 2016, and member of the PhD jury of Lotfi Jaiem, University of Montpellier, november 21, 2016.

10.3. Popularization

- Large cover in general media (radio, TV, newspapers) of Cybathlon project http://freewheels.inria.fr/
- Christine Azevedo presented Cybathlon project at DIRCOM Inria, Rocquencourt, in the context of Handicap national week.
- Christine Azevedo presented Freewheels experience at Carrefour du Pôle EUROBIOMED (Marseille).
- Christine Azevedo presented the job of researcher in secondary school Collège Léon Cordas (Montpellier)

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Major publications by the team in recent years

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[12] W. TIGRA.*Restauration de la préhension chez le sujet paraplégique par stimulation électrique chez le patient tétraplégique*, I2S, Université de Montpellier, Dec 2016.

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Project-Team CASTOR

Control, Analysis and Simulations for TOkamak Research

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

IN PARTNERSHIP WITH:
CNRS

Université Nice - Sophia Antipolis

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Earth, Environmental and Energy Sciences

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Project-Team CASTOR

Creation of the Team: 2012 July 01, updated into Project-Team: 2014 July 01

Keywords:

Computer Science and Digital Science:

6. - Modeling, simulation and control
6.1. - Mathematical Modeling
6.1.1. - Continuous Modeling (PDE, ODE)
6.1.4. - Multiscale modeling
6.1.5. - Multiphysics modeling
6.2. - Scientific Computing, Numerical Analysis & Optimization
6.2.1. - Numerical analysis of PDE and ODE
6.2.6. - Optimization
6.2.7. - High performance computing
6.2.8. - Computational geometry and meshes
6.3. - Computation-data interaction
6.3.1. - Inverse problems
6.3.2. - Data assimilation
6.3.4. - Model reduction
6.4. - Automatic control
6.4.1. - Deterministic control
6.4.4. - Stability and Stabilization

Other Research Topics and Application Domains:

4. - Energy
4.2.2. - Fusion

1. Members

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Holger Heumann [Inria, Starting Research position]
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2. Overall Objectives

2.1. Presentation

In order to fulfill the increasing demand, alternative energy sources have to be developed. Indeed, the current rate of fossil fuel usage and its serious adverse environmental impacts (pollution, greenhouse gas emissions, ...) lead to an energy crisis accompanied by potentially disastrous global climate changes.

Controlled fusion power is one of the most promising alternatives to the use of fossil resources, potentially with a unlimited source of fuel. France with the ITER (http://www.iter.org/default.aspx) and Laser Megajoule (http://www-lmj.cea.fr/) facilities is strongly involved in the development of these two parallel approaches to master fusion that are magnetic and inertial confinement. Although the principles of fusion reaction are well understood from nearly sixty years, (the design of tokamak dates back from studies done in the '50 by Igor Tamm and Andreï Sakharov in the former Soviet Union), the route to an industrial reactor is still long and the application of controlled fusion for energy production is beyond our present knowledge of related physical processes. In magnetic confinement, beside technological constraints involving for instance the design of plasma-facing component, one of the main difficulties in the building of a controlled fusion reactor is the poor confinement time reached so far. This confinement time is actually governed by turbulent transport that therefore determines the performance of fusion plasmas. The prediction of the level of turbulent transport in large machines such as ITER is therefore of paramount importance for the success of the researches on controlled magnetic fusion.

The other route for fusion plasma is inertial confinement. In this latter case, large scale hydrodynamical instabilities prevent a sufficiently large energy deposit and lower the return of the target. Therefore, for both magnetic and inertial confinement technologies, the success of the projects is deeply linked to the theoretical understanding of plasma turbulence and flow instabilities as well as to mathematical and numerical improvements enabling the development of predictive simulation tools.

CASTOR gathers the activities in numerical simulation of fusion plasmas with the activities in control and optimisation done in the laboratory Jean-Alexandre Dieudonné of the University of Nice. The main objective of the CASTOR team is to contribute to the development of innovative numerical tools to improve the computer simulations of complex turbulent or unstable flows in plasma physics and to develop methods allowing the real-time control of these flows or the optimisation of scenarios of plasma discharges in tokamaks. CASTOR is a common project between Inria (http://www.inria.fr/centre/sophia) and the University of Nice Sophia-Antipolis and CNRS through the laboratory Jean-Alexandre Dieudonné, UMR UNS-CNRS 7351, (http://math.unice.fr).

3. Research Program

3.1. Plasma Physics

Participants: Jacques Blum, Cédric Boulbe, Blaise Faugeras, Hervé Guillard, Holger Heumann, Sebastian Minjeaud, Boniface Nkonga, Richard Pasquetti, Afeintou Sangam.

The main reseach topics are:

1. Modelling and analysis
   - Fluid closure in plasma
   - Turbulence
   - Plasma anisotropy type instabilities
   - Free boundary equilibrium (FBE)
   - Coupling FBE – Transport
2. Numerical methods and simulations
   - High order methods
   - Curvilinear coordinate systems
   - Equilibrium simulation
   - Pressure correction scheme
   - Anisotropy
   - Solving methods and parallelism
3. Identification and control
   - Inverse problem: Equilibrium reconstruction
   - Open loop control
4. Applications
   - MHD instabilities : Edge-Localized Modes (ELMs)
   - Edge plasma turbulence
   - Optimization of scenarii

4. New Software and Platforms

4.1. Equinox

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. A deposit with APP (Agence pour la protection des programmes) has been done in 2016.

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

4.2. VacTH

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 for the 2D interpolation and extrapolation of discrete magnetic measurements in a tokamak. 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. VacTH is foreseen to be used in the real-time plasma control loop on the WEST tokamak.

- Contact: Blaise Faugeras

4.3. CEDRES++

FUNCTIONAL DESCRIPTION

In Tokamaks, at the slow resistive diffusion time scale, the magnetic configuration in the plasma can be described by the MHD equilibrium 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 P_1 finite element code CEDRES++ solves this free boundary equilibrium problem in direct and inverse mode and in static and evolutive formulations. 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) for the static case and the voltages applied to PF supplies in the evolutive one. The aim of the inverse problem is to find currents in the PF coils in order to best fit a given plasma shape. The code is one of the free boundary codes avalaible in the european Eurofusion - WPCD (WorkPackage Code Development for integrated modelling) platform.

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

4.4. FEEQS.M

Finite Element Equilibrium Solver in MATLAB
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 (see [4]). The recent developments include:

- the comparison of FEM-BEM coupling (with B. Faugeras),
- overlapping mesh methods for free-boundary equilibrium,
- direct and inverse modes for simulations and optimal control approach to breakdown (with Eric Nardon, CEA Cadarache)
- Participant: Holger Heumann
- Contact: Holger Heumann
- URL: https://scm.gforge.inria.fr/svn/holgerheumann/Matlab/FEEQS.M

4.5. 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: Remi Abgrall, Boniface Nkonga, Michael Papin and Mario Ricchiuto
- Contact: Boniface Nkonga

4.6. Jorek-Django

FUNCTIONAL DESCRIPTION

Jorek-Django is a new version of the JOREK software, for MHD modelling 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.

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

4.7. 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

4.8. PlaTo

A platform for Tokamak simulation

FUNCTIONAL DESCRIPTION

PlaTo (A platform for Tokamak simulation) is a suite of data and software 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. Plato is no more developed and is in the process of being merged with Jorek-Django

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

5. New Results

5.1. Mathematical theory of reduced MHD models

Participant: Hervé Guillard.

In the modelling of strongly magnetized plasma, one of the fundamental model used is the magnetohydrodynamic (MHD) model. However, in practice, many theoretical and numerical works in this field use specific approximations of this model known as *reduced* MHD models. These models assume that in the presence of a strong magnetic field, the main dynamic reduces to incompressible motion in the plane perpendicular to the plasma and to the propagation of Alfvén waves in the magnetic field direction. In the framework of the slab approximation for large aspect ratio tokamaks ($R/a >> 1$ where R and a are respectively the major and minor radius of the machine) we have studied the validity of this assumption using techniques coming from the asymptotic theory of hyperbolic equations with a large parameter. In particular, we have proved that the solutions of the full MHD system converge in a weak sense to the solutions of an appropriate reduced model even in the presence of ill-prepared initial data.

5.2. Behavior of upwind finite volume scheme for Low Mach number flows

Participants: Hervé Guillard, Boniface Nkonga.

We have performed a review of different modifications proposed to enable compressible flow solvers to compute accurately flows near the incompressible limit. The reasons of the failure of upwind solvers to obtain accurate solutions in the low Mach number regime have been explained and different corrections proposed in the literature have been reviewed and discussed. Numerical experiments to illustrate the behavior of the different methods have been done and presented. This work will be published in 2017 as a contribution for the "Handbook of numerical analysis" collection.

5.3. Finite volume approximations for fusion plasma

Participants: Hervé Guillard, Afeintou Sangam, Elise Estibals.

The MHD model used for plasma studies in tokamak is very often based on the magnetic vector potential form of the equations where the vector potential satisfies $\nabla \times \mathbf{A} = \mathbf{B}$ with $\mathbf{B}$ the magnetic field and only a small number of numerical models uses the conservative formulation based on $\mathbf{B}$. One of the shortcomings of this latter formulation is the necessity to enforce numerically the divergence free constraint on the magnetic field that can be difficult to achieve and/or computationally costly. Another difficulty is that the equilibrium solution of the MHD equation given by the Grad-Shafranov equation is not an exact solution of the discrete equation.

We have begun to investigate the use of the $\mathbf{B}$ formulation for tokamak studies. The divergence free constraint is taken into account by a projection at each time step on a rotated gradient field. This step ensures a strict respect of the divergence free constraint while being extremely cheap since the scalar field is simply advected by the flow. The numerical experiments performed show that this method is efficient for the study of discontinuous MHD flows. For plasma fusion flows, the method experiences presently some difficulties to compute steady equilibrium flows.

5.4. Bi-temperature Euler equations

Participants: Hervé Guillard, Afeintou Sangam, Elise Estibals.

A particular class of extended MHD models uses a description of the plasma where the ionic and electronic temperatures are different while velocities and densities are common to the two species. This preliminary work has examined the construction of finite volume numerical schemes for two-temperature models in the context of the Euler equations. The finite volume scheme uses the assumption that the electronic entropy is constant across the shocks to define the weak solutions of the system and the numerical fluxes are obtained with a relaxation scheme. Numerical simulations of several test-cases involving strong shocks show that this numerical strategy is efficient even in the presence of strong temperature differences between ions and electrons.

5.5. Domain segmentation using the Reeb Graph

Participants: Hervé Guillard, Adrien Loseille (gamma3 Inria-Saclay), Alexis Loyer.

The generation of block structured meshes is a difficult task that is not easily automated and very often ask for manual intervention and specific expertise. We show in this work that if the required mesh is constrained to be aligned on the contour lines of a Morse function, then the mesh generation process can be done in a fully automatic way and reduces to only two basic meshing operations. This technique can be useful for a large number of potential applications. It is here studied for the construction of flux surface aligned meshes in the framework of the EoCoE project.

5.6. Equilibrium reconstruction

Participants: Blaise Faugeras, Jacques Blum, Cédric Boulbe, Holger Heumann.

Within the framework of the European Integrated Tokamak Modelling WPCD project we have been involved in a benchmark study between the equilibrium reconstruction codes EQUINOX, EQUAL and CLISTE on AUG (Asdex Upgrade) equilibriums. This work has been presented at the 2016 EPS conference.

The benchmark study leads us to include new functionalities to EQUINOX such as the possibility to use a radially variable regularization and the computation of error bars on the reconstructed profiles.
In order to be used on the WEST tokamak, EQUINOX has been adapted to the ITER standard "IMAS" using IDS as data type.
A numerical method for equilibrium reconstruction using magnetic measurements as well as polarimetry measurements with their Stokes vector representation has been developped in order to take into account the so-called Cotton-Mouton effect. The algorithm is based on optimal control of a coupled partial and ordinary differential equations system. The method is being tested on an ITER test case.

5.7. FEB-BEM numerical methods for equilibrium computation

Participants: Blaise Faugeras, Holger Heumann.

A code which treats the quasi-static free-boundary equilibrium problem needs to solve nonlinear elliptic or parabolic problems with nonlinear source terms representing the current density profile vanishing outside the unknown free boundary of the plasma. The computational challenges in the design of such a code are: a problem setting in an unbounded domain with a nonlinearity due to the current density profile in the unknown plasma domain and the nonlinear magnetic permeability if the machine has ferromagnetic structures. In this project we focused on how the simulation on the unbounded domain can be reduced to computations on an interior bounded domain thanks to analytical Green's functions. The numerical solution on the interior domain is coupled through boundary conditions to the Green's function representation of the solution in the unbounded exterior domain. This approach is today fairly standard in many other application areas such as electromagnetics or elasticity and falls into the framework of the boundary element method (BEM). Most authors in the fusion literature deal with this question using the same method from von Hagenow and Lackner whereas the coupling can be conceived in different ways. In this project we implemented 3 different schemes in order to assess their performance. One of them, the classical Johnson-Nédélec FEM-BEM coupling (JNC) has never been tested before in a fusion equilibrium code.

5.8. A finite element method with overlapping meshes for free-boundary toroidal plasma equilibria in realistic geometry

Participants: Francesca Rapetti, Holger Heumann.

Existing finite element implementations for the computation of free-boundary axisymmetric plasma equilibria approximate the unknown poloidal flux function by standard lowest order continuous finite elements with discontinuous gradients. The location of critical points of the poloidal flux, that are of paramount importance in tokamak engineering, is constrained to nodes of the mesh, which leads to undesired jumps in transient problems. Moreover, recent numerical results for the self-consistent coupling of equilibrium with resistive diffusion and transport suggest the necessity of higher regularity when approximating the flux map.

In [23], we have proposed a mortar element method that employs two overlapping meshes. One mesh with Cartesian quadrilaterals covers the vacuum domain and one mesh with triangles discretizes the region outside the vacuum domain. The two meshes overlap in a narrow region around the vacuum domain. This approach gives the flexibility to achieve easily and at low cost higher order regularity for the approximation of the flux function in the domain covered by the plasma, while preserving accurate meshing of the geometric details exterior to the vacuum. The continuity of the numerical solution in the region of overlap is weakly enforced by a mortar-like projection. We have shown that the numerical calculation of free boundary plasma equilibria highly benefits from approximating the poloidal flux through some higher regular FE functions in the interior of the limiter.

In [19], we have rather analysed the precision of the proposed approach, by varying the discretization parameters. We thus compute the approximation error between the computed and the synthetic solution of a model problem for the same method adopted in [1], by changing, for example, the local polynomial degree in the subdomains, the size of the overlap between the meshes, the local size of the mesh elements. Indeed, FE methods on composite meshes are widely used in practice, but their theoretical foundation is fairly limited in the literature. Therefore, we have reported in [2] some experimental convergence results for different discretization schemes involving composite meshes.

5.9. Circuit Equations

Participant: Holger Heumann.

We derived a new formulation to combine the circuit equations due to the poloidal field coil system with free boundary equilibrium calculations. The previous formulations based on a least squares formulation developed for and implemented in CEDRES++, was suffering from numerical instabilities. The new formulation was implemented in FEEQS.M and successfully validated.

5.10. Optimization of tokamak breakdown scenarios

Participants: Holger Heumann, Eric Nardon.

The standard method to initiate a plasma in a tokamak is to realize a so called Townsend avalanche by applying a high enough toroidal electric field (i.e. loop voltage) by means of a fast variation of the current in the poloidal field coils (in particular the central solenoid). For the avalanche to take place, the electrons need to be able to travel along the field lines over a long enough distance, so that they can gain an energy significantly larger than the ionization energy of the atoms. An empirical criterion for a successful breakdown is thus $EL_c > 70V$, where E is the toroidal electric field and L_c the connection length of the field lines. Hence, it is highly desirable to create a configuration in which the field length is as large as possible, or equivalently, in which the poloidal component of the field is as small as possible. We reformulated this task as a constrained optimization problem and used an implementation in FEEQS.M to find in an automated fashion such optimal configurations. Publication is in preparation.

5.11. High order C^0-continuous Galerkin schemes for high order PDEs

Participants: Sebastian Minjeaud, Richard Pasquetti.

We show that it is possible to develop reliable and effective schemes, in terms of accuracy, computational efficiency, simplicity of implementation and, if required, conservation of linear or quadratic invariants, for high order partial differential equation on the basis of a (only) H^1-conformal Galerkin approximation, namely the Spectral Element Method. We address the Korteweg-de Vries equation but the proposed approach is *a priori* easily extensible to other partial differential equations and to multidimensional problems.

5.12. A MUSCL–scheme on staggered grids with kinetic–like fluxes for the barotropic Euler system

Participants: Julia Llobell, Thierry Goudon, Sebastian Minjeaud.

We set up a MUSCL version of the scheme introduced in [27] for solving the barotropic Euler equations. The scheme works on staggered grids, with numerical densities and velocities stored at dual locations, while the numerical fluxes are derived in the spirit of kinetic schemes. We have identified stability conditions for the second order method and have shown the ability of the scheme to capture the structure of complex flows with 2D simulations on MAC grids.

5.13. Stabilized SEM approximation of the 2D Saint-Venant system

Participant: Richard Pasquetti.

Following a study restricted to one space dimension, R. Pasquetti has developped a stabilized Spectral Element approximation of the two-dimensional Saint-Venant system. This stabilized SEM model uses the entropy viscosity method (EVM), that is a non linear viscous stabilization with viscosity proportional to the entropy production and bounded from above by a first order viscosity. We have especially focused on problems involving dry-wet transitions and proposed an elaborated variant of the EVM that allows to support the presence of dry zones. The algorithm has been tested against benchmarks problems, involving planar oscillations and axisymmetric oscillations in a paraboloid, for which exact solutions are known. The method was also checked successfully for flows combining dry-wet transitions and shocks. Part of this study was carried out in the National Center for Theoretical Science (Taipei, Taiwan). The work was presented at the ICOSAHOM 2016 congress (Rio, June 2016, see [16]).

5.14. Isoparametric mappings

Participant: Richard Pasquetti.

R. Pasquetti has carried out a numerical study to compare different isoparametric mappings for the approximation of non polygonal domains with high order triangular finite elements. For elliptic problems and Fekete-Gauss spectral elements, it turns out that isoparametric mappings based on PDEs (Laplace, linear elasticity) yield better results than those based on transfinite mappings. The results are summarized in a JCP Note (see [15]).

5.15. Full MHD numerical modelling with $C1$ finite element.

Participants: José Costa, Boniface Nkonga.

Many theoretical and numerical works in the field of tokamak modelling use specific approximations of the MHD model known as *reduced* MHD models. This is in particular the case of the Jorek software. The main objective of this work is therefore to extend the capability of this software to solve the full MHD equations while using the same finite element numerical method. This requires to design new stabilization strategies as well as appropriate projections of the momentum equation. This has been done during the thesis of José Costa [6] This work allowed a detailed study of the resistive internal kink instability as well as some preliminary results on X-point plasmas.

5.16. 2D Triangular Powell-Sabin Finite Elements

Participants: Giorgio Giorgiani, Hervé Guillard, Boniface Nkonga.

In order to avoid some mesh singularities when using quadrangular meshes for complex geometries and flux surfaces shapes, the use of triangular elements is a possible option that we are studying in view of its application to MHD modelling. It is not so easy to derive smooth finite element on triangle with reduced number of degree of freedom (ddl). The Bell reduced-quintic finite elements we have considered in the previous years have too much unknowns (6 per vertex). Powell-Sabin splines are piece-wise quadratic polynomials with a global C1-continuity and 3 unknowns per vertex, they have a local support, they form a convex partition of unity, they are stable, and they have a geometrically intuitive interpretation involving control triangles. In the previous years, we have developed the geometrical tools necessary to the construction of the Powell-Sabin splines and we are now beginning the study of the applicability of Powell-Sabin finite element for the numerical solution of PDE. We have used the Powell-Sabin starting from elliptic partial differential equations (including Grad-shafranov). We have applied these tools to solve hyperbolic 2D Euler equations with VMS stabilization. These results have been published in [11] and [18]

5.17. Massive gaz Injection

Participant: Boniface Nkonga.

The massive injection of impurity gas into a plasma has been proved to reduce forces and localized thermal loads caused by disruptions in tokamaks. This mitigation system is routinely used on JET to shut down plasmas with a locked mode. The DMV's injectors of JET have been modelled with all the 3D details (see Figure 1, 2 and 3) . We have performed many 3D simulations and the predicted flight times are in accordance with experimental measurements. Moreover, the computations give also a clear domain for the application of 1D approximations and scaling.

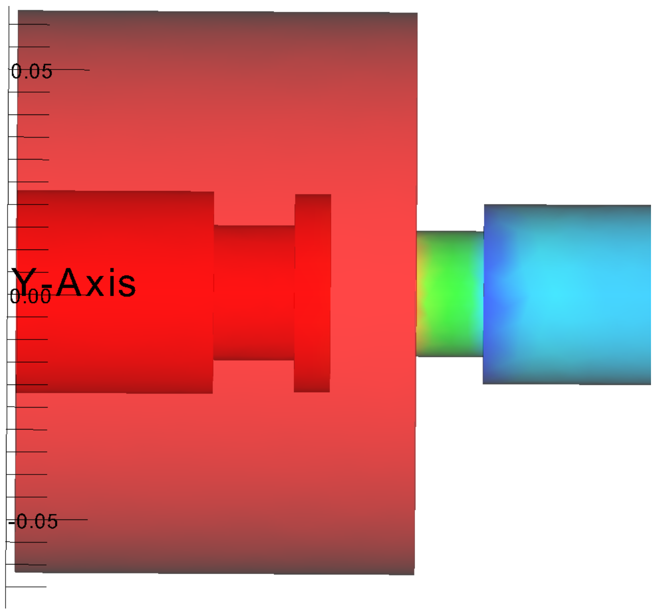

Figure 1. DMV resevoir of the JET Tokamak

5.18. A Multidimensional Analogue of the HLLI Riemann Solver for Conservative Hyperbolic Systems

Participants: Boniface Nkonga, Dinshaw Balsara.

Just as the quality of a one-dimensional approximate Riemann solver is improved by the inclusion of internal sub-structure, the quality of a multidimensional Riemann solver is also similarly improved. Such multidimensional Riemann problems arise when multiple states come together at the vertex of a mesh. The interaction of the resulting one-dimensional Riemann problems gives rise to a strongly-interacting state. We

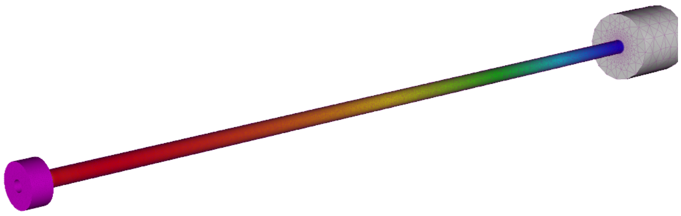

Figure 2. Reservoir, tube and plasma front of the Injection system of JET.

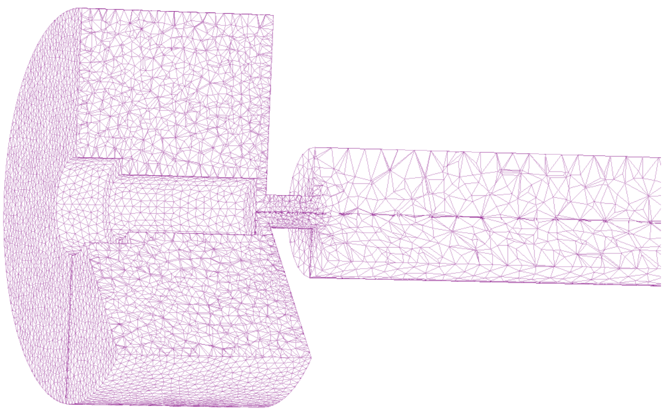

Figure 3. 3D Mesh of tetrahedral elements.

wish to endow this strongly-interacting state with physically-motivated sub-structure. The fastest way of endowing such sub-structure consists of making a multidimensional extension of the HLLI Riemann solver for hyperbolic conservation laws. Presenting such a multidimensional analogue of the HLLI Riemann solver with linear sub-structure for use on structured meshes is the goal of this work. The multidimensional MuSIC Riemann solver documented here is universal in the sense that it can be applied to any hyperbolic conservation law.

The multidimensional Riemann solver is made to be consistent with constraints that emerge naturally from the Galerkin projection of the self-similar states within the wave model. When the full eigenstructure in both directions is used in the present Riemann solver, it becomes a complete Riemann solver in a multidimensional sense. I.e., all the intermediate waves are represented in the multidimensional wave model. The work also presents, for the very first time, an important analysis of the dissipation characteristics of multidimensional Riemann solvers. The present Riemann solver results in the most efficient implementation of a multidimensional Riemann solver with sub-structure. Because it preserves stationary linearly degenerate waves, it might also help with well-balancing. Implementation-related details are presented in pointwise fashion for the one-dimensional HLLI Riemann solver as well as the multidimensional MuSIC Riemann solver.

Several stringent test problems drawn from hydrodynamics, MHD and relativistic MHD are presented to show that the method works very well on structured meshes. Our results demonstrate the versatility of our method.

5.19. Modelling of plasma instabilities

Participants: Feng Liu, Boniface Nkonga, Guido Huijsmans, Alberto Loarte.

Non-linear simulations of MHD modes from 0 to 20 which include kink-peeling modes (KPM) and ballooning modes with different plasma equilibrium by varying both pedestal pressure and edge current have been studied further. The simulations indicated that sufficient high edge current is essential requirements for plasma saturate to edge harmonic oscillation (EHO), meanwhile the pedestal pressure is the key parameter for plasma saturating to ballooning mode. The influence of RMP (Resonant Magnetic Perturbations) on QH-mode (Quiescent High Confinement mode) has been re-evaluated by using the correct coil currents. Large number ergodic islands caused by RMP stabilize toroidal harmonics n=1, 2, 3, 4 modes in the edge of QH-mode plasma. ITER baseline scenario Q=10 plasma has been analyzed with respect to the access to a possible QH-mode regime. KPM is obtained at the edge plasma of ITER plasma for n=1 and n=1-5 modes (see Fig. 4).

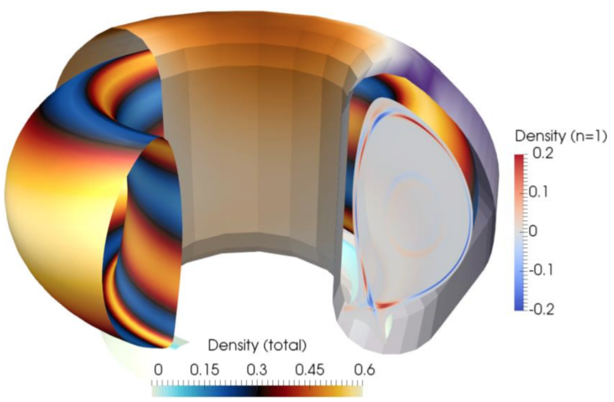

Figure 4. 3-D density structure at the separatrix and resistive wall potential of a n=1 saturated kink mode in ITER Q=10 scenario.

5.20. Amoss : Comparison with experimental results and unreduced model on flat plane

Participants: B. Nkonga, H. Guillard, S. Gavrilyuck, Y-C. Tai, F. Yang, K.m. Shyue, C-Y Kuo.

The purpose of this work was the numerical study of the roll-waves that develop from a uniform unstable flow down an inclined rectangular channel. In particular, the formation of the roll-waves is studied by two different approaches. In the first approach, the roll-waves were produced in a long channel where a wave maker perturbed the free surface only at the channel inlet. The average discharge was fixed. In the second approach, the roll-waves were produced in a "periodic box" with a uniform flow velocity. The average depth of a perturbed free surface was the same as in the long channel. Formally, the "periodic box" and a long channel correspond to two different physical situations. However, the stationary profile formed for long time in these cases is the same. This allows us to use the "periodic box" as a simpler mathematical tool to study the asymptotic behavior of roll waves. In particular, the "periodic box" does not require a big space domain resolution. Several interesting phenomena were observed. First, it was proven that there exists Lmax such that any single roll wave of length $L > L_{\max}$ not stable. This can help to generalize the analytical results obtained by Liapidevskii (modulational stability study) and Baker et al. (the linear stability study) for the SV equations, to the case of the generalized models. The minimal length of periodic box for which a single roll wave is stable, was not observed. Second, a coarsening phenomenon was observed. When the inlet perturbation has two different frequencies, it produces the waves of the different wavelengths. The waves begin to interact. The short waves transfer their energy to the long waves, and finally we obtain the train of roll waves of a larger wavelength. A strong non-stationary modulation of the wave amplitude was observed. The formation of periodic roll wave train was shown for both long a channel and a "periodic box" for two sets of experimental parameters. In both cases, the free surface profile for the generalized models was found in a very good agreement with the experimental results. Finally, for a 2D simplified "Toy Model" we show that steady numerical solution corresponding to experimental data does not depend of transverse perturbations.

6. Partnerships and Cooperations

6.1. National Initiatives

6.1.1. ANR

- ANEMOS : ANR-11-MONU-002

  ANEMOS : Advanced Numeric for Elms : Models and Optimized Strategies associates JAD Laboratory/Inria (Nice, Manager), IRFM-CEA (Cadarache), Maison de la Simulation (Saclay) and Inria EPI Bacchus (Bordeaux). Final report, oral talk and poster to the "Journées des Rencontres Numériques de l'ANR" (16-17 nov. 2016), http://www.rencontres-numerique-anr.fr/.

6.1.2. 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

6.2. European Initiatives

6.2.1. FP7 & H2020 Projects

6.2.1.1. EuroFusion Consortium

CASTOR participates to the following EuroFusion consortium projects :

- CfP-WP14-ER-01/Swiss Confederation-01. École Polytechnique Fédérale de Lausanne (PI: Paolo Ricci) “Synergetic numerical-experimental approach to fundamental aspects of turbulent transport in the tokamak edge”
- CfP-WP14-ER-01/CEA-01. CEA (PI: Matthias Hoelzl IPP) “JOREK, BOUT++ non-linear MHD modelling of MHD instabilities and their control in existing tokamaks and ITER”
- EUROfusion WPCD (Working Package Code Development)
  - ACT1: Extended equilibrium and stability chain (participation)
  - ACT2: Free boundary equilibrium and control (participation and coordination)

6.2.1.2. EoCoE

The team also participates in the EoCoE European project. Grant Agreement number: 676629 — EoCoE — H2020-EINFRA-2014-2015/H2020-EINFRA-2015-1.

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 à 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 (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.

6.3. International Initiatives

6.3.1. Inria Associate Teams Not Involved in an Inria International Labs

6.3.1.1. AMOSS

Title: Advanced modelling on Shear Shallow Flows for Curved Topography : water and granular flows.

International Partner (Institution - Laboratory - Researcher):

NCKU (Taiwan) - Yih-Chin Tai

Start year: 2014

Our objective here is to generalize the promising modelling strategy proposed by S. Gavrilyuk (2012-2013) to genuinely 3D shear flows and also take into account the curvature effects related to topography. Special care will be exercised to ensure that the numerical methodology can take full advantage of massively parallel computational platforms and serve as a practical engineering tool. Cross validations will be achieved by experiments and numerical simulations with applications to landslides.

Closing workshop of the associated team, 7-10 nov. 2016 - Tainan (Taïwan)

6.3.2. Inria International Partners

6.3.2.1. Informal International Partners

The team collaborates with TUC (Technical University of Crete, Prof. Argyris Delis) on the subject of shallow water models. Part of this collaboration is common with the works done in the framework of the AMOSS associate team.

7. Dissemination

7.1. Promoting Scientific Activities

7.1.1. Scientific Events Organisation

7.1.1.1. Member of the Organizing Committees

- D. Auroux, C. Boulbe and L. Busé (Aromath - Inria) have organized a SEME (Semaine d'Etudes Maths-Entreprises) under the initiative of AMIES.
  - Project proposed by Option Way, Optis, Thales Alenia Space, Wever, Exact Cure
  - 25-29 Juanary 2016, Campus Sophia Tech (Inria, Univ. Nice Sophia Antipolis)
  - http://math.unice.fr/~auroux/SEME/
- From April 12th to 15th 2016, CASTOR (Boniface Nkonga, Hervé Guillard, Afeintou Sangam) has organized in Sophia Antipolis, the annual user meeting of the Jorek code that has gathered 25 plasma specialists around the development of this code dedicated to MHD studies in Tokamaks.
- Minisymposium: Numerical Methods for Magnetohydrodynamics/Méthodes numériques pour les équations de la magnétohydrodynamique, CANUM 2016, 43e Congrès National d'Analyse Numérique, Obernai, France, May 09-13, 2016.

  The simulation of electrical conducting fluids relies on numerical methods from computational fluid dynamics and computational electrodynamics. As the underlying magnetohydrodynamic (MHD) models are non-standard coupled systems of non-linear partial differential equations, the main ingredients of numerical solution methods such as preconditioners, iteration schemes and stability require special attention. Moreover, in many applications such as plasmas, where we have no unique canonical MHD formulation in terms of PDEs, the development of numerical methods goes hand in hand with modelling: the models depend on the time and length scales of interest, but particular variations can avoid pitfalls in the numerical simulation.

  In this minisymposium we gathered talks from different application areas. Contributions included numerical analysis and computational methods for both established MHD models as well as specialized models for applications in plasma physics:
  - José Costa, CASTOR, Inria, SAM: High order stabilized finite element method for MHD and Reduced-MHD plasma modelling
  - Emmanuel Franck, Inria NANCY GRAND EST: Analyse des préconditionneurs physiques pour les équations d'Euler et de la MHD linéarisée
  - Céline Caldini-Queiros, MPI Garching: Couplage de modèles MHD et cinétiques dans des géométries complexes
  - Tahar Boulmezaoud, Université de Versailles: Equilibres magnétohydrostatiques et champs force-free

7.1.2. Journal

7.1.2.1. 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 commitee of the collection "Mathématiques et Statistiques" of the ISTE publications,
  - editor in chief of the ISTE Open Science journal: "Mathématiques appliquées et stochastiques".

7.1.2.2. Reviewer - Reviewing Activities

H. Guillard is reviewer for several journals including

- Journal of computational physics
- Computers and Fluids

7.1.3. Invited Talks

- J. Blum, The use of optimal control theory for equilibrium identification and optimization of plasma scenarios, Swiss Plasma Center, EPFL, Switzerland, November 28, 2016
- H.Heumann, Control methods for the optimization of plasma scenarios in a tokamak. Oberseminar Scientific Computing, University Würzburg, Würzburg, Germany, November 14, 2016
- H.Heumann, Numerical methods for tokamak plasma equilibrium evolution at the resistive diffusion timescale, Zurich Colloquium in Applied and Computational Mathematics, ETH Zurich, Zurich, Switzerland, March 16, 2016
- H.Heumann, Free-Boundary Axisymmetric Plasma Equilibria: Computational Methods and Applications , Theory Group Seminar, Princeton Plasma Physcis Laboratory, Princeton, USA, March 3, 2016
- H.Heumann, Quasi-static Free-Boundary Equilibrium of Toroidal Plasma: Computational Methods and Applications, Magneto-fluid dynamics seminar, Courant Institut, New York University, New York, USA, February 23, 2016

7.1.4. Leadership within the Scientific Community

- J. Blum is:
  - a member of the scientific committee of Academy 1 of UCA-IDEX JEDI: «Networks, Information and Digital society»,
  - member of the "bureau" and the director committee of the Fédération FR-FCM (Fédération de Recherche Fusion par Confinement Magnétique - ITER).
- H. Guillard is coordinator of the topic "Turbulence and transport of edge plasma" within the Fédération FR-FCM
- C. Boulbe is task coordinator of the ACT2: Free boundary equilibrium and Control within the Eurofusion WPCD workpackage.
- B. Nkonga is chairman of the GAMNI ("Groupe pour l'Avancement des Méthodes Numériques de l'Ingénieur"), group of the SMAI.

7.2. Teaching - Supervision - Juries

7.2.1. 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: B. Faugeras, Optimisation, 18h, M1, Université de Nice Sophia Antipolis, France

Master: J. Blum, Optimisation et contrôle, 20h, M2, Université de Nice Sophia Antipolis, France

Master: J. Blum, Optimisation, 18h, M1, Université de Nice Sophia Antipolis, France

Ecole d'ingénieur: J. Blum, Commande Optimale, 37.5h, M2, Polytech Nice Sophia, 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, Méthodes numériques - EDP, 66h, M1, 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, 36 h, M1, Université de Nice Sophia Antipolis, France.

Master: S. Minjeaud, module Analyse et simulations numériques pour les EDP, 20 h, M2, Université de Nice Sophia Antipolis, France.

Master: S. Minjeaud, module Simulations numériques des problèmes d'évolution, 20 h, M2, Université de Nice Sophia Antipolis, France.

Master: S. Minjeaud, Méthodes numériques en EDP, 18 h, M1, 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

Ecole d'ingénieur/Master: B. Nkonga, Scilab, 28h, L3, Polytech Nice Sophia, France

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

Licence: A. Sangam, Modélisation, 10h, L1, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Analyse, 50h, L2, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Méthodes Numériques et Formelles, 40h, L2, Université Nice Sophia Antipolis, France

Licence: A. Sangam, Mathématiques Appliquées, 50h, L3, Université de Nice Sophia Antipolis, France

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

7.2.2. Supervision

- PhD in progress: E. Estibals, "MHD réduite: Modélisation et Simulation numérique utilisant des éléments finis stabilisés d'ordre élevé sur un maillage courbe non-structuré. Application à l'injection de glaçons et de masse dans ITER", 15th october 2013, Hervé Guillard, Afeintou Sangam.
- PhD in progress : X. Song, "Model based control oriented scenario construction in Tokamak", october 2016, Blaise Faugeras, Holger Heumann.
- PhD in progress : J. Llobell, "Schémas numériques sur grilles décalées pour la dynamique des gaz", October 1st 2015, T. Goudon, S. Minjeaud.

7.2.3. Juries

R. Pasquetti was in the following juries:

- HdR : Pascal Henri Biwole, Université Côte d'Azur,
- PhD : Benjamin Gaume, Université d'Evry Val-d'Essonne.

B. Nkonga was referee in the following juries:

- HdR: Jérôme Breil, Université de Bordeaux,
- PhD: Quentin Viville, Université de Bordeaux,
- PhD: Sara Pavan, Université Paris-Est.

H. Guillard was in the PhD jury thesis of

- PhD: José Costa, Université Côte d'Azur.
- PhD:: Léo Nouveau, Université de Bordeaux.

J. Blum was in the PhD jury thesis of

- PhD: Vladimir Groza, Université Côte d'Azur,
- PhD: Bienvenu Youmbi, Université Côte d'Azur,
- PhD: Michel Massaro, Université de Strasbourg.

7.3. Popularization

J. Blum has been invited to a dinner-conference organized by the Rotary Club of Grenoble Sud.
Title of the talk: "L'énergie de demain, ITER un soleil miniature?"

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Major publications by the team in recent years

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[2] B. FAUGERAS, J. BLUM, C. BOULBE, P. MOREAU, E. NARDON.*2D interpolation and extrapolation of discrete magnetic measurements with toroidal harmonics for equilibrium reconstruction in a Tokamak*, in "Plasma Phys. Control Fusion", 2014, vol. 56.

[3] H. GUILLARD, B. KOREN, E. UTE, G. TAMAS, K. RONY, K. DANA. , B. KOREN, U. EBERT, T. GOMBOSI, H. GUILLARD, R. KEPPENS, D. KNOLL (editors)*Special Issue: Computational Plasma Physics of the journal of Computational Physics*, 3, Elsevier, 2012, vol. 231, p. 717-1080, https://hal.inria.fr/hal-00870451.

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[6] J. TARCISIO-COSTA.*Variational Multi-Scale stabilized Finite Elements for the magnetohydrodynamic models of fusion plasmas*, Université Nice Sophia Antipolis [UNS], December 2016, https://hal.inria.fr/tel-01419260.

Articles in International Peer-Reviewed Journal

[7] D. S. BALSARA, J. VIDES, K. GURSKI, B. NKONGA, M. DUMBSER, S. GARAIN, E. AUDIT.*A two-dimensional Riemann solver with self-similar sub-structure – Alternative formulation based on least squares projection*, in "Journal of Computational Physics", January 2016, vol. 304 [*DOI :* 10.1016/J.JCP.2015.10.013], https://hal.archives-ouvertes.fr/hal-01254231.

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[9] M. Blommaert, H. Heumann, M. Baelmans, N. R. Gauger, D. R. Reiter.*Towards automated magnetic divertor design for optimal heat exhaust*, in "ESAIM: Proceedings and Surveys", 2016, vol. 53, p. 49-63 [*DOI :* 10.1051/proc/201653004], https://hal.archives-ouvertes.fr/hal-01389537.

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[17] E. ESTIBALS, H. Guillard, A. Sangam.*Finite Volume for Fusion Simulations*, in "Jorek Meeting 2016", Sophia Antipolis, France, Matthias Hoelzl, April 2016, https://hal.inria.fr/hal-01397086.

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Project-Team COATI

Combinatorics, Optimization and Algorithms for Telecommunications

IN COLLABORATION WITH: Laboratoire informatique, signaux systèmes de Sophia Antipolis (I3S)

IN PARTNERSHIP WITH:
CNRS

Université Nice - Sophia Antipolis

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Networks and Telecommunications

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Project-Team COATI

Creation of the Team: 2013 January 01, updated into Project-Team: 2013 January 01

Keywords:

Computer Science and Digital Science:

1.2.1. - Dynamic reconfiguration
1.2.3. - Routing
1.2.9. - Social Networks
1.6. - Green Computing
3.5.1. - Analysis of large graphs
7.1. - Parallel and distributed algorithms
7.2. - Discrete mathematics, combinatorics
7.3. - Optimization
7.9. - Graph theory
7.10. - Network science

Other Research Topics and Application Domains:

1.1.1. - Structural biology
6.3.3. - Network Management
6.3.4. - Social Networks
7.2. - Smart travel
9.5.3. - Economy, Finance

1. Members

Research Scientists

David Coudert [Team leader, Inria, Senior Researcher, HDR]
Jean-Claude Bermond [CNRS, Senior Researcher, HDR]
Frédéric Giroire [CNRS, Researcher]
Frédéric Havet [CNRS, Senior Researcher, HDR]
Nicolas Nisse [Inria, Researcher, HDR]
Stéphane Pérennes [CNRS, Senior Researcher, HDR]
Bruce Reed [CNRS, Senior Researcher]

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Julien Bensmail [Univ. Côte d'Azur, from Sep 2016, Associate Professor]
Christelle Caillouet [Univ. Côte d'Azur, on maternity leave from February to September 2016, Associate Professor]
Joanna Moulierac [Univ. Côte d'Azur, on maternity leave since April 2016, Associate Professor]
Michel Syska [Univ. Côte d'Azur, Associate Professor]

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Idriss Hassine [Inria, until Nov 2016]
Luc Hogie [CNRS]

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Guillaume Ducoffe [Univ. Nice, supervisor: David Coudert]

Nicolas Huin [Inria, supervisor: Frédéric Giroire and Dino Lopez (I3S)]
William Lochet [Univ. Nice, supervisor: Frédéric Havet and Stéphan Thomassé (ENS Lyon)]
Fionn Mc Inerney [Inria, from Oct 2016, supervisor: Nicolas Nisse]
Steven Roumajon [Bourse Région (BDR) with Eurolio, supervisors: Patrick Musso (Gredeg) and Frédéric Giroire]
Andrea Tomassilli [Univ. Nice, from Mar 2016, supervisors: Stéphane Pérennes and Frédéric Giroire]

Visiting Scientist

Nathann Cohen [CNRS, LRI]

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Sylvie Dupas [Univ. Nice]
Patricia Lachaume [Inria]

Others

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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 WDM, wireless (radio), satellite, overlay, 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, transportation networks and economics.

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, 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. More precisely, we plan to 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.
- **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.

4. Application Domains

4.1. Telecommunication Networks

COATI is mostly interested in telecommunications networks. Within this domain, we consider applications that follow the needs and interests of our industrial partners, in particular Orange Labs or Nokia Bell-Labs, but also SME like 3-Roam.

We focus on the design and management of heterogeneous networks. The project has kept working on the design of backbone networks (optical networks, radio networks, IP networks). We also study routing algorithms such as dynamic and compact routing schemes, as we did in the context of the FP7 EULER led by Alcatel-Lucent Bell-Labs (Belgium), 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 intend to collaborate with experts of these other domains.

For instance, we have recently started a collaboration in Structural Biology with EPI ABS (Algorithms Biology Structure) from Sophia Antipolis (described in Section 7.2). Furthermore, we are working on robot moving problems coming from Artificial Intelligence/Robotic in collaboration with Japan Advanced Institute of Science and Technology. In the area of transportation networks, we have started a collaboration with Amadeus on complex trip planning, and a collaboration with SME Instant-System on dynamic car-pooling combined with multi-modal transportation systems. Last, we have started a collaboration with GREDEG (Groupe de Recherche en Droit, Economie et Gestion, Univ. Nice Sophia Antipolis) on the analysis and the modeling of systemic risks in networks of financial institutions.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

David Coudert and Nathann Cohen (LRI) won the Flinders Hamiltonian Cycle Problem (FHCP) Challenge 2016 (http://fhcp.edu.au/fhcpcs).

Fatima Zahra Moataz, former PhD student of COATI, is the recipient of an accessit to the PhD prize Graphes "Charles Delorme" 2016 for her PhD thesis entitled "Towards Efficient and Fault-Tolerant Optical Networks: Complexity and Algorithms".

6. New Software and Platforms

6.1. BigGraphs

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.

- Participants: Luc Hogie, Nicolas Chleq, David Coudert, Michel Syska.
- Partner: This project is a joint work of the three EPI COATI, DIANA and SCALE and is supported by an ADT grant.
- Contact: Luc Hogie
- URL : http://www.i3s.unice.fr/~hogie/biggrph/

ADDITIONAL SOFTWARES

The following software are useful tools that bring basic services to the platform (they are not dedicated to BIGGRPH). Participants : Luc Hogie, Nicolas Chleq

- JAC-A-BOO is a framework aiming at facilitating the deployment and the bootstrapping of distributed Java applications over Share-Nothing Clusters (SNCs). The primary motivation for developing JAC-A-BOO is to have an efficient and comprehensive deployment infrastructure for the BIGGRPH distributed graph library. http://www.i3s.unice.fr/~hogie/jacaboo
- LDJO (Live Distributed Java Objects) is a framework for the development and the deployment of Java distributed data structures. Alongside with data aspect of distributed data structures, LDJO comes with mechanisms for processing them in a distributed/parallel way. In particular it provides implementations of Map/Reduce and Bulk Synchronous Parallel (BSP). http://www.i3s.unice.fr/~hogie/ldjo
- OCTOJUS provides an object-oriented RPC (Remote Procedure Call) implementation in Java. At a higher abstraction level, OCTOJUS provides a framework for the development of systolic algorithms, a batch scheduler, as well as an implementation of Map/Reduce. The latter is used in the BIGGRPH graph computing platform. http://www.i3s.unice.fr/~hogie/octojus

6.2. GRPH

The high performance graph library for Java

FUNCTIONAL DESCRIPTION

GRPH is an open-source Java library for the manipulation of graphs. Its main design objectives are to make it simple to use and extend, 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 solvers, a framework for distributed computing, etc.

GRPH achieves great efficiency through the use of multiple code optimization techniques such as multi-core parallelism, caching, performant data structures and use of primitive objects, interface to CPLEX linear solver, exploitation of low-level processor caches, on-the-fly compilation of specific C/C++ code, etc.

Unlike other graph libraries which impose the user to first decide if he wants to deal with directed, undirected, hyper (or not) graph, the model offered by GRPH is unified in a very general class that supports mixed graphs made of undirected and directed simple or hyper edges.

We have identified more than 600 users of GRPH since 2013. Inside Inria we collaborate with the AOSTE EPI, for example we recently added a new algorithm (proposed by N. Cohen / LRI) for iterating over the cycles of a given graph in the TimeSquare tool. We also have integrated the discrete-events simulation engine of DRMSIM and some dynamic models (evolution of the connectivity with the mobility of nodes) to GRPH. GRPH includes bridges to other graph libraries such as JUNG, JGraphT, CORESE (a software developed by the WIMMICS team Inria-I3S), LAD (C. Solnon, LIRIS), Nauty (B. D. McKay) or Sagemath. L. Viennot has proposed an implementation of the 4-sweep diameter algorithm designed at LIAFA .

- Participants: Luc Hogie, Nathann Cohen, David Coudert and Michel Syska.
- Contact: Luc Hogie
- URL: http://www.i3s.unice.fr/~hogie/grph/

6.3. Sagemath

SageMath
SageMath is a free open-source mathematics software system, initially created by William Stein (Professor of mathematics at Washington University), and now maintained by a large community of contributors. 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.
We contribute the addition of new graph algorithms along with their documentations and the improvement of underlying data structures.

- 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, Nicolas Huin, Joanna Moulierac, Stéphane Pérennes.

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 three topics: firstly Fixed wireless Backhaul Networks, with the objective of achieving a high reliability of the network. Secondly, Software-Defined networks, in which 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. Finally, the third topic investigated is Energy Efficiency within Backbone networks and for content distribution. We focus on Redudancy Elimination, and we use SDN as a tool to turn-off the links in real networks. We validated our algorithms on a real SDN platform [0].

7.1.1. Fault tolerance

7.1.1.1. Survivability in networks with groups of correlated failures

The notion of Shared Risk Link Groups (SRLG) captures survivability issues when a set of links of a network may fail simultaneously. The theory of survivable network design relies on basic combinatorial objects that are rather easy to compute in the classical graph models: shortest paths, minimum cuts, or pairs of disjoint paths. In the SRLG context, the optimization criterion for these objects is no longer the number of edges they use, but the number of SRLGs involved. Unfortunately, computing these combinatorial objects is NP-hard and hard to approximate with this objective in general. Nevertheless some objects can be computed in polynomial time when the SRLGs satisfy certain structural properties of locality which correspond to practical ones, namely the star property (all links affected by a given SRLG are incident to a unique node) and the span 1 property (the links affected by a given SRLG form a connected component of the network). The star property is defined in a multi-colored model where a link can be affected by several SRLGs while the span property is defined only in a mono-colored model where a link can be affected by at most one SRLG. We have extended in [23] these notions to characterize new cases in which these optimization problems can be solved in polynomial time. We have also investigated the computational impact of the transformation from the multi-colored model to the mono-colored one. Reported experimental results validate the proposed algorithms and principles.

7.1.1.2. Reliability of fixed wireless backaul networks

The reliability of a fixed wireless backhaul network is the probability that the network can meet all the communication requirements considering the uncertainty (e.g., due to weather) in the maximum capacity of each link. In [48], we provide an algorithm to compute the exact reliability of a backhaul network, given a discrete probability distribution on the possible capacities available at each link. The algorithm computes a conditional probability tree, where each leaf in the tree requires a valid routing for the network. Any such tree provides an upper and lower bound on the reliability, and the algorithm improves these bounds by branching in the tree. We also consider the problem of determining the topology and configuration of a backhaul network that maximizes reliability subject to a limited budget. We provide an algorithm that exploits properties of the conditional probability tree used to calculate reliability of a given network design. We perform a computational study demonstrating that the proposed methods can calculate reliability of large backhaul networks, and can optimize topology for modest size networks.

7.1.1.3. Fault tolerance of Linear Access Network

In [52], we study the disconnection of a moving vehicle from a linear access network composed by cheap WiFi Access Points in the context of the telecommuting in massive transportation systems. In concrete, we analyze the probability for a user to experience a disconnection longer than a threshold t_*, leading to a disruption of all on-going communications between the vehicle and the infrastructure network. We provide an approximation formula to estimate this probability for large networks. We then carry out a sensitivity analysis and supply a guide for operators when choosing the parameters of the networks. We focus on two scenarios: an intercity bus and an intercity train. Last, we show that such systems are viable, as they attain a very low probability of long disconnections with a very low maintenance cost.

[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.

7.1.2. Routing in Software Defined Networks (SDN)

Software-defined Networks (SDN), in particular OpenFlow, 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.

7.1.2.1. MINNIE: an SDN World with Few Compressed Forwarding Rules

While SDN brings flexibility in the management of flows within the data center fabric, this flexibility comes at the cost of smaller routing table capacities. Indeed, the Ternary Content Addressable Memory (TCAM) needed by SDN devices has smaller capacities than CAMs used in legacy hardware. In [34], [54], we investigate compression techniques to maximize the utility of SDN switches forwarding tables. We validate our algorithm, called MINNIE, with intensive simulations for well-known data center topologies, to study its efficiency and compression ratio for a large number of forwarding rules. Our results indicate that MINNIE scales well, being able to deal with around a million of different flows with less than 1000 forwarding entry per SDN switch, requiring negligible computation time. To assess the operational viability of MINNIE in real networks, we deployed a testbed able to emulate a $k = 4$ fat-tree data center topology. We demonstrate on one hand, that even with a small number of clients, the limit in terms of number of rules is reached if no compression is performed, increasing the delay of new incoming flows. MINNIE, on the other hand, reduces drastically the number of rules that need to be stored, with no packet losses, nor detectable extra delays if routing lookups are done in ASICs. Hence, both simulations and experimental results suggest that MINNIE can be safely deployed in real networks, providing compression ratios between 70% and 99%.

7.1.2.2. Energy-Aware Routing in Software-Defined Networks

In [51], we focus on using SDN for energy-aware routing (EAR). Since traffic load has a small influence on power consumption of routers, EAR allows to put unused devices 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 forwarding table of OpenFlow switch can hold an infinite number of rules. In practice, this assumption 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 this paper, 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

7.1.3. Reducing Networks' Energy Consumption

Due to the increasing impact of ICT (Information and Communication Technology) on power consumption and worldwide gas emissions, energy efficient ways to design and operate backbone networks are becoming a new concern for network operators. Recently, energy-aware routing (EAR) has gained an increasing popularity in the networking research community. The idea is that traffic demands are redirected over a subset of the network devices, allowing other devices to sleep to save energy. We studied variant of this problems.

7.1.3.1. Energy efficient Content Distribution

To optimize energy efficiency in network, operators try to switch off as many network devices as possible. Recently, there is a trend to introduce content caches as an inherent capacity of network equipment, with the objective of improving the efficiency of content distribution and reducing network congestion. In [36], we study the impact of using in-network caches and CDN cooperation on an energy-efficient routing. We formulate this problem as Energy Efficient Content Distribution. The objective is to find a feasible routing, so that the total energy consumption of the network is minimized subject to satisfying all the demands and link capacity. We exhibit the range of parameters (size of caches, popularity of content, demand intensity, etc.) for which caches are useful. Experiment results show that by placing a cache on each backbone router to store the most popular content, along with well choosing the best content provider server for each demand to a CDN, we can save a total up to 23% of power in the backbone, while 16% can be gained solely thanks to caches.

7.1.3.2. 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, network functions can be implemented dynamically on generic hardware. This is of primary interest to implement energy efficient solutions, which imply to adapt dynamically the resource usage to the demands. In [53], [55], 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 a decomposition model that relies on lightpath configuration to solve the problem. We show that virtualization allows to obtain between 30% to 55% of energy savings for networks of different sizes.

7.1.4. Other results

7.1.4.1. Well Balanced design for Data placement

The have considered in [17] a problem motivated by data placement, in particular data replication in distributed storage and retrieval systems. We are given a set V of v servers along with b files (data, documents). Each file is replicated on exactly k servers. A placement consists in finding a family of b subsets of V (representing the files) called blocks, each of size k. Each server has some probability to fail and we want to find a placement which minimizes the variance of the number of available files. It was conjectured that there always exists an optimal placement (with variance better than that of any other placement for any value of the probability of failure). We show that the conjecture is true, if there exists a well balanced design, that is a family of blocks, each of size k, such that each j-element subset of V , $1 \leq j \leq k$, belongs to the same or almost the same number of blocks (difference at most one). The existence of well balanced designs is a difficult problem as it contains as a subproblem the existence of Steiner systems. We completely solve the case $k = 2$ and give bounds and constructions for $k = 3$ and some values of v and b.

7.1.4.2. Study of Repair Protocols for Live Video Streaming Distributed Systems

In [33], we study distributed systems for live video streaming. These systems can be of two types: structured and un-structured. In an unstructured system, the diffusion is done opportunistically. The advantage is that it handles churn, that is the arrival and departure of users, which is very high in live streaming systems, in a smooth way. On the opposite, in a structured system, the diffusion of the video is done using explicit diffusion trees. The advantage is that the diffusion is very efficient, but the structure is broken by the churn. In this paper, we propose simple distributed repair protocols to maintain, under churn, the diffusion tree of a structured streaming system. We study these protocols using formal analysis and simulation. In particular, we provide an estimation of the system metrics, bandwidth usage, delay, or number of interruptions of the streaming. Our work shows that structured streaming systems can be efficient and resistant to churn.

7.1.4.3. Gathering in radio networks

In [16], we consider the problem of gathering information in a gateway in a radio mesh access network. Due to interferences, calls (transmissions) cannot be performed simultaneously. This leads us to define a round as a set of non-interfering calls. Following the work of Klasing, Morales and Pérennes, we model the problem as a Round Weighting Problem (RWP) in which the objective is to minimize the overall period of non-interfering calls activations (total number of rounds) providing enough capacity to satisfy the throughput demand of the nodes. We develop tools to obtain lower and upper bounds for general graphs. Then, more precise results are obtained considering a symmetric interference model based on distance of graphs, called the distance-d interference model (the particular case d = 1 corresponds to the primary node model). We apply the presented tools to get lower bounds for grids with the gateway either in the middle or in the corner. We obtain upper bounds which in most of the cases match the lower bounds, using strategies that either route the demand of a single node or route simul- taneously flow from several source nodes. Therefore, we obtain exact and constructive results for grids, in particular for the case of uniform demands answering a problem asked by Klasing, Morales and Pérennes.

7.2. Graph Algorithms

Participants: Jean-Claude Bermond, Nathann Cohen, David Coudert, Guillaume Ducoffe, Frédéric Giroire, Nicolas Nisse, Stéphane Pérennes.

COATI is also 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. In particular, we try to find the most efficient algorithms to solve the problems, sometimes focusing on specific graph classes from which the problems are polynomial-time solvable. Many results introduced here are presented in detail in the PhD thesis of Guillaume Ducoffe on *Metric properties of large graphs* https://team.inria.fr/coati/phd-defense-of-guillaume-ducoffe/.

7.2.1. Graph decompositions

It is well known that many NP-hard problems are tractable in the class of bounded treewidth graphs. In particular, tree-decompositions of graphs are an important ingredient of dynamic programming algorithms for solving such problems. This also holds for other width-parameters of graphs. Therefore, computing these widths and associated decompositions of graphs has both a theoretical and practical interest.

7.2.1.1. Width parameters of graphs

In [22], we design a Branch and Bound algorithm that computes the exact pathwidth of graphs and a corresponding path-decomposition. Our main contribution consists of several non-trivial techniques to reduce the size of the input graph (pre-processing) and to cut the exploration space during the search phase of the algorithm. We evaluate experimentally our algorithm by comparing it to existing algorithms of the literature. It appears from the simulations that our algorithm offers a significative gain with respect to previous work. In particular, it is able to compute the exact pathwidth of any graph with less than 60 nodes in a reasonable running-time (10 min.). Moreover, our algorithm also achieves good performance when used as a heuristic (i.e., when returning best result found within bounded time-limit). Our algorithm is not restricted to undirected graphs since it actually computes the vertex-separation of digraphs (which coincides with the pathwidth in case of undirected graphs).

Many tree-decomposition-like parameters are related to particular layouts (ordering) of the vertices of the input graph. In [45], we present a new set of constraints for modeling linear ordering problems on graphs using Integer Linear Programming (ILP). These constraints express the membership of a vertex to a prefix rather than the exact position of a vertex in the ordering. We use these constraints to propose new ILP formulations for well-known linear ordering optimization problems, namely the Pathwidth, Cutwidth, Bandwidth, SumCut and Optimal Linear Arrangement problems. Our formulations are not only more compact than previous proposals, but also more efficient as shown by our experimental evaluations on large benchmark instances.

7.2.1.2. Metric properties of graph decompositions

The decomposition of graphs by clique-minimal separators is a common algorithmic tool, first introduced by Tarjan. Since it allows to cut a graph into smaller pieces, it can be applied to pre-process the graphs in the computation of many optimization problems. However, the best known clique-decomposition algorithms have respective $O(nm)$-time and $O(n^{2.69})$-time complexity, that is prohibitive for large graphs. Here we prove that for every graph G, the decomposition can be computed in $O(T(G) + \min\{n^{2.3729}, \omega^2 n\})$-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 clique-decomposed in $O(n^{2.3729})$-time. Based on prior work from Kratsch et al., in [46], we prove in addition that computing the clique-decomposition is at least as hard as triangle detection. Therefore, the existence of any $o(n^{2.3729})$-time clique-decomposition algorithm 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 clique-decomposed in linear or quasi-linear time.

In [21], we establish general relationships between the topological properties of graphs and their metric properties. For this purpose, we upper-bound the diameter of the *minimal separators* in any graph by a function of their sizes. More precisely, we prove that, in any graph G, the diameter of any minimal separator S in G is at most $\lfloor\frac{\ell(G)}{2}\rfloor \cdot (|S|-1)$ where $\ell(G)$ is the maximum length of an isometric cycle in G. We refine this bound in the case of graphs admitting a *distance preserving ordering* for which we prove that any minimal separator S has diameter at most $2(|S|-1)$. Our proofs are mainly based on the property that the minimal separators in a graph G are connected in some power of G. Our result easily implies that the *treelength*$tl(G)$ of any graph G is at most $\lfloor\frac{\ell(G)}{2}\rfloor$ times its *treewidth*$tw(G)$. In addition, we prove that, for any graph G that excludes an *apex graph*H as a minor, $tw(G) \leq c_H \cdot tl(G)$ for some constant c_H only depending on H. We refine this constant when G has bounded genus. As a consequence, we obtain a very simple $O(\ell(G))$-approximation algorithm for computing the treewidth of n-node m-edge graphs that exclude an apex graph as a minor in $O(nm)$-time.

In [32], [50], we study metric properties of the bags of tree-decompositions of graphs. Roughly, the length and the breadth of a tree-decomposition are the maximum diameter and radius of its bags respectively. The treelength and the treebreadth of a graph are the minimum length and breadth of its tree-decompositions respectively. Pathlength and pathbreadth are defined similarly for path-decompositions. In this paper, we answer open questions of [Dragan and Köhler , Algorithmica 2014] and [Dragan, Köhler and Leitert, SWAT 2014] about the computational complexity of treebreadth, pathbreadth and pathlength. Namely, we prove that computing these graph invariants is NP-hard. We further investigate graphs with treebreadth one, i.e., graphs that admit a tree-decomposition where each bag has a dominating vertex. We show that it is NP-complete to decide whether a graph belongs to this class. We then prove some structural properties of such graphs which allows us to design polynomial-time algorithms to decide whether a bipartite graph, resp., a planar graph, has treebreadth one.

7.2.2. Graph hyperbolicity

The Gromov hyperbolicity is an important parameter for analyzing complex networks which expresses how the metric structure of a network looks like a tree (the smaller gap the better). It has recently been used to provide bounds on the expected stretch of greedy-routing algorithms in Internet-like graphs, and for various applications in network security, computational biology, the analysis of graph algorithms, and the classification of complex networks.

Topologies for data center networks have been proposed in the literature through various graph classes and operations. A common trait to most existing designs is that they enhance the symmetric properties of the underlying graphs. Indeed, symmetry is a desirable property for interconnection networks because it minimizes congestion problems and it allows each entity to run the same routing protocol. However, despite sharing similarities these topologies all come with their own routing protocol. Recently, generic routing schemes have been introduced which can be implemented for any interconnection networks. The performances of such universal routing schemes are intimately related to the hyperbolicity of the topology. Motivated by the good performances in practice of these new routing schemes, we propose in [19], [29] the first general study of the hyperbolicity of data center interconnection networks. Our findings are disappointingly negative: we prove that the hyperbolicity of most data center topologies scales linearly with their diameter, that it the worst-case possible for hyperbolicity. To obtain these results, we introduce original connection between hyperbolicity and the properties of the endomorphism monoid of a graph. In particular, our results extend to all vertex and edge-transitive graphs. Additional results are obtained for de Bruijn and Kautz graphs, grid-like graphs and networks from the so-called Cayley model.

In [20], we investigate more specifically on the hyperbolicity of bipartite graphs. More precisely, given a bipartite graph $B = (V_0 \cup V_1, E)$ we prove it is enough to consider any one side V_i of the bipartition of B to obtain a close approximate of its hyperbolicity $\delta(B)$ — up to an additive constant 2. We obtain from this result the sharp bounds $\delta(G) - 1 \leq \delta(L(G)) \leq \delta(G) + 1$ and $\delta(G) - 1 \leq \delta(K(G)) \leq \delta(G) + 1$ for every graph G, with $L(G)$ and $K(G)$ being respectively the line graph and the clique graph of G. Finally, promising extensions of our techniques to a broader class of intersection graphs are discussed and illustrated with the case of the biclique graph $BK(G)$, for which we prove $(\delta(G) - 3)/2 \leq \delta(BK(G)) \leq (\delta(G) + 3)/2$.

7.2.3. Combinatorial games on graphs

We study several two-player games on graphs.

7.2.3.1. Games and graph decompositions

Graph Searching is a game where a team of searchers aims at capturing a fugitive in a graph. Graph Searching games have been widely studied because they are an algorithmic interpretation of tree/path-decompositions of graphs.

In [18], we define a new variant of graph searching, where searchers have to capture an invisible fugitive with the constraint that no two searchers can occupy the same node simultaneously. This variant seems promising for designing approximation algorithms for computing the pathwidth of graphs. The main contribution in [18] is the characterization of trees where k searchers are necessary and sufficient to win. Our characterization leads to a polynomial-time algorithm to compute the minimum number of searchers needed in trees.

We also study graph searching in directed graphs. We prove that the graph processing variant is monotone which allows us to show its equivalence with a particular digraph decomposition [25].

7.2.3.2. Distributed computing

We also investigate the games described above in a distributed setting.

Consider a set of mobile robots with minimal capabilities placed over distinct nodes of a discrete anonymous ring. Asynchronously, each robot takes a snapshot of the ring, determining which nodes are either occupied by robots or empty. Based on the observed configuration, it decides whether to move to one of its adjacent nodes or not. In the first case, it performs the computed move, eventually. The computation also depends on the required task. In [24], we solve both the well-known Gathering and Exclusive Searching tasks. In the former problem, all robots must simultaneously occupy the same node, eventually. In the latter problem, the aim is to clear all edges of the graph. An edge is cleared if it is traversed by a robot or if both its endpoints are occupied. We consider the exclusive searching where it must be ensured that two robots never occupy the same node. Moreover, since the robots are oblivious, the clearing is perpetual, i.e., the ring is cleared infinitely often. In the literature, most contributions are restricted to a subset of initial configurations. Here, we design two different algorithms and provide a characterization of the initial configurations that permit the resolution of the problems under minimal assumptions.

7.2.3.3. Spy games in graphs

In [28], we define and study the following two-player game on a graph G. Let $k \in \mathbb{N}^*$. 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 $s \in \mathbb{N}^*$ is his *speed*. Then, each guard may move along one edge. The spy and the guards may occupy same vertices. The spy has to escape the surveillance of the guards, i.e., must reach a vertex at distance more than $d \in \mathbb{N}$ (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). First, we consider the computational complexity of the problem, showing that it is NP-hard and that it is PSPACE-hard in DAGs. Then, we establish tight tradeoffs between the number k of guards and the required distance d when G is a path or a cycle. Our main result is that there exists $\beta > 0$ such that $\Omega(n^{1+\beta})$ guards are required to win in any $n \times n$ grid.

7.2.4. Complexity of graph problems

We also investigate several graph problems coming from various applications. We mainly consider their complexity in general or particular graph classes. When possible, we present polynomial-time (approximation) algorithms or Fixed Parameter Tractable algorithms.

7.2.4.1. Bin packing

Motivated by an assignment problem arising in MapReduce computations , we investigate a generalization of the Bin Packing problem which we call Bin Packing with Colocations Problem [41]. Given a set V of items with positive integer weights, an underlying graph G = (V, E), and an integer q, the goal is to pack the items into a minimum number of bins so that (i) the total weight of the items packed in every bin is at most q, and (ii) for each edge (i, j) ∈ E there is at least one bin containing both items i and j. We first show that when the underlying graph is unweighted (i.e., all the items have equal weights), the problem is equivalent to the q-clique problem, and when furthermore the underlying graph is a clique, optimal solutions are obtained from covering designs. We prove that the problem becomes NP-hard even for weighted paths and un-weighted trees and we propose approximation algorithms for particular families of graphs, including: a $(3 + \sqrt{5})$-approximate algorithm for weighted complete graphs (improving a previous 8-approximation), a 2-approximate algorithm for weighted paths, a 5-approximate algorithm for weighted trees, and an (1+)-approximate algorithm for unweighted trees. For general weighted graphs, we propose a 3 + 2mad(G)/2-approximate algorithm, where mad(G) is the maximum average degree of G. Finally, we show how to convert any ρ-approximation algorithm for the Bin Packing (resp. the Densest q-Subgraph problem) into an approximation algorithm for the problem on weighted (resp. unweighted) general graphs.

7.2.4.2. distance preserving ordering

For every connected graph G, a subgraph H of G is isometric if for every two vertices $x, y \in V(H)$ there exists a shortest xy-path of G in H. A distance-preserving elimination ordering of G is a total ordering of its vertex-set $V(G)$, denoted $(v_1, v_2, \cdots, v_n)$, such that any subgraph $G - i = G \setminus \{v_1, v_2, \cdots, v_i\}$ with $1 \leq i < n$ is isometric. This kind of ordering has been introduced by Chepoi in his study on weakly modular graphs. In [47], 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 describe a heuristic in order to compute a distance-preserving ordering when it exists one that we compare to an exact exponential algorithm and an ILP formulation for the problem. Lastly, we prove on the positive side that the problem of computing a distance-preserving ordering when it exists one is fixed-parameter-tractable in the treewidth.

7.2.4.3. cycle convexity

Many notions in graph convexity have been defined and studied for various applications, such as geode-tic convexity (generalizing the classical convexity in Euclidean space to graphs), monophonic convexity (to model spreading of rumor or disease in a network), etc. Each of the convexity notions led to the study of important graph invariants such as the hull number (minimum number of vertices whose hull set is the entire graph) or the interval number (minimum number of vertices whose interval is the whole graph). Recently, Araujo et al. introduced the notion of Cycle Convexity of graphs for its application in Knot Theory. Roughly, the tunnel number of a knot embedded in a plane is equivalent to the hull number of a corresponding planar 4-regular graph in cycle convexity. In [35], we study the interval number of a graph in cycle convexity. Precisely, given a graph G, its interval number in cycle convexity, denoted by incc(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 $G[S]$. In this work, first we provide bounds on incc(G) and its relations to other graph convexity parameters, and explore its behavior on grids. Then, we present some hardness results by showing that deciding whether $incc(G) \leq k$ is NP-complete, even if G is a split graph or a bounded-degree planar graph, and that the problem is W[1]-hard in bipartite graphs when k is the parameter. As a consequence, we obtain that it cannot be approximated up to a constant factor in the class of split graphs (unless P = N P). On the positive side, we present polynomial-time algorithms to compute incc(G) for outerplanar graphs, cobipartite graphs and interval graphs. We also present FPT algorithms to compute it for (q, q - 4)-graphs, where q is the parameter and for bounded treewidth graphs.

7.3. Graph theory

Participants: Nathann Cohen, Guillaume Ducoffe, Frédéric Havet, William Lochet, Nicolas Nisse.

Coati also studies theoretical problems in graph theory. If some of them are directly motivated by applications (see Subsection 7.3.3), others are more fundamental. In particular, we are putting an effort on understanding better directed graphs (also called *digraphs*) and partionning problems, and in particular colouring problems. We also try to better the understand the many relations between orientation 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.

7.3.1. Substructures in digraphs

7.3.1.1. Arc-disjoint branching flows

The concept of arc-disjoint flows in networks was introduced by Bang-Jensen and Bessy [Theoret. Comput. Science 526, 2014]. This is a very general framework within which many well-known and important problems can be formulated. In particular, the existence of arc-disjoint branching flows, that is, flows which send one unit of flow from a given source s to all other vertices, generalizes the concept of arc-disjoint out-branchings (spanning out-trees) in a digraph. A pair of out-branchings $B^+_{s,1}, B^+_{s,2}$ from a root s in a digraph $D=(V,A)$ on n vertices corresponds to arc-disjoint branching flows x_1, x_2 (the arcs carrying flow in x_i are those used in $B^+_{s,i}$, $i=1,2$) in the network that we obtain from D by giving all arcs capacity $n-1$. It is then a natural question to ask how much we can lower the capacities on the arcs and still have, say, two arc-disjoint branching flows from the given root s. In [15], we prove that for every fixed integer $k \geq 2$ it is

- an NP-complete problem to decide whether a network $\mathcal{N}=(V,A,u)$ where $u_{ij}=k$ for every arc ij has two arc-disjoint branching flows rooted at s.
- a polynomial problem to decide whether a network $\mathcal{N}=(V,A,u)$ on n vertices and $u_{ij}=n-k$ for every arc ij has two arc-disjoint branching flows rooted at s.

The algorithm for the later result generalizes the polynomial-time algorithm, due to Lovász, for deciding whether a given input digraph has two arc-disjoint out-branchings rooted at a given vertex. Finally we prove that under the so-called Exponential Time Hypothesis (ETH), for every $\epsilon > 0$ and for every $k(n)$ with $(\log(n))^{1+\epsilon} \leq k(n) \leq \frac{n}{2}$ (and for every large i we have $k(n)=i$ for some n) there is no polynomial algorithm for deciding whether a given digraph contains two arc-disjoint branching flows from the same root so that no arc carries flow larger than $n-k(n)$.

7.3.1.2. Subdivision of oriented cycles

An *oriented cycle* is an orientation of a undirected cycle. In [43], [27], 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 cycle C with two blocks, every strongly connected digraph with sufficiently large chromatic number contains a subdivision of C. This settles a conjecture of Addario-Berry et al. [J. Combin. Theory B, 97, 2007]. More generally, we conjecture that this result holds for any oriented cycle. As a further evidence, we prove this conjecture for the antidirected cycle on four vertices (in which two vertices have out-degree 2 and two vertices have in-degree 2).

7.3.2. Colourings and partitioning (di)graphs

7.3.2.1. 2-partitions of digraphs

A *k-partition* of a (di)graph D is a partition of $V(D)$ into k disjoint sets. Let $\mathbb{P}_1, \mathbb{P}_2$ be two (di)graph properties, then a *$(\mathbb{P}_1, \mathbb{P}_2)$-partition* of a (di)graph D is a 2-partition (V_1, V_2) where V_1 induces a (di)graph with property $\mathbb{P}_1$ and V_2 a (di)graph with property $\mathbb{P}_2$. In [14], [13] and [38], [37], we give a complete characterization for the complexity of $(\mathbb{P}_1, mathbbP_2)$-partition problems when $\mathbb{P}_1, \mathbb{P}_2$ are one of the following standard properties: acyclic, complete, independent (no arcs), oriented (no directed 2-cycle), semicomplete, tournament, symmetric (if two vertices are adjacent, then they induce a directed 2-cycle), strongly connected, connected, minimum out-degree at least 1, minimum in-degree at least 1, minimum semi-degree at least 1, minimum degree at least 1, having an out-branching, having an in-branching. We also investigate the influence of strong connectivity of the input digraph on this complexity. In particular, we show that some NP-complete probems become polynomial-time solvable when restricted to strongly connected input digraphs.

7.3.2.2. 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. In [57], we discuss some results and open problems about extensions of this conjecture to oriented graphs. 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.

7.3.2.3. Locally irregular decompositions of subcubic graphs

A graph G is *locally irregular* if every two adjacent vertices of G have different degrees. A *locally irregular decomposition* of G is a partition $E_1, ..., E_k$ of $E(G)$ such that each $G[E_i]$ is locally irregular. Not all graphs admit locally irregular decompositions, but for those who are decomposable, in that sense, it was conjectured by Baudon, Bensmail, Przybylo and Wozniak that they decompose into 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. In [39], we focus on locally irregular decompositions of subcubic graphs, which form an important family of graphs in this context, as all non-decomposable graphs are subcubic. As a main result, we prove that decomposable subcubic graphs decompose into at most 5 locally irregular graphs, and only 4 when the maximum average degree is less than 12/5. We then consider weaker decompositions, where subgraphs can also include regular connected components, and prove the relaxations of the conjecture above for subcubic graphs.

7.3.2.4. Orientation and edge-weigthing inducing colouring

An orientation of a graph G is *proper* if two adjacent vertices have different indegrees. The *proper-orientation number* of a graph G is the minimum maximum indegree of a proper orientation of G. In a previous paper, we raise the question whether the proper orientation number of a planar graph is bounded. In [12], we prove that every cactus admits a proper orientation with maximum indegree at most 7. We also prove that the bound 7 is tight by showing a cactus having no proper orientation with maximum indegree less than 7. We also prove that any planar claw-free graph has a proper orientation with maximum indegree at most 6 and that this bound can also be attained.

7.3.2.5. Sum-distinguishing edge-weightings

A *k-edge-weighting* of a graph G is an application from $E(G)$ into $\{1, \cdots, k\}$. An edge-weigthing is *sum-distinguishing* if for every two adajcent vertices u and v, the sum of weights of edges incident to u is distinct from the sum of of weights of edges incident to v. The celebrated 1-2-3-Conjecture (raised in 2004 by Karoński, Luczak and Thomason) asserts that every connected graph (except K_2, the complete graph on two vertices) admits a sum-distinguishing 3-edge-weighting. This conjecture attracted much attention and many variants are now studied. We study several of them.

In [58], we study the existence of sum-distinguishing injective $|E(G)|$-edge-weightings. We conjecture that such an edge-weighting always exists (except from K_2). We prove this conjecture for some classes of graphs, such as trees and regular graphs. In addition, for some other classes of graphs, such as 2-degenerate graphs and graphs with maximum average degree at most 3, we prove that, provided we use a constant number of additional edge weights, the desired edge-weighting always exists. Our investigations are strongly related to several aspects of the well-known 1-2-3 Conjecture and the Antimagic Labelling Conjecture.

One of the variants consists in considering total-labelling rather than edge-weighting. A *k-total-weighting* of a graph G is an application from $V(G) \cup E(G)$ into $\{1, \cdots, k\}$. An edge-weigthing is *sum-distinguishing* if for every two adajcent vertices u and v, the sum of of weights of u and the edges incident to u is distinct from the sum of weights of v and the edges incident to v. The 1-2 Conjecture raised by Przybylo, lo and Wozniak in 2010 asserts that every undirected graph admits a 2-total-weighting (both vertices and eedges receives weights) such that the sums of weights "incident" to the vertices yield a proper vertex-colouring. Following several recent works bringing related problems and notions (such as the well-known 1-2-3 Conjecture, and the notion of locally irregular decompositions) to digraphs, we introduce in [40] and study several variants of the 1-2 Conjecture for digraphs. For every such variant, we raise 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 ones that are still open.

7.3.2.6. Colouring game

We wish to motivate the problem of finding decentralized lower-bounds on the complexity of computing a Nash equilibrium in graph games. While the centralized computation of an equilibrium in polynomial time is generally perceived as a positive result, this does not reflect well the reality of some applications where the game serves to implement distributed resource allocation algorithms, or to model the social choices of users with limited memory and computing power. As a case study, we investigate in [31] on the parallel complexity of a game-theoretic variation of graph colouring. These “colouring games" were shown to capture key properties of the more general welfare games and Hedonic games. On the positive side, it can be computed a Nash equilibrium in polynomial-time for any such game with a local search algorithm. However, the algorithm is time-consuming and it requires polynomial space. The latter questions the use of colouring games in the modeling of information-propagation in social networks. We prove that the problem of computing a Nash equi- librium in a given colouring game is PTIME-hard, and so, it is unlikely that one can be computed with an efficient distributed algorithm. The latter brings more insights on the complexity of these games.

7.3.3. Identifying codes

Let G be a graph G. The *neighborhood* of a vertex v in G, denoted by $N(v)$, is the set of vertices adjacent to v i G. It *closed neighborhood* is the set $N[v] = N(v) \cup \{v\}$. A set $C \subseteq V(G)$ is an *identifying code* in G if (i) for all $v \in V(G)$, $N[v] \cap C \neq \varnothing$, and (ii) for all $u, v \in V(G)$, $N[u] \cap C \neq N[v] \cap C$. The problem of finding low-density identifying codes was introduced in [Karpovsky et al., IEEE Trans. Inform. Theory 44, 1998] in relation to fault diagnosis in arrays of processors. Here the vertices of an identifying code correspond to controlling processors able to check themselves and their neighbors. Thus the identifying property guarantees location of a faulty processor from the set of “complaining” controllers. Identifying codes are also used in [Ray et al., IEEE Journal on Selected Areas in Communications 22, 2004] to model a location detection problem with sensor networks.

Particular interest was dedicated to grids as many processor networks have a grid topology. There are three types of regular infinite grids in the plane, namely the hexagonal grids, the square grids and the triangular grids. In [26], [42], we study the square grid $\mathcal{S}_k)$ with infinite width and bounded height k. We prove that the minimum density of an identifying code in $\mathcal{S}_k$ is at least $\frac{7}{20} + \frac{1}{20k}$ and at most $\frac{7}{20} + \frac{3}{10k}$. We also establish that the minimum density of a code in an infinite square grid of height 3 is $\frac{7}{18}$. In [49], [30], we study the minimum density $d^*(\mathcal{T}_k)$ of the triangular grid $\mathcal{S}_k)$ with infinite width and bounded height k. We prove that $d^*(T_k) = \frac{1}{4} + \frac{1}{4k}$ for every odd k and $\frac{1}{4} + \frac{1}{4k} \leq d^*(T_k) \leq \frac{1}{4} + \frac{1}{2k}$ for every even k. We also prove $d^*(T_2) = \frac{1}{2}$ and $d^*(T_4) = d^*(T_6) = \frac{1}{3}$. All these proofs are made using the discharging method, which seems not have been very rarely used for such problems whereas it applies very well.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Grants with Industry

8.1.1. Allocation Carnot Inria / Instant System

Participants: David Coudert, Idriss Hassine.

The Instant System startup company develop a platform in the area of Intelligent transportation systems (ITS). The partnership with COATI aims at designing algorithms for itinerary planning in multimodal transportation networks. The main objective is to combine public transport system and dynamic car-pooling.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

9.1.1.1. ANR Blanc STINT, 2014-2017

Participants: Pierre Aboulker, Jean-Claude Bermond, David Coudert, Frédéric Havet, Luc Hogie, William Lochet, Nicolas Nisse, Stéphane Pérennes, Michel Syska.

The STINT project (*STructures INTerdites*) is led by the MC2 group (LIP, ENS-Lyon) and involves the G-SCOP laboratory (Grenoble).

The aim of STINT is to answer the following fundamental question: *given a (possibly infinite) family ψ of graphs, what properties does a ψ-free graph have?* To this end, it will firstly establish bounds on some classical graph parameters (e.g., clique number, stability number, chromatic number) for ψ-free graphs. Then, it will design efficient algorithms to recognize ψ-free graphs and to determine or approximate some parameters for those graphs. These studies shall result in the development of new proof techniques.

(http://www.ens-lyon.fr/LIP/MC2/STINT/)

9.1.2. PEPS

9.1.2.1. PEPS MoMis SYSTEMIC, 2015 (extended in 2016)

Participant: Frédéric Giroire.

The SYSTEMIC project was led by COATI and involves the LAMA (Paris Est), GREDEG (Sophia Antipolis) and CREM (Rennes) laboratories.

The aim of SYSTEMIC was to bring together the expertises of researchers in economics, graph theory and financial mathematics to propose new models to evaluate the systemic risk of networks of financial institutions, and to propose new methods to mitigate the risk of contagions in such networks. The novelty of the project was in particular to consider strategies for a dynamic control of heterogeneous networks.

9.1.3. GDR Actions

9.1.3.1. Action ResCom, ongoing (since 2006)

Réseaux de communications, working group of GDR RSD, CNRS.

(http://rescom.asr.cnrs.fr/)

9.1.3.2. Action Graphes, ongoing (since 2006)

Action Graphes, working group of GDR IM, CNRS.

(http://gtgraphes.labri.fr/)

9.2. European Initiatives

9.2.1. Collaborations with Major European Organizations

AOR (Vassilis Zissimopoulos) : University of Athens, Department of Informatics and Telecommunications (Greece)

Combinatorial Optimization, Games and Applications (COGA), June 2015- September 2016

Participants : Jean-Claude Bermond, David Coudert, Frédéric Giroire, Nicolas Nisse, Stéphane Pérennes

9.3. International Initiatives

9.3.1. Inria International Labs

Inria Chile

Associate Team involved in the International Lab:

9.3.1.1. 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, www.sagemath.org/) 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.

9.3.2. Inria International Partners

9.3.2.1. Informal International Partners

Apart from formal collaboration COATI members maintain strong connections with the following international teams, with regular visits of both sides.

Univ. of Southern Denmark, Prof. Jorgen Bang Jensen

RWTH Aachen Univ., Lehrstuhl II für Mathematik, Germany, Prof. Arie M.C.A. Koster

Concordia Univ. - Montréal, Quebec, Canada, Prof. Brigitte Jaumard

9.3.3. Participation in Other International Programs

GAIATO : Graphs and Algorithms Applied to Telecommunications, International Cooperation FUNCAP/FAPs/Inria/INS2i-CNRS, no. INC-0083-00047.01.00/13, with Federal University of Ceará, Brasil, 2014-2016.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

Daniela Aguirre Guerrero

Universitat de Girona, Girona, Spain, Visiting PhD Student, from Sep 2016 until Nov 2016.

Jean Francois Baffier

Japanese-French Laboratory for Informatics UMI 3527, Japan, Visiting Scientist, June 2016.

Jorgen Bang Jensen

University of Southern Denmark, Odensee, Denmark, Visiting Scientist, from June 2016 until Jul 2016.

Augustin Chaintreau

Columbia University, New York, US, Visiting Scientist, 19-21st January 2016.

Clément Charpentier

Université Joseph Fourier, Grenoble, France, Visiting Scientist, 21-26th February 2016.

Romuald Elie

Université Paris-Est Marne-la-Vallée, Visiting Scientist, October 24-November 2, 2016.

Takako Kodate

Tokyo Woman's Christian Univ., Japan, Visiting Scientist, Apr 2016.

Christian Konrad

Reykjavik University, Iceland, Visiting Scientist, February 28th to March 3rd, 2016.

Aurélie Lagoutte

Université de Princeton, USA, 9-11th March, 2016.

Zvi Lotker

Ben Gurion University of the Negev, Israel, 22-27th February, 2016.

Ana Karolinna Maia De Oliveira

Univ. Federal do Ceara, Fortaleza, Brazil, Visiting Scientist, Oct 2016.

Colin McDiarmid

University of Oxford, UK, Visiting Scientist, September 26-30th 2016.

Ioannis Milis

Athens University of Economics and Business, Athens, Greece, Visiting Scientist, Feb 2016.

Eduardo Moreno

Univ. Adolfo Ibanez, Santiago, Chile, Visiting Scientist, Sep 2016.

Julio Cesar Silva Araujo

Univ. Federal do Ceara, Fortaleza, Brazil, Visiting Scientist, Oct 2016.

Guillem Perarnau-Llobet

University of Birmingham, UK, Visiting Scientist, May 9-13rd 2016.

Jean-Sébastien Sereni

CNRS, France, 22-25th February.

Yllka Velaj

Gran Sasso Science Institute, L'Aquila, Italia, Visiting PhD Student, from Feb 2016 until Apr 2016.

Joseph Yu

University of the Fraser Valley, Abbotsford, Canada, Visiting Scientist, Apr 2016.

Vassilis Zissimopoulos

National and Kapodistrian University of Athens, Athens, Greece, Visiting Scientist, Feb 2016.

9.4.2. Visits to International Teams

9.4.2.1. Research Stays Abroad

Julien Bensmail

LaBRI, University of Bordeaux, October 10-14, 2016;

LIF, Aix-Marseille University, October 17-19, 2016.

Jean-Claude Bermond

Department of Informatics and Telecommunications of the National and Kapodistrian University of Athens, Greece, June7-21, 2016.

David Coudert

LIP6, UPMC, Paris, October 11-13, 2016;

Univ. Adolfo Ibañez and Univ. Chile, Santiago, Chile, in the context of Inria associated team AlDyNet, October 24-November 11, 2016.

Frédéric Giroire

Orange Labs, Chatillon, May 17-20, 2016;

Computer Science and Software Engineering department, Concordia University, Montréal, Canada, September 28-October 7, 2016.

Nicolas Huin

Concordia University, Montreal, Canada, August 22-November 22, 2016.

William Lochet

Université libre de Bruxelles, Belgique, June 20-25th, 2016.

Nicolas Nisse

Univ. Federal do Ceará, Fortaleza, Brazil, April, 2016;

LIF, Aix-Marseille University, July 18-22, 2016;

Univ. Adolfo Ibañez and Univ. Chile, Santiago, Chile, in the context of Inria associated team AlDyNet, October 24-November 11, 2016.

Bruce Reed

National Institute of Informatics Tokyo Japan, June 1-28th 2016;

Pacific Institute of Mathematical Sciences, June 28th-September 5th 2016;

National Institute of Informatics Tokyo Japan, October 1st-December 31th 2016.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Organizing Committees

Frédéric Havet

GCO 2016: 2nd French Brazilian Workshop on Graphs and Combinatorial Optimization, Redonda, Ceara, Brazil, May 28-April 1, 2016;

4th STINT meeting, January 25-27, Saint Bonnet de Champsaur, France;

Workshop on Shannon capacity, September 11-16, Cassis, France.

Bruce Reed

Workshop on Shannon capacity, September 11-16, Cassis, France.

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

David Coudert

ONDM'16 : 20th International Conference on Optical Networking Design and Modeling, Cartagena, Spain, May 9-12, 2016;

IEEE ICC'16 : IEEE International Conference on Communications, Kuala Lumpur, Malaysia, May 23-27, 2016;

USRR'16 : 4th International Workshop on Understanding the Inter-play between Sustainability, Resilience and Robustness in networks, Halmstad, Sweden, September 15, 2016;

IEEE Globecom'16 : IEEE Global Communications Conference, Washington, DC, USA, December 4-8, 2016.

Frédéric Havet

AAIM 2016: 11th International Conference on Algorithmic Aspects in Information and Management, Bergamo, Italy, July 18-20, 2016;

JGA 2016: 18th Journées Graphes et Algorithmes, Paris, France, November 16-18, 2016.

Nicolas Nisse

AlgoTel 2016: 18es Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications, Bayonne, France, 24-27 May, 2016.

10.1.3. Journal

10.1.3.1. 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 , Discrete Mathematics, Algorithms and Applications.

David Coudert

Discrete Applied Mathematics (Elsevier); Networks (Wiley).

Frédéric Havet

Discrete Mathematics and Theoretical Computer Science;

Nicolas Nisse

Guest editor of Special issue on Theory and Applications of Graph Searching Problems for Theoretical Computer Science (December 2016).

Bruce Reed

Journal of Graph Theory, Electronic Journal of Combinatorics;

10.1.3.2. Reviewer - Reviewing Activities

Members of COATI have reviewed numerous manuscripts submitted to international journals, including: Algorithmica, Algorithms, Bulletin of the Malaysian Mathematical Sciences Society, Computer Communications, Computer Networks, Computers & Operations Research, Discrete Applied Mathematics, European Journal of Operational Research, IEEE/OSA Journal of Lightwave Technology, Networks, Photonic Network Communications, The Computer Journal, Theoretical Computer Science, IEEE/ACM Transactions on Communications, IEEE/ACM Transactions on Networking, IEEE Transactions on Network and Service Management, etc.

10.1.4. Invited Talks

David Coudert

On the design of reliable wireless backhaul networks. International Conference on Ad Hoc Networks and Wireless (AdHoc-Now'16), Lille, France (July 4-5, 2016);

On the notion of hyperbolicity in graphs. Seminar of the Complex Networks team, LIP6, UPMC, Paris (October 12, 2016).

Nicolas Nisse

Spy Games. Groupe de travail de l'équipe CRO, LIF, Marseille, July 18th, 2016;

Recovery of disrupted airline operations. Seminar of LIMOS, Univ. Blaise Pascal, Clermont-Ferrand, January 28th, 2016.

Bruce Reed

The Typical Structure of H-Free Graphs. Sao Paulo Advanced School on Algorithms, Combinatorics, and Optimization, Sao Paulo, Brazil, July 216;

How To Determine If A Random Graph With A Fixed Degree Sequence Has A Giant Component. Sao Paulo Advanced School on Algorithms, Combinatorics, and Optimization, Sao Paulo, Brazil. July 2016;

On The Structure Of Typical H-Free Graphs. University of Birmingham Combinatorics Seminar, Birmingham, United Kingdom, May 2016;

How To Determine If A Random Graph With A Fixed Degree Sequence Has A Giant Component. Simon Fraser University, July 2016;

40th Australian Conference on Combinatorial Mathematics and Combinatorial Computing, NewCastle Australia, December 2016;

How To Determine If A Random Graph With A Fixed Degree Sequence Has A Giant Component. 13th Workshop on Algorithms and Models for the Wb Graph, Montreal, Canada, December 2016.

10.1.5. Leadership within the Scientific Community

David Coudert

Member of the steering committee of *Pôle ResCom du GDR RSD du CNRS* (since 2005);

Member of the steering committee of *Rencontres francophones sur les aspects algorithmiques des télécommunications* (AlgoTel).

Frédéric Havet

Member of the steering committee of *GT Graphes du GDR IM du CNRS*;

Member of the steering committee of *Journées Graphes et Algorithmes (JGA)*;

Member of the steering committee of *Journée Combinatoire et Algorithmes du Littoral Méditerranéen (JCALM)*.

Bruce Reed

Member of the selection committee for the CRM-Fields-Pims Prize.

10.1.6. Scientific Expertise

Jean-Claude Bermond

Expert for DRTT-MESR (Crédit impôt recherche(CIR et agréments) and various projects outside France.

David Coudert

Expert for the Future and Emerging Technologies Open Scheme (FET-Open) European program, and the ANR.

Frédéric Giroire

Expert for ANR.

Frédéric Havet

Expert for ANR.

Michel Syska

Expert for DRTT PACA.

10.1.7. Research Administration

Jean-Claude Bermond

Responsible fo the cooperation between Inria and Greece (meeting with the french Embassy in greece, obtention of join grants and of financial support for internships via the Bodossakis Fundation).

David Coudert

Scientific coordinator of the evaluation seminar of the Inria theme “Networks and Telecommunications”, Rungis, France, March 22-24, 2016.

Frédéric Havet

Responsible of the ComRed Team of I3S;

Recruiting committee (comité de sélection) University of Nice Sophia Antipolis.

Michel Syska

Elected member of CPRH (Comité Permanent de Ressources Humaines) University of Nice Sophia Antipolis;

Recruiting committee (comité de sélection) University of Nice Sophia Antipolis.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence

Pierre Aboulker

Recherche opérationnelle, 74h ETD, Niveau L2, IUT de Nice Côte d’Azur, UNS.

Julien Bensmail

Système d’information et logistique, 36h ETD, niveau S3, IUT Nice Côte d’Azur, UNS.

Christelle Caillouet

Database and advanced information system, 36h ETD, Level L2, IUT Nice Côte d’Azur, UNS;

Delivery Optimization, 30h ETD, Level L3, IUT Nice Côte d’Azur, UNS;

Introduction to Programming, 60h ETD, Level L1, IUT Nice Côte d’Azur, UNS;

Guillaume Ducoffe

Introduction au Web, 28h30 ETD, Level L2, Polytech Nice Sophia, France

Programmation Orientée Objet, 39h ETD, Level L2, Polytech Nice Sophia, France

Principes des systèmes d’exploitation, 26h ETD, Level L2, IUT de Nice Côte d’Azur, UNS.

Valentin Garnero

Introduction aux systèmes informatiques, 108h, niveau S1, IUT Nice Côte d'Azur, UNS.

Luc Hogie

Programmation Répartie, 36h ETD, IUT Nice Côte d'Azur, UNS.

Nicolas Huin

Introduction aux réseaux, 21h ETD, niveau S1, IUT Nice Côte d'Azur, UNS.

William Lochet

Paradigmes et interprétation, 18h ETD, L3, Univ. Côte d'Azur

Programmation objet, 18h ETD, L3, Univ. Côte d'Azur

Compilation, 18h ETD, L3, Univ. Côte d'Azur

Projet scientifique, 30h ETD, L2, Univ. Côte d'Azur

Informatique générale, 36h ETD, L1, Univ. Côte d'Azur

Intro programmation C, 12h ETD, L1, Univ. Côte d'Azur

Joanna Moulierac

Networks, 100h ETD, L1, IUT Nice Côte d'Azur, UNS.

Nicolas Nisse

Introduction à l'algorithmique, 24h ETD, MPSI, Lycée International Valbonne, France.

Steven Roumajon

Architecture des réseaux, 48h ETD, L2, IUT Nice Côte d'Azur, UNS.

Michel Syska

Operating Systems: Advanced Programming, 40h ETD, Level L2, IUT Nice Côte d'Azur, UNS;

Data Structures and Algorithms, 20h ETD, Level L2, IUT Nice Côte d'Azur, UNS;

Algorithmics, 30h ETD, Level L2, IUT Nice Côte d'Azur, UNS;

Distributed Programming, 30h ETD, Level L2, IUT Nice Côte d'Azur, UNS;

Bash Scripting, 30h ETD, Level L3, IUT Nice Côte d'Azur, UNS;

Introduction to Algorithms and Complexity, 60h ETD, Level L3, IUT Nice Côte d'Azur, UNS;

Linux System Administration, 35h ETD, Level L3, IUT Nice Côte d'Azur, UNS.

Master

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;

Green Networks, 18h ETD, stream UbiNet of Master 2 IFI, UNS;

Introduction to probability and statistics, 15h ETD, International Master 1, UNS;

Frédéric Havet

Graph colouring, 4h ETD, M2 MDFI, Aix Marseille Univ., France.

Nicolas Nisse

Graph Algorithms, 18h ETD, M2 IFI, parcours UBINET, UNS, France.

Resolution Methods, 15h ETD, M1 international, UNS, France;

Graph decompositions, 4h ETD, M2 MDFI, Aix Marseille Univ. , France

Stéphane Pérennes

Calcul concurrent et distribué en Java, 30h TP, Master 1 Miage. Polytec Nice.

Responsabilités pédagogiques

Julien Bensmail

Co-organizer of the « Forum sur les poursuites d'études », IUT Nice Côte d'Azur (November 10, 2016);

Representative of the QLIO department at « Salon de l'étudiant », Palais des expositions, Nice (November 26, 2016).

Christelle Caillouet

Co-Responsible of QLIO Department, until February 2016.

Joanna Moulierac

Co-Responsible of the DUT Informatique en Alternance, Computer Science Department, from January 2014 to March 2016.

10.2.2. Supervision

PhD : Guillaume Ducoffe, *Metric properties of large graphs* https://team.inria.fr/coati/phd-defense-of-guillaume-ducoffe/, Université Nice Sophia Antipolis, December 9, 2016. Supervisor : David Coudert;

PhD in progress : Nicolas Huin, *Energy efficient Software Defined Networks*, since Oct. 2014, Supervisors: Frédéric Giroire and Dino Lopez (I3S);

PhD in progress : William Lochet, *Forcing subdivisions in digraphs*, since Sept. 2015, Supervisors: Frédéric Havet and Stéphan Thomassé (ENS Lyon);

PhD in progress : Fionn McInerney, *Combinatorial Games in Graphs*, since Oct. 2016, Supervisor: Nicolas Nisse;

PhD in progress : Steven Roumajon, *Les déterminants de la compétitivité régionale : données microéconomiques et réseaux d'innovation*, since Nov. 2015, Supervisors: Patrick Musso (Gredeg) and Frédéric Giroire;

PhD in progress : Andrea Tomassilli, *Diffusion of information on large dynamic graphs*, since Oct. 2016, Supervisors: Stéphane Pérennes and Frédéric Giroire.

10.2.2.1. Internships

Rohit Agarwal

Date: from Jul 2016 until Aug 2016

Institution: Univ. Nice Sophia Antipolis (France)

Supervisor: Nicolas Nisse

Theodoros Karagkioules

Date: until March 2016

Institution: NKUA, Athens (Greece)

Supervisor: Nicolas Nisse

Raul Wayne Teixeira Lopez

Date: from Sep 2016 until Nov 2016

Institution: UFC, Fortaleza (Brazil)

Supervisor: Frédéric Havet

Ioannis Mantas

Date: from Mar 2016 until Aug 2016

Institution: Univ. Nice Sophia Antipolis (France)

Supervisor: David Coudert

Simon Nivelle

Date: from Jun 2016 until Jul 2016

Institution: ENS Cachan (France)

Supervisor: Guillaume Ducoffe et Nicolas Nisse

Stefano Ponziani

Date: from Mar 2016 until Aug 2016

Institution: Univ. Nice Sophia Antipolis (France)

Supervisor: Guillaume Ducoffe et Frédéric Giroire

Konstantinos Priftis

Date: until March 2016

Institution: Univ. of Patras (Greece)

Supervisor: David Coudert

Panagiotis Pylarinos

Date: from Nov. 2016

Institution: NKUA, Athens (Greece)

Supervisor: David Coudert

Andrea Thomassilli

Date: from Mar 2016 until Aug 2016

Institution: Univ. Nice Sophia Antipolis (France)

Supervisor: Nicolas Huin et Frédéric Giroire

Vladyslav Zaika

Date: from Mar 2016 until Aug 2016

Institution: Univ. Nice Sophia Antipolis (France)

Supervisor: Nicolas Nisse

10.2.3. Juries

David Coudert :

Member of the PhD jury of Guillaume Ducoffe, Univ. Nice Sophia Antipolis, December 9, 2016;

Referee and member of the PhD jury of Mohamad Kanj, Univ. Rennes, December 20, 2016;

Frédéric Giroire:

Member of the PhD jury of Leonardo Linguaglossa, Université Paris Diderot (Paris 7), September 9, 2016.

Frédéric Havet :

Member of the PhD jury of G. Duvillié, Université Montpellier, October 7 2016.

Nicolas Nisse :

Referee and member of the PhD jury of Valentin Garnero, Université Montpellier, July 4 2016.

Referee and member of the PhD jury of Jean-Florent Raymond, Université Montpellier, November 18 2016.

Member of the PhD jury of Guillaume Ducoffe, Univ. Nice Sophia Antipolis, December 9, 2016;

10.3. Popularization

Guillaume Ducoffe:

Fête de la Science: presented the stand "Introduction à l'algorithmique" at Valrose, Univ. Nice Sophia Antipolis, France, October 12nd, 2016.

Frédéric Havet:

Fête de la Science: co-organised the Village des Sciences at Vinon-sur-Verdon, France (November 10-14, 2016). F. Havet gave many talks and animated several stands during the whole week.

Semaine des Mathématiques : presented the stand “Les formes de largeur constantes” at Vinon sur Verdon (March 17, 2016)

Culture Science au Lycée : gave thé conference “Magie mathématique et binaire” at Lycée Caucadis Vitrolles (April 28, 2016) and the conferences “La magie du bonaire” and “La Science du Ballon de Football” at Lycée Caucadis Vitrolles (December 9, 2016).

Vendredis de la Science: conducted scientific workshops for school children (6-11 year old) on friday afternoon. Weekly in Januray-February and May-June 2016.

General audience conference : gave the conference “La Science du Ballon de Football” at Rians, Var, France (January 29, 2016).

Nicolas Nisse:

Fête de la Science: animated several stands during the Village des Sciences at Vinon-sur-Verdon, France (November 10-14, 2016).

Fête de la Science: animated several stands in Palais des Congrès de Juan-Les-Pins, October 22-23rd, 2016

Steven Roumajon:

Fête de la Science: presented the stand "Introduction à l'algorithmique" at Valrose, Univ. Nice Sophia Antipolis, France, October 12nd, 2016.

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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

Keywords:

Computer Science and Digital Science:

6.1.1. - Continuous Modeling (PDE, ODE)
6.1.4. - Multiscale modeling
6.1.5. - Multiphysics modeling
6.2.1. - Numerical analysis of PDE and ODE
6.2.7. - High performance computing

Other Research Topics and Application Domains:

1.1.10. - Mathematical biology
3.3.1. - Earth and subsoil
4.1. - Fossile energy production (oil, gas)
4.2. - Nuclear Energy
7.1. - Traffic management

1. Members

Research Scientist

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Magali Ribot [Professor, Univ. Orléans, Faculty member, HDR]

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Arthur Vavasseur [Univ. Nice & ATER]
Nabil Birgle [Inria-ANDRA]
Feng Xing [Inria-BRGM]

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. Porous Media

Clearly, the analysis and simulation of flows in porous media is a major theme in our team. It is strongly motivated by industrial partnerships, with Total, GdF-Suez, ANDRA, BRGM, etc. with direct applications in geothermy, geological storages, and oil and gas recovery.

Our research has first dealt with the discretization and convergence analysis of multiphase Darcy flows on general polyhedral meshes and for heterogeneous anisotropic media. We have investigated both the Vertex Approximate Gradient (VAG) scheme using both cell and vertex unknowns and the Hybrid Finite Volume (HFV) scheme using both cell and face unknowns. It is remarkable that the VAG scheme is much more accurate than existing nodal approaches (such as CVFE) for heterogeneous test cases: since it avoids the mixing of different rocktypes inside the control volumes, while preserving the low cost of nodal discretizations thanks to the elimination of cell unknowns without any fill-in. The convergence of the numerical discretizations has been studied for the problem of contaminant transport with adsorption in the case of HFV scheme and for two phase Darcy flows in global pressure formulation using particular VAG or HFV schemes, as well as the more general framework of gradient schemes. To reduce the Grid Orientation Effect, a general methodology is proposed in on general meshes. It is based on the recombination of given conservative fluxes to define new conservative fluxes on a richer stencil. On the same token, we have considered the transport of radionucleides by water in porous media. The question is naturally motivated by security studies of nuclear waste storage. We have dealt with the non linear Peaceman system, set on a heterogeneous domain, typically a layered geological medium. The system couples anisotropic diffusion equation and a diffusion-dispersion equation for the pollutant concentration. We have developed and analyzed a specific DDFV scheme to investigate such flows

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 is supported by a ANR-project, led by M. Ribot, and it is the main topic of the PhD thesis of B. Polizzi.

5. New Software and Platforms

5.1. APPartFlow

FUNCTIONAL DESCRIPTION

We are developing experimental codes, mainly based on Finite Differences, for the simulation of particulate flows. A particular attention is paid to guaranty the asymptotic properties of the scheme, with respect to relaxation parameters.

- Contact: Thierry Goudon

5.2. Compass

FUNCTIONAL DESCRIPTION

Compass is a parallel code for the discretization of polyphasic flows by Finite Volumes methods. The code is mainly devoted to applications in porous media. It works on quite general polyhedral meshes.

- Participants: Thierry Goudon, Roland Masson, Cindy Guichard, Chang Yang and Robert Eymard
- Contact: Roland Masson
- URL: http://math.unice.fr/~massonr/ComPASSHighEnergyGeothermy.html

5.3. NS2DDV

FUNCTIONAL DESCRIPTION

It is devoted to the simulation of non-homogeneous viscous flows, in two-dimensional geometries. The code is based on an original hybrid Finite Volume/Finite Element scheme, it works on unstructured meshes and can include mesh refinements strategies.

- Contact: Creusé Emmanuel
- URL: math.univ-lille1.fr/~simpaf/SITE-NS2DDV/home.html

5.4. SimBiof

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. New Results

6.1. A few words on the results of the year

- Analysis of wave propagation in mechanics, partly in collaboration with phsyicsts [40], [24]
- Analysis of PDE system in chromatography [5] and in traffic flows modelling [30]
- Analysis of conservation laws, with many application like traffic flows, fluid mechanics, etc [29], [36], [37], [11], [18]
- Modeling of attractive dynamics between individuals, pattern formation, with the derivation, the analysis and simulations of hierarchies of mathematical models, from microscopic to macroscopic, [9], [17]
- Derivation and simulation of hydrodynamic models in biology (biofilms growth, intestinal gut), partly in collaboration with INRA, [4], [7], [16], [41], [2]
- Modeling and simulation of compositional multiphase flows in porous media, with many indisutrial collaborations with ANDRA< BRGM, EdF... [22], [32], [23], [33], [21], [34], [39], [42], [6], [20]
- Analysis of Finite Volume schemes in fluid mechanics [35], [15], [12], [38]
- Domain decomposition methods [43], [31]
- Many particles systems, effect of stochasticity [27], [1], [28], [8], [13], [10], [19], [3]

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Grants with Industry

The project has industrial collaborations with Total, GDFSuez EP and Storengy on oil and gas recovery and gas storage.

The collaboration with Andra is concerned with the modelling and the simulation of mass and heat exchanges between porous media and ventilation channels. It leads to consider porous medium equations and hydrodynamic systems, coupled through intricate boundary conditions. Clearly one of the difficulties relies on the multiphase nature of the flows (at least water and air are present). We identify relevant physical scales, typical of the flows under consideration in nuclear waste engineering. We start by dealing with quite simple geometries, in order to discuss properly the order of magnitude of the different phenomena, and to design suitable schemes.

COFFEE has also a collaboration with BRGM, funded through the program "Carnot Institutes", devoted to the setting of a parallel computing platform for the simulation of geothermal reservoirs. We aim at contributing to the design of a new generation of parallel tools of simulations, addressing the stiffness issues of actual reservoirs, a large variety of mesh geometries, able to handle faulted media.

A large part of these works is based on the development of the software COMPASS.

8. Partnerships and Cooperations

8.1. Regional Initiatives

The team is involved in the recently granted project UCA-JEDI.

8.2. National Initiatives

8.2.1. ANR

The ANR-project Monumentalg, led by M. Ribot, is devoted to the modeling and simulation of biological damage on monuments and algae proliferation.

Coffee is among the partners of the project CHARMS, with a funding starting in 2016; the project is devoted to the modeling of reservoirs in complex hydrothermal networks.

8.2.2. 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 the GdR-e "Wave Propagation in Complex Media for Quantitative and non Destructive Evaluation".

8.3. International Initiatives

8.3.1. Declared Inria International Partners

Team COKLYCO

Title: Modeling, analysis and simulation of kinetic and fluid models for MEMS

International Partner (Institution - Laboratory - Researcher):

Kyoto (Japan) - Department of Mechanical Engineering and Science (ME) - Aoki Kazuo

Start year: 2014 End year: 2016.

See also: https://team.inria.fr/coffee/?page_id=323

We wish to elaborate and analyse new models of microscopic and macroscopic type for Micro-Electro-Mechanical Systems (MEMS). The tiny scales of such technical devices induce new and challenging difficulties. A specific attention will be paid to the treatment of coupling conditions from moving boundaries, and to the multi-scale character of the problem. The project is based on a strong interplay between mathematical analysis, experiments and numerical simulations, made possible by the composition of the team.

8.3.2. Informal International Partners

Quite recently, S. Junca has started a collaboration with Mathias Legrand, from the Mechanical Engineering department at Mc Gill, Montréal with the supervision of the internship of a master student (S. Heng, 6 months, June-Nov. 2013). Furthermore, S. Junca is an active member of the European network "Wave propagation in complex media for quantitative and non destructive evaluation" [0]

S. Krell has a collaboration with Martin Gander (University of Geneva, Switzerland) on domain decomposition methods, adapted to DDFV discretizations.

M. Ribot started a collaboration with Roberto Natalini a couple of years ago. Connections with experts in Firenze was the starting point of the research on biofilm formation and algae proliferation. M. Ribot and R. Natalini have also worked on new well-balanced strategy — the so-called AHO schemes — in order to preserve equilibria and to capture correctly large time solutions for complex PDEs system, without knowing explicitly the equilibrium solution. They have co-advised 2 PhD thesis.

Finally, we have many international collaborations, with variable peaks of activity, in our research networks: A. Vasseur (U. T. Austin), P.E. Jabin (Univ. Maryland), J.-A. Carrillo (Imperial College London), S. Jin (U. W. Madison and Jiao Tong Univ.), R. Aavatsmark (Univ. of Bergen), etc.

M. Ribot spent a semester, funded by CNRS at ICL, UK.

8.4. International Research Visitors

Kazuo Aoki, from Taiwan, Satushi Taguchi, Takeru Yano, Shingo Kosuge from Kyoto and Osaka University.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

We do not keep track of such activities.

9.1.1.2. Member of the Organizing Committees

We do not keep track of such activities.

9.1.2. Scientific Events Selection

9.1.2.1. Chair of Conference Program Committees

We do not keep track of such activities.

9.1.2.2. Member of the Conference Program Committees

We do not keep track of such activities.

9.1.2.3. Reviewer

We do not keep track of such activities.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

T. Goudon if founding editor and co-Editor in chief of SMAI-J. Computational Mathematics

9.1.4. Invited Talks

We do not keep track of such activities.

[0] http://www.gdre-us.cnrs-mrs.fr/spip.php?rubrique8

9.1.5. Scientific Expertise

FONDECYT (Chili), CERG (Hong-Kong), National Evaluation and Foresight Agency (Espagne), FRS-FNRS (Belgique), ANR and AERES/HCERES.

T. Goudon is member of Scientific Committees of CIRM and FSMP.

9.1.6. Research Administration

Roland Masson is the head of the team PDE and Numerical Analysis of the laboratory J.A. Dieudonné.

Thierry Goudon is member of the Evaluation Committee of Inria.

Thierry Goudon is Scientific Officer at the French Ministry of Education and Research.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Members of the team are faculties of University Nice Sophia Antipolis and they teach in all degrees of the University.

T. Goudon is President of the national competition to hire teachers (agregation de mathematiques).

9.2.2. Supervision

PhD : Arthur Vavasseur, Kinetic models for particles interacting with their environment , Univ. Côte d'Azur, Oct. 2016, supervised by T. Goudon

PhD : Nathalie Ayi, Influence of stochasticity on many-scale problems, Univ. Côte d'Azur, Sept. 2016, supervised by F. Berthelin & L. Saint Raymond (DMA-ENS)

PhD : Bastien Polizzi, Modeling and numerical simulations for fluid mechanics systems with constraints ; application to biology and road traffic, Univ. Côte d'Azur, Sept. 2016, supervised by M. Ribot & T. Goudon

PhD : Maya Grozza, Modelization and discretization of two-phase flows in porous media with discrete fracture networks Univ. Côte d'Azur, Nov. 2016, supervised by R. Masson with Laurent Jeannin (GDFSuez EP), and Jean Frédéric Thebault (Storengy)

PhD in progress : Laurence Beaude, started in november 2015, co-supervised by R. Masson, K. Brenner from LJAD and S. Lopez, F. Smai from BRGM, Discretization of high energy geothermal systems in faulted porous media

PhD in progress : Julian Hennicker, started in june 2014, co-supervised by R. Masson, K. Brenner and P. Samier from TOTAL, Discretization of multiphase Hybrid dimensional Darcy flow models in fractured porous media.

PhD in progress : Julie Llobell, stated Sept. 2015, co-supervised by T. Goudon and S. Minjeaud (team Castor), Staggered schemes for conservation laws of gas dynamics.

PhD in progress : Giulia Lissoni, started Sept. 2016, co-supervised by T. Goudon and S. Krell, Domain decomposition and DDFV methods.

PhD in progress : Thi Huong, started June 2014, Le, supervised by S. Junca, vibrations and mechanical systems, nonlinear modes with an unilateral constraint.

PhD in progress : Pierre Castelli, started Sept. 2013, supervised by S. Junca, smoothing effect for conservation laws (P. Castelli is teacher at Lycée d'Audiberti, Antibes)

The bibliography is automatically extracted form hal; it looks far from complete.

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[3] A. VAVASSEUR.*Kinetic models for particles interacting with their environment*, Universite Cote d'Azur, October 2016, https://hal.archives-ouvertes.fr/tel-01421822.

Articles in International Peer-Reviewed Journal

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Project-Team DIANA

Design, Implementation and Analysis of Networking Architectures

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THEME
Networks and Telecommunications

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Project-Team DIANA

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Computer Science and Digital Science:

1.1.7. - Peer to peer
1.1.13. - Virtualization
1.2.1. - Dynamic reconfiguration
1.2.2. - Supervision
1.2.3. - Routing
1.2.4. - QoS, performance evaluation
1.2.8. - Network security
1.2.9. - Social Networks
1.3. - Distributed Systems
1.4. - Ubiquitous Systems

Other Research Topics and Application Domains:

6.2. - Network technologies
6.2.1. - Wired technologies
6.2.2. - Radio technology
6.2.3. - Satellite technology
6.3.2. - Network protocols
6.3.3. - Network Management
6.3.4. - Social Networks
8.5.2. - Crowd sourcing
9.1.1. - E-learning, MOOC
9.4.1. - Computer science
9.4.5. - Data science
9.6. - Reproducibility
9.8. - Privacy

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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 will 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 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. 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, fifteen years ago the Internet for the end-users was mostly the Web. Only eight 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

The $\mathrm{R}^2\mathrm{lab}$ testbed, part of the national FIT facility, was inaugurated on the SophiaTech campus this year. This new anechoic chamber can be used to remotely perform reproducible wireless network experimentation (5G/software-defined radio). The live public demonstration at the inauguration presented a 4G network being deployed remotely in merely three minutes. For more details see http://r2lab.inria.fr/news.md.

The soTweet project studying the impact Twitter on Media web sites popularity has triggered worldwide media coverage (*Washington Post, Les échos, Le Vif, El Diaro, BFM TV*, etc.) Details and links are in http://www-sop.inria.fr/members/Arnaud.Legout/Projects/sotweet.html. The results are published in [18].

This year witnessed the publication of three RFCs (7834 [36], 7835 [35] and 7927 [31]). These RFCs are the result of a long term contribution by Damien Saucez to the activities on the LISP protocol and in parallel on Information Centric Networking at the IETF and IRTF.

A third session of the Python MOOC by Arnaud Legout and Thierry Parmentelat has been programmed in 2016 and it was also a very big success: 12954 persons registered to the course, out of them 1603 qualified for the final attestation of achievement. This MOOC is adopted by several universities and engineering schools: UPMC L3 program (200 students), first year in CentralSupelec (529 students), SIO Master in CentralParis (16 students), first year of ESISAR school from the Institut Polytechnique de Grenoble group (67 students).

5. New Software and Platforms

5.1. ACQUA

Participants: Chadi Barakat [contact], Thierry Spetebroot, Damien Saucez.

ACQUA is an Application for prediCting Quality of User experience at Internet Access. It was supported by the French ANR CMON project on collaborative monitoring and will be supported in 2016 by both the Inria ADT ACQUA and the ANR Project BottleNet. 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, etc), ACQUA targets the estimated quality of experience 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 that links the network-level measurements to the expected quality of experience. In its first version (the version available online), ACQUA was concentrating on delay measurements at the access and on the detection and estimation of the impact of delay anomalies (local problems, remote problems, etc). The current work is concentrating on using the ACQUA principle in the estimation and prediction of the quality of experience of main user's applications. An Android version is under development supported by the Inria ADT ACQUA.

- URL: http://team.inria.fr/diana/acqua/
- Version: 1.1
- ACM: C.2.2, C.2.3
- Keywords: Internet measurement, Internet Access, Quality of Experience
- License: GPL (3)
- Type of human computer interaction: GUI for client, Web interface for experimentation
- OS/Middleware: MS Windows
- Required library or software: visual studio http://www.visualstudio.com/en-us/products/visual-studio-express-vs.aspx
- Programming language: C# for client, java for server, CGI and Dummynet for experimentation

5.2. ElectroSmart

Participants: Arnaud Legout [contact], Mondi Ravi.

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 (funding the engineer Mondi Ravi) In August 2016, we released the first stable public release of ElectroSmart. On the 20th December 2016 we had 1502 downloads in Google Play, an average score of 4,66/5, 800 active users, 22 millions measured signals and 500k measured geographic zones.

- URL: http://es.inria.fr
- Version: 1.1
- Keywords: background electromagnetic radiations
- License: Inria proprietary licence
- Type of human computer interaction: Android application
- OS/Middleware: Android
- Required library or software: Android
- Programming language: Java
- Documentation: javadoc

5.3. nepi-ng

Participants: Thierry Parmentelat [correspondant], Thierry Turletti, Mario Antonio Zancanaro.

During the past couple of years, we had developped NEPI, the Network Experimentation Programming Interface, as a wide spectrum tool for orchestrating network experiments on network experimentation platforms.

In the more specific context of R2lab, we have been facing more stringent requirements in terms of response time, especially when synchonizing the parallel parts of a wireless experiment. For that reason, and also because the NEPI codebase was starting to feel much too large for its actual usage, and consequently very brittle, we have decided to start and put together a new set of components, named **nepi-ng** for nepi new generation.

At this point, nepi-ng has a much smaller scope than NEPI 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.

For that reason, the actual size of the nepi-ng codebase is about 12 times smaller than the one of NEPI. However, running the same experiment on R2lab turns out to be about 10 times faster using nepi-ng rather than NEPI, that in this context is impeded by its generic model for resources, that prevents NEPI from being as reactive as what can be achieved with nepi-ng.

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 this becomes necessary.

- URL: http://nepi-ng.inria.fr
- Version: 0.5
- 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

5.4. OpenLISP

Participant: Damien Saucez [contact].

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. As of 2016, OpenLISP is used to provide connectivity between satellite sites of the LISP-Lab project.

- http://www.lisp-lab.org/
- Version: 3.2
- ACM: C.2.1, C.2.2, C.2.6
- Keywords: routing, LISP, control-plane
- License: BSD
- Type of human computer interaction: XML, CLI
- OS/Middleware: POSIX
- Required library or software: Expat 2
- Programming language: C
- Documentation: Unix man
- Deployment: http://ddt-root.org

5.5. Platforms

5.5.1. *Reproducible research laboratory* ($\mathrm{R}^2\mathrm{lab}$)

Scientific evaluation of network protocols requires for experiment results to be reproducible before they can be considered as valid. This is particularly difficult to obtain in the wireless networking domain, where characteristics of wireless channels are known to be variable, unpredictable and hardly controllable.

We have built at Inria Sophia-Antipolis, in the last couple of years, an anechoic chamber, with RF absorbers preventing radio waves reflections and with a Faraday cage blocking external interferences. This lab, named $\mathrm{R}^2\mathrm{lab}$, represents an ideal environment for experiments reproducibility.

$\mathrm{R}^2\mathrm{lab}$ has been operated for 2 years now, in the context of the FIT 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 2016, our focus regarding $\mathrm{R}^2\mathrm{lab}$ has been set on the following aspects. First, we have deployed USRPs (Universal Software Radio Peripherals) together with hardware devices for controlling these USRP extensions. This is extremely interesting, as it considerably widens the fields of application for the tesbed. In particular, and that was our second angle for improvements this year, we have taken advantage of the USRP hardware to provide support for OpenAirInterface-based deployments in the chamber. That feature was demonstrated for example during the formal opening that took place on November 9 this year, where it was demonstrated how to set up a private LTE network in 3 minutes.

For more details see http://r2lab.inria.fr.

6. New Results

6.1. Service Transparency

6.1.1. From Network-level Measurements to Expected QoE

Participants: Chadi Barakat, Thierry Spetebroot, Muhammad Jawad Khokhar, Damien Saucez and Nawfal Abbassi Saber.

Internet applications, especially those of multimedia type and in a mobile context, are very sensitive to the delivery service they get from the network. However, the relation between this network service and the quality of these applications as perceived by the end users is often unknown and hard to be quantified. Some of the applications dispose of their own quality estimation techniques such as Skype and Viber. Others leave the users to their own interpretation of the quality they perceive. Linking the quality of Internet applications as perceived by the Internet users to network-level measurements such as bandwidth or delay is more than ever necessary. Such dependence, known in the literature as linking Quality of Experience (QoE) to Quality of Service (QoS) parameters, serves many purposes. On one side it allows the estimation of the quality an Internet user will obtain before launching the application or even before heading to the place where she/he will connect. On the other side, it helps network operators properly dimension their networks so that to anticipate service degradation and optimize the quality they deliver. The correlation of quality measurements among users, or for the same user among different of his/her locations, can help in troubleshooting the reasons of any degraded quality.

Our project, called ACQUA, aims at the estimation of the quality of Internet applications at the access departing from network-level measurements. It leverages measurements done at the network level as done today (bandwidth, delay, loss rate, etc), and applies over them well calibrated models to estimate/predict the quality of experience for main applications even before launching them. ACQUA is an extensible solution in terms of the applications it can track. It allows a fine-grained profiling of the Internet access at the level of application quality. In a recent work, we have proved the feasibility of the approach with the Skype use case. We have integrated into ACQUA a new model based on decision trees for the estimation of Skype QoE. The model has been validated with both local controlled and PlanetLab experiments. In 2016, we focused on the popular YouTube use case. We set up a new experimental setup to automatically stream videos, change network conditions, and write down the corresponding Quality of Experience (modeled as a function of application level Quality of Service metrics). One of the challenges we had to face is the reduction of the complexity of experimentation that we had to solve using sampling techniques. The first results are very promising as we can considerably reduce the complexity of experimentation while reaching high level of accuracy in the prediction of Youtube Quality of Experience. A paper is currently under submission illustrating the methodology and the obtained results. More details on this approach and on our project ACQUA can be found in section 5.1 and on the project web page http://project.inria.fr/acqua/.

6.1.2. Testing for Traffic Differentiation with ChkDiff: The Downstream Case

Participants: Ricardo Ravaioli and Chadi Barakat.

In the past decade it has been found that some Internet operators offer degraded service to selected user traffic by applying various differentiation techniques. If from a legal point of view many countries have discussed and approved laws in favor of Internet neutrality, confirmation with measuring tools for even an experienced user remains hard in practice. In this contribution, we extend and complete our tool ChkDiff, previously presented for the upstream case, by checking for shaping also on the user's downstream traffic. After attempting to localize shapers at the access ISP on upstream traffic, we replay downstream traffic from a measurement server and analyze per-flow one-way delays and losses, while taking into account the possibility of multiple paths between the two endpoints. As opposed to other proposals in the literature, our methodology does not depend on any specific Internet application a user might want to test and it is robust to evolving differentiation techniques that alter delays or induce losses. In a recent publication [22], we provide a detailed description of the downstream tool and a validation in the wild for wired, WiFi and 3G connections. This work is the result of collaboration with the SIGNET group at I3S in the context of a PhD thesis funded by the UCN@Sophia Labex and defended in 2016.

6.1.3. Traceroute facility for Content-Centric Network

Participant: Thierry Turletti.

In the context of the UHD-on-5G associated team with our colleagues at NICT, Japan, we have proposed the Contrace tool for Measuring and Tracing Content-Centric Networks (CCNs). CCNs are fundamental evolutionary technologies that promise to form the cornerstone of the future Internet. The information flow in these networks is based on named data requesting, in-network caching, and forwarding – which are unique and can be independent of IP routing. As a result, common IP-based network tools such as ping and traceroute can neither trace a forwarding path in CCNs nor feasibly evaluate CCN performance. We designed Contrace, a network tool for CCNs (particularly, CCNx implementation running on top of IP) that can be used to investigate 1) the Round-Trip Time (RTT) between content forwarder and consumer, 2) the states of in-network cache per name prefix, and 3) the forwarding path information per name prefix. This tool can estimate the content popularity and design more effective cache control mechanisms in experimental networks. We have published an Internet-Draft [30] describing the specification of Contrace.

6.1.4. How news media use Twitter to attract traffic?

Participants: Arnaud Legout, Maksym Gabielkov.

Online news domains increasingly rely on social media to drive traffic to their website. Yet we know surprisingly little about how social media conversation mentioning an online article actually generates a click to it. Posting behaviors, in contrast, have been fully or partially available and scrutinized over the years. While this has led to to multiple assumptions on the diffusion of information, each were designed or validated while ignoring this important step.

We present in [18] a large scale, validated and reproducible study of social clicks – that is also the first data of its kind – gathering a month of web visits to online resources that are located in 5 leading news domains and that are mentioned in the third largest social media by web referral (Twitter). Our dataset amounts to 2.8 million posts, together responsible for 75 billion potential views on this social media, and 9.6 million actual clicks to 59,088 unique resources. We design a reproducible methodology, carefully corrected its biases, enabling data sharing, future collection and validation. As we prove, properties of clicks and social media Click-Through-Rates (CTR) impact multiple aspects of information diffusion, all previously unknown. Secondary resources, that are not promoted through headlines and are responsible for the long tail of content popularity, generate more clicks both in absolute and relative terms. Social media attention is actually long-lived, in contrast with temporal evolution estimated from posts or impressions. The actual influence of an intermediary or a resource is poorly predicted by their posting behavior, but we show how that prediction can be made more precise.

6.1.5. ReCon: Revealing and Controlling PII Leaks in Mobile Network Traffic

Participant: Arnaud Legout.

It is well known that apps running on mobile devices extensively track and leak users' personally identifiable information (PII); however, these users have little visibility into PII leaked through the network traffic generated by their devices, and have poor control over how, when and where that traffic is sent and handled by third parties. In this paper, we present the design, implementation, and evaluation of ReCon: a cross-platform system that reveals PII leaks and gives users control over them without requiring any special privileges or custom OSes. ReCon leverages machine learning to reveal potential PII leaks by inspecting network traffic, and provides a visualization tool to empower users with the ability to control these leaks via blocking or substitution of PII. We evaluate ReCon's effectiveness with measurements from controlled experiments using leaks from the 100 most popular iOS, Android, and Windows Phone apps, and via an Institutional Review Board approved user study with 92 participants. We show that ReCon is accurate, efficient, and identifies a wider range of PII than previous approaches.

6.2. Open Network Architecture

6.2.1. Storage on Wheels: Offloading Popular Contents Through a Vehicular Cloud

Participants: Luigi Vigneri and Chadi Barakat.

The increasing demand for mobile data is overloading the cellular infrastructure. Small cells and edge caching is being explored as an alternative, but installation and maintenance costs for sufficient coverage are significant. In this work, we perform a preliminary study of an alternative architecture based on two main ideas: (i) using vehicles as mobile caches that can be accessed by user devices; compared to small cells, vehicles are more widespread and require lower costs; (ii) combining the mobility of vehicles with delayed content access to increase the number of cache hits (and reduce the load on the infrastructure). Contrary to standard DTN-type approaches, in our system max delays are guaranteed to be kept to a few minutes (beyond this deadline, the content is fetched from the infrastructure). We first propose an analytical framework to compute the optimal number of content replicas that one should cache, in order to minimize the infrastructure load. We then investigate how to optimally refresh these caches to introduce new contents, as well as to react to the temporal variability in content popularity. Simulations suggest that our vehicular cloud considerably reduces the infrastructure load in urban settings, assuming modest penetration rates and tolerable content access delays. This work has been published in [24]. It is the result of collaboration with Thrasyvoulos Spyropoulos from the Mobile Communications Department at Eurecom in the context of a PhD thesis funded by the UCN@Sophia Labex.

In another work, published in [25], and always in the context of the same collaboration with Thrasyvoulos Spyropoulos, we studied the feasibility of the approach using the popular video streaming case. In this work, we assume such a vehicular cloud is in place to provide video streaming to users, and that the operator can decide which content to store in the vehicle caches. Users can then greedily fill their playout buffer with video pieces of the streamed content from encountered vehicles, and turn to the infrastructure immediately when the playout buffer is empty, to ensure uninterrupted streaming. Our main contribution is to model the playout buffer in the user device with a queuing approach, and to provide a mathematical formulation for the idle periods of this buffer, which relate to the bytes downloaded from the cellular infrastructure. We also solve the resulting content allocation problem, and perform trace-based simulations to finally show that up to 50% of the original traffic could be offloaded from the main infrastructure.

6.2.2. SDN for QoE-based network optimization and management

Participants: Vitalii Poliakov, Damien Saucez.

The naive approach of the networking community is to always increase network capacity to absorb the traffic. In this thesis, we take the counterpoint of this approach claiming that it is possible to better use network resources if we take into account the Quality of Experience (QoE) of users while making routing decisions. The idea is that each network service (e.g., video streaming, web, chat) has different requirements in terms of network performances such as bandwidth or delay and that modern networks present high path diversity, particularly 5G. Our work is thus to provide mechanisms to decide how to route traffic in the network, potentially using multiple paths in parallel, based on their real impact on the QoE. For example, if the experience of a user is not negatively impacted if their traffic is diverted on a slow path, we can use it to free resources for traffic that really needs the high speed path. Initial results for this new activities are published in [27] and [21].

6.2.3. Measurements of LISP

Participant: Damien Saucez.

To face the new challenges of the Internet such as the Cloud and mobility the Locator/ID Separation Protocol (LISP) leverages the separation of the identifier and the locator roles of IP addresses. Contrarily to the classical BGP-based routing architecture, LISP relies on a pull model. In particular, routing information is pulled from a new network element, the Mapping System, to provide the association between the identifier (i.e., the address used to identify a host inside a domain) and a list of locators (i.e., the addresses to locate an attachment point) upon an explicit query. We evaluate a LISP Mapping System deployment in the public LISP Beta Network deployment from two aspects: Stability and Consistency. Our measurements show that the mapping information is stable over time and consistent between the different mapping entities and the vantage points. Due to the presence of few cases where the Mapping System is unstable and/or inconsistent, we propose a taxonomy in order to classify such instabilities and/or inconsistencies and investigate them in depth to provide hints on how to improve LISP performance. Results are published in [26].

6.2.4. Rules Placement Problem in OpenFlow Networks

Participants: Xuan Nam Nguyen, Damien Saucez, Chadi Barakat and Thierry Turletti.

Software-Defined Networking (SDN) abstracts low-level network functionalities to simplify network management and reduce costs. The OpenFlow protocol implements the SDN concept by abstracting network communications as flows to be processed by network elements. In OpenFlow, the high-level policies are translated into network primitives called rules that are distributed over the network. While the abstraction offered by OpenFlow allows to potentially implement any policy, it raises the new question of how to define the rules and where to place them in the network while respecting all technical and administrative requirements. We proposed a comprehensive study of the so-called OpenFlow rules placement problem with a survey of the various proposals intending to solve it [17].

6.2.5. Scalable Multicast Service in Software Defined ISP networks

Participants: Hardik Soni, Thierry Turletti, Walid Dabbous.

In the context of the SDN-based multicast mechanisms activity, we have proposed an architectural solution to provide scalable multicast service in ISP networks. In fact, new applications where anyone can broadcast video are becoming very popular on smartphones. With the advent of high definition video, ISP providers may take the opportunity to propose new high quality broadcast services to their clients. Because of its centralized control plane, Software Defined Networking (SDN) seems an ideal way to deploy such a service in a flexible and bandwidth-efficient way. But deploying large scale multicast services on SDN requires smart group membership management and a bandwidth reservation mechanism to support QoS guarantees that should neither waste bandwidth nor impact too severely best effort traffic. We have proposed a Network Function Virtualization based solution for Software Defined ISP networks to implement scalable multicast group management. We also propose in the same paper a routing algorithm called Lazy Load balancing Multicast (L2BM) for sharing the network capacity in a friendly way between guaranteed-bandwidth multicast traffic and best-effort traffic. Our implementation of the framework made on Floodlight controllers and Open vSwitches is used to study the performance of L2BM. A paper on this work is under submission [37].

6.2.6. Towards unifying content level and network level operations

Participants: Amine Loukili, Damien Saucez, Thierry Turletti.

Programmability of the network to provide content level operations is highly desirable. With the advent of virtualization and network function softwarization, the networking world shifts to Software Defined Networking (SDN) and OpenFlow is one of the most suitable candidates to implement the southbound API (the interface allowing the SDN-controller to program network devices). In the meanwhile, the generalization of broadband Internet has led to massive content consumption. However, while content is usually retrieved via layer 7 protocols, OpenFlow operations are performed at lower layers (layer 4 or lower) making the protocol ineffective to deal with contents. To address this issue, we define an abstraction to unify network level and content level operations and present a straw-man logically centralized architecture proposal to support it. Our implementation demonstrates the feasibility of the solution and its advantage over fully centralized approach. This work has been published in the CoNext student workshop [19]. A demonstration was also presented at IEEE SDN/NFV conference [32].

6.2.7. Resiliency in Service Function Chaining

Participants: Ghada Moualla, Damien Saucez, Thierry Turletti.

In the context of the dynamic placement of Virtual Network Functions in the network activity, we have studied the importance of resiliency in service functions chaining. When deploying network service function chains the focus is usually given on metrics such as the cost, the latency, or the energy and it is assumed that the underlying cloud infrastructure provides resiliency mechanisms to handle with the disruptions occurring in the physical infrastructure. In a position paper on this topic published in PROCON 2016 [20], we advocate that while usual performance metrics are essential to decide on the deployment of network service function chains, the notion of resiliency should not be neglected as the choice of virtual-to-physical placement may dramatically improve the ability of the service chains to handle with failures of the infrastructure without requiring complex resiliency mechanisms.

6.2.8. SDN for Public Safety Networks

Participants: Damien Saucez, Xuan Nam Nguyen, Thierry Turletti.

Commercial users of modern communications networks have benefited from a huge progress of the related technologies. However, Public Safety Networks (PSNs) and devices did not follow the same trend. Very often, they still rely on voice or low speed data communications, tempting first responders to use their own private devices when they need to exchange real-time video or geolocation information. Under this consideration, national authorities and specialized organizations have recently initiated the integration of more recent technologies, such as cellular Long Term Evolution (LTE), even though they need further developments to cope with the harsh usages that safety personnel may face. We wrote a report showing the evolution of these networks towards the recent evolution of networking technologies started with Software Defined networking (SDN) and Network Functions Virtualization (NFV). Based on the requirements derived from a standardized earthquake scenario and a study of the main improvements brought by this network softwarization, it analyzes how SDN and NFV can solve part of the issues raised with commercial LTE and enhance PSN communications. The capabilities of these new technologies are applied to a list of characteristics required by mission-critical networks, e.g., rapid deployment, reliability, security or resilience, taking advantage of features such as the separation between control and data planes or the simplified dynamic resources management. The resulting enhancements are then illustrated using example frameworks published in the literature for Cloud Radio Access Networks, resilient backhaul solution, isolated base stations, SDN-based architecture or Service Function Chaining [28].

6.2.9. Standardization Activities

Participant: Damien Saucez.

The Locator/ID Separation Protocol (LISP) aims to improve the Internet routing by leveraging separating the roles of IP addresses. In RFC7834 [36] we studied the impact that the deployment of LISP would have on both the routing infrastructure and the end user if it was largely deployed in today's Internet. In addition, as bringing new protocols to the Internet opens new security questions, in RFC7835 [35] we provide an exhaustive threat analysis of LISP. Both RFCs are used as insights to extend the architecture of LISP to make it more efficient and safer.

Information Centric Networking (ICN) is a radically new way to conceive networks by promoting content information as routing primitives, instead of content location. In RFC7927 [31], we list the research challenges hidden behind this revolutionary approach of networking. This RFC aims to be the baseline for the development of ICN solutions.

6.3. Experimental Evaluation

6.3.1. ORION: Orientation Estimation Using Commodity Wi-Fi

Participants: Mohamed Naoufal Mahfoudi, Thierry Turletti, Thierry Parmentelat, Walid Dabbous.

With MIMO, Wi-Fi led the way to the adoption of antenna array signal processing techniques for fine-grained localization using commodity hardware. These techniques, previously exclusive to specific domains of applications, open the road to reach beyond localization, and now allow to consider estimating the device's orientation in space, that once required other sources of information. Wi-Fi's popularity and the availability of metrics related to channel propagation (CSI), makes it a candidate readily available for experimentation. We have recently proposed the ORION system to estimate the orientation (heading and yaw) of a MIMO Wi-Fi equipped object, relying on a joint estimation of the angle of arrival and the angle of departure. Although the CSI's phase data is plagued by several phase inconsistencies, we demonstrate that an appropriate phase compensation strategy significantly improves estimation accuracy. By feeding the estimation to a Kalman filter, we further improve the overall system accuracy, and lay the ground for an efficient tracking. Our technique allows estimating orientations within high precision. The results of the study were submitted to a specialized workshop on Network Localization on Navigation [33].

7. Bilateral Contracts and Grants with Industry

7.1. Enabling network function composition with Click middleboxes

In the context of the common Inria - Nokia Bell-Labs laboratory on Communication networks of the future, we participate to the Content Centric Networking ADR (Action de Recherche). In the context of this ADR, a post-doctoral researcher, Anandatirtha Nandugudi Sathyaraja, is working on enabling network function composition with Click middleboxes. In fact, the Click modular router has significant advantages for middlebox development, including modularity, extensibility, and reprogrammability. Despite these features, Click still has no native TCP support and only uses nonblocking I/O, preventing its applicability to middleboxes that require access to application data and blocking I/O. In this paper, we attempt to bridge this gap by introducing Click middleboxes (CliMB). CliMB provides a full-fledged modular TCP layer supporting TCP options, congestion control, both blocking and nonblocking I/O, as well as socket and zero-copy APIs to applications. As a result, any TCP network function may now be realized in Click using a modular L2-L7 design. As proof of concept, we develop a zero-copy SOCKS proxy using CliMB that shows up to 4 times gains compared to an equivalent implementation using the Linux in-kernel network stack.

8. Partnerships and Cooperations

8.1. Inria internal funding

- **User Discrimination on the Web:** we have been awarded funding for two post-doc positions each for one year with the the “Inria Actions Marquantes” with Nataliia Bielova from the INDES project-team. Natasa Sarafijanovic-Djukic have just started her post-doc on this project.
- **ADT ElectroSmart:** in the context of the Inria ADT call, we have a funding for a two year engineering position on the ElectroSmart project for the 2017-2019 period.
- **Transverse Master Interships:** we have a funding for a 6-month internship with Nataliia Bielova on Pixel Tracking.
- **ACQUA:** 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.

8.2. UCN@Sophia Labex and UCA Idex funding

- **ElectroSmart:** this project has a funding for a two year engineering position from the UCN@Sophia Labex for the 2016-2018 period (Ravi Mondi is hired on this position) and 30KEuros fron the UCA (Université Côte d’Azur) RISE Academy.
- **PhD sholarships:** our team has currently four ongoing PhD thesis (Karyna Gogunska, Mohamed Naoufal Mahfoudi, Vitalii Poliakov and Luigi Vigneri) funded by the UCN@Sophia Labex.

8.3. Regional Initiatives

- **Plate-forme Telecom (Com4innov)** (2011-2017) is a DGCIS funded project, in the context of the competitivity cluster SCS, that aims at providing to PACA region industrials wishing to develop or validate new products related to future mobile networks and services and M2M application, a networking infrastructure and tools helpful for development, test and validation of those products. Other partners : 3Roam, Audilog Groupe Ericsson, Ericsson, Eurecom, Inria, iQsim, MobiSmart, Newsteo, OneAccess, Orange Labs, SCS cluster, ST Ericsson, Telecom Valley. Our contribution is centred around providing a test methodology and tools for wireless networks experimentation. In the context of this project we have realized a study on MPTCP performance in a wireless-wired environment with Orange Labs Sophia. The software tools that were developed in the project have been integrated in the $\mathrm{R^2lab}$ anechoic chamber.

8.4. National Initiatives

8.4.1. ANR

- **ANR FIT** (2011-2018): 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. See also http://fit-equipex.fr/.

- **ANR DISCO** (2014-2016): DISCO (DIstributed SDN COntrollers for rich and elastic network services) aims at exploring the way how Software Defined Networking changes network monitoring, control, urbanisation and abstract description of network resources for the optimisation of services. The project works throughout experimentations and application use cases on the next generation of Software-Defined Networking solutions for large and critical distributed systems. The project studied the distribution of the current SDN control plane and the optimization of network operations that the integrated system view of cloud computing-based architectures allows. See also http://anr-disco.ens-lyon.fr/.
- **ANR REFLEXION** (2015-2017): REFLEXION (REsilient and FLEXible Infrastructure for Open Networking) research project will study the robustness and scalability of the current SDN architectures and the flexibility leveraged by SDN for provisioning resources and virtualized network functions (VNF). The project will address four main scientific objectives: (1) Fault and disruption management for virtualized services, (2) Robust and scalable control plane for next generation SDN, (3) Dynamic performance management of low level resources in SDN/NFV environments and (4) Distribution and optimization of virtual network functions in SDN environments. Our contribution in this project will be focused on fault and disruption management for virtualized services. See also http://anr-reflexion.telecom-paristech.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.

8.5. European Initiatives

8.5.1. 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's 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.

8.6. International Initiatives

8.6.1. Inria Associate Teams Not Involved in an Inria International Labs

8.6.1.1. UHD-on-5G

Title: Ultra High Definition video streaming on future 5G networks

International Partner (Institution - 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 a previous associated team (SIMULBED) 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 $\mathrm{R}^2\mathrm{lab}$ testbed developed by Inria.

8.7. International Research Visitors

8.7.1. Visits of International Scientists

Max Ott from Data61/CSIRO (previously NICTA) visited us in November 2016. He gave a seminar on "Confidential Computing - Analysing Data Without Seeing Data" and an invited talk at the $\mathrm{R}^2\mathrm{lab}$ inauguration ceremony.

8.7.1.1. Internships

Ramon Dos Reis Fontes

Date: from Apr 2016 until Sep 2016

Institution: PhD intern, University of Campinas

Supervisor: Thierry Turletti

Subject: Evaluating and Validating Mininet-WiFi

Anastasia Kuznetsova

Date: from Mar 2016 until Aug 2016

Institution: Ubinet Master intern, University of Nice Sophia Antipolis

Supervisor: Arnaud Legout

Subject: User discrimination on Pinterest

Ahmed Loukili

Date: from Mar 2016 until Aug 2016

Institution: Ubinet Master intern, University of Nice Sophia Antipolis

Supervisor: Damien Saucez

Subject: Content Distribution over Software Defined Networks

Hakob Melkonyan

Date: from Mar 2016 until Aug 2016

Institution: Ubinet Master intern, University of Nice Sophia Antipolis

Supervisor: Arnaud Legout

Subject: ElectroSmart Android Project for Exploring Electromagnetic Exposition

Farzaneh Pakzad

Date: from November 2016 to December 2016

Institution: PhD intern, University of Queensland

Supervisor: Thierry Turletti and Walid Dabbous

Subject: Using $\mathrm{R^2lab}$ to evaluate MANET routing protocols

Jimmy Rogala

Date: from May 2016 until Aug 2016

Institution: ENS Rennes intern

Supervisor: Arnaud Legout

Subject: Collecting statistics on Pinterest users

Nawfal Abbassi Saber

Date: from Mar 2016 until Aug 2016

Institution: Ubinet Master intern, University of Nice Sophia Antipolis

Supervisor: Chadi Barakat

Subject: Experimenting and modeling YouTube Quality of Experience

8.7.2. Visits to International Teams

Walid Dabbous, Thierry Turletti and Hardik Soni visited NICT in Tokyo Japan in the context of the UHD-on-5G associated team in December 2016.

9. Dissemination

9.1. Promoting Scientific Activities

Chadi Barakat is on the editorial board of the *Computer Networks* journal, on the Technical Program Committee for the ACM Internet Measurement Conference (IMC) 2017, the ACM CoNext Conference 2016, the International Teletraffic Congress (ITC) 2017, the Passive and Active Measurement (PAM) Conference 2016, the IEEE Measurement and Networking (M&N) Workshop 2017, the Algotel Conference 2016, and the Asian Internet Engineering Conference (AINTEC) 2016. 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 in member of the technical program committee of the IEEE INFOCOM International Workshop on Computer and Networking Experimental Research Using Testbeds, CNERT 2016. He is founding member of the ns-3 consortium. He co-organizeed the workshop on Future challenges in User-Centric Networks, co-located with Sigmetrics 2016 in June 2016. He is member of the scientific council of the Inria Bell-Labs laboratory on Communication networks of the future. He also servers as a chair of the scientific committee of the User Centric Networking (UCN@Sophia) Laroratory of Excellence. He was member of board of directors of the Telecom Platform Association responsible for the deployment and operation of the Com4Innov mutualized platform until July 2016. He is also member of the Ubinet International Master program steering committee. He is member of the Inria Sophia Antipolis project committee's bureau (Bureau du CP).

Arnaud Legout is on the editorial board of the *Computer Networks* journal, and was PC member of the ACM IMC 2016 conference. Arnaud Legout is the president of the Commission of the users of IT resources of Sophia Antipolis Inria research center.

Damien Saucez was co-organizer of the GdR RSD – Journées Cloud 2016 – with Fabien Hermenier (I3S). The conference over 2 days was composed of 16 presentations and two industrial keynotes (Amazon Web Services and Amadeus) with 50 attendees. The objective of this annual conference is to provide a forum for French researchers from the networking community and the distributed system community to exchange their latest findings. Damien Saucez was TPC member of IEEE ICC 2017, IEEE CCNC 2017, ACM CoNEXT Student Workshop 2016, DRCN 2016, IEEE CCNC 2016, ACM WNS3 2016, and IEEE Globecom 2016 SAC CN.

Thierry Turletti, Senior ACM and IEEE member, served in 2016 in the program committees of the following international workshops and conferences: the ACM SIGCOMM 2016 Posters and Demos, Salvador, Brazil, August 2016, the 7th Workshop on ns-3 at Seattle, Washington, June 15-16, 2016 and the 11th ACM Workshop on Challenged Networks (CHANTS), New York, USA, October 2016. Thierry Turletti is member of the Editorial Boards of the *Journal of Mobile Communication, Computation and Information* (WINET) published by Springer Science and of the *Advances in Multimedia Journal* published by Hindawi Publishing Corporation. He is chairman 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 International: Chadi Barakat, Algorithms for Networking, 22.5 hours, M1, University of Nice-Sophia Antipolis, France.

Master Estel: Chadi Barakat, Voice over IP, 9 hours, University of Nice-Sophia Antipolis, France.

Master RISM: Chadi Barakat, Mobility and wireless networking, 10.5 hours, University of Avignon, France.

Master Ubinet: Arnaud Legout, From BitTorrent to Privacy, 36 hours, M2, University of Nice-Sophia Antipolis, France.

Master 1 International: 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.

IUT : Damien Saucez, Advanced Network Services and Operator Network Technologies, 27h, L1 and L2, University of Nice-Sophia Antipolis, France.

E-learning

Python: Arnaud Legout and Thierry Parmentelat are co-authors of the MOOC “Python : des fondamentaux à l’utilisation du langage” that lasts 7 weeks on FUN (https://www.france-universite-numerique-mooc.fr/), Inria. For the third session there were 12954 registered persons among them 1603 qualified for the final attestation of achievement.

Bioinformatics: As part of our contribution to E-learning activities, Thierry Parmentelat was co-author in a MOOC published on the FUN platform and named "Bioinformatique : algorithmes et génomes". This MOOC is dedicated to an introduction to the algorithmic techniques used in the interpretation of DNA sequences. It was played for the second time in French in 2016, and Thierry’s contribution, as compared with the first session that was played in 2015. has been the addition of notebooks where the various algorithms are brought to the students’ disposal, so they can run them interactively, or any variation they would want to study, on any DNA fragment they want, including all the ones from the ENA database https://www.ebi.ac.uk/ena/data/sequence/search. The first notebook-enhanced version of this MOOC in French was played in spring 2016 https://www.fun-mooc.fr/courses/inria/41003S02/session02/info, and attracted 3270 students. An English version of the notebook-enhanced MOOC is scheduled to run on the same FUN platform in spring 2017.

9.2.2. Supervision

PhD: Maksym Gabielkov defended his PhD on "Information propagation in social networks" in June 2016. His thesis was supervised by Arnaud Legout.

PhD: Xuan Nam Nguyen defended his PhD on "Software Defined Networking in challenged environments" April 22, 2016. His thesis was co-supervised by Thierry Turletti and Walid Dabbous. Damien Saucez also actively contributed to the thesis direction.

PhD: Riccardo Ravaioli defended his PhD on "Active and Passive Inference of Network Neutrality" on July 13th 2016. His thesis was co-supervised by Chadi Barakat and Guillaume Urvoy-Keller (I3S).

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 in progress: Vitalii Poliakov works on "the application of Software Defined Networking on 5G networks in order to optimise the Quality of Experience of network services" since November 2015. His thesis is co-supervised by Damien Saucez and Lucile Sassatelli (I3S).

PhD in progress: Hardik Soni works on "Software Defined Networking in challenged environments" since September 2014. His thesis is co-supervised by Thierry Turletti and Walid Dabbous.

PhD in progress: Luigi Vigneri works on "Vehicles as a Mobile Cloud: Leveraging mobility for content storage and dissemination" since April 2014. His thesis is co-supervised by Chadi Barakat and Thrasyvoulos Spyropoulos (Eurecom).

9.2.3. Juries

Chadi Barakat served as reviewer of Panagiotis Matzakos PhD thesis, "Scheduling and Congestion Management Policies for QoS Provision in Disruption Tolerant Networks" defended in October at Eurecom.

Walid Dabbous served as reviewer of Leonardo Linguaglossa PhD thesis, "Two challenges of Software Networking: Name-based Forwarding and Table Verification", defended on September 9th 2016 at the Université Sorbonne Paris Cité.

Walid Dabbous served as jury member of Nikolaos Spountzis PhD thesis, "Network Layer Optimization for Next Generation Heterogeneous Networks", defended on December 14th 2016 at Eurecom.

Walid Dabbous served as reviewer for mid-term PhD defense of Sumit Kumara at Eurecom for his thesis entitled "Simultaneous multi-standard SDR platform".

Arnaud Legout served as reviewer of Riccardo Petrocco PhD thesis, "Scalable Video Coding Support for P2P Networks", defended on April 9, 2016, at TU Delft.

Damien Saucez served as reviewer for mid-term PhD defense of Sergio Livi at Université de Nice Sophia Antipolis for his thesis entitled "Towards NFV-based Green Networks".

Thierry Turletti served as reviewer of Sadaf Yasmin PhD thesis, "Cost-effective routing and cooperative framework or opportunistic networks", defended on February 17 2016 at the Faculty of Computing Mohammad Ali Jinnah University, Islamabad, Pakistan.

Thierry Turletti served as reviewer of Guillaume Gaillard PhD thesis, "Opérer les réseaux de l'Internet des Objets à l'aide de contrats de qualité de service (SLA)", defended on December 19 at University of Lyon, INSA Lyon, France.

9.3. Popularization

Chadi Barakat keeps participating to the organization of the Mediterranean Students Days @ Campus SophiaTech. The fourth edition took place on March 9-11, 2016, and the fifth edition will took place on February 28-March 2, 2017. All details on this event can be found at http://univ-cotedazur.fr/events/meddays.

Walid Dabbous contributed to a large audience book on Big Data (“Les Big Data à Découvert”, CNRS Editions, 2017). His participation [29] is on "Networks for Big Data".

Arnaud Legout gave a presentation on Internet Privacy to high school students at Lycée Amiral in Grasse.

Damien Saucez was invited at AuvernIX to give a tutorial on the Locator/ID Separation Protocol (LISP) in December 2016.

Damien Saucez was invited in December 2016 to present Future Internet challenges to high school students at Lycée Aubrac de Bollène in the context of “Science culture au lycée”.

Damien Saucez was invited at the Amadeus Global Forum in June 2016 to present the future of Software Defined Networking.

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Project-Team ECUADOR

Program transformations for scientific computing

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Numerical schemes and simulations

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Project-Team ECUADOR

Creation of the Project-Team: 2014 January 01

Keywords:

Computer Science and Digital Science:

2.1.1. - Semantics of programming languages
2.2.1. - Static analysis
2.5. - Software engineering
6.1.1. - Continuous Modeling (PDE, ODE)
6.2.6. - Optimization
6.2.7. - High performance computing
6.3.1. - Inverse problems
6.3.2. - Data assimilation

Other Research Topics and Application Domains:

1.1.2. - Molecular biology
3.2. - Climate and meteorology
3.3.2. - Water: sea & ocean, lake & river
3.3.4. - Atmosphere
5.2.3. - Aviation
5.2.4. - Aerospace
9.5.3. - Economy, Finance

1. Members

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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.
- Development of the adjoint AD model towards Parallel Languages.
- 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, Ala Taftaf.

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 [6].

Any execution of P amounts to a sequence of instructions, which is identified with a composition of vector functions. Thus, if

$$\begin{array}{ccc} P & \text{runs} & \{I_1; I_2; \cdots I_p;\}, \\ F & \text{then is} & f_p \circ f_{p-1} \circ \cdots \circ f_1, \end{array} \tag{3}$$

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

$$F'(X) = f'_p(X_{p-1}) \,.\, f'_{p-1}(X_{p-2}) \,.\, \cdots \,.\, f'_1(X_0) \tag{4}$$

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.

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:

$$F'(X).\dot{X} = f'_p(X_{p-1}) \,.\, f'_{p-1}(X_{p-2}) \,.\, \cdots \,.\, f'_1(X_0) \,.\, \dot{X} \quad . \tag{5}$$

  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:

$$F'^*(X).\overline{Y} = f_1'^*(X_0).f_2'^*(X_1). \;\cdots\; .f_{p-1}'^*(X_{p-2}).f_p'^*(X_{p-1}).\overline{Y} \quad . \tag{6}$$

  This expression is most efficiently computed from right to left, because matrix×vector products are cheaper than matrix×matrix products. This is the *adjoint mode* of AD, most effective for optimization, data assimilation [37], adjoint problems [32], or inverse problems.

Adjoint AD builds a very efficient program [34], 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, Ala Taftaf.

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 [25] 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 [28], [35], [26]. 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* [29] 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 [41], [30] 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.

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 input parameters. Consider one particular scalar characteristic. Its sensitivity, (or gradient) with respect to the input parameters can be defined as the solution 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* i.e. to detect and to lower preference to a solution which, although maybe optimal, is 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 [32], 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 [31] 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 [36], [39] 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 [33], [27] 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,
- 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.

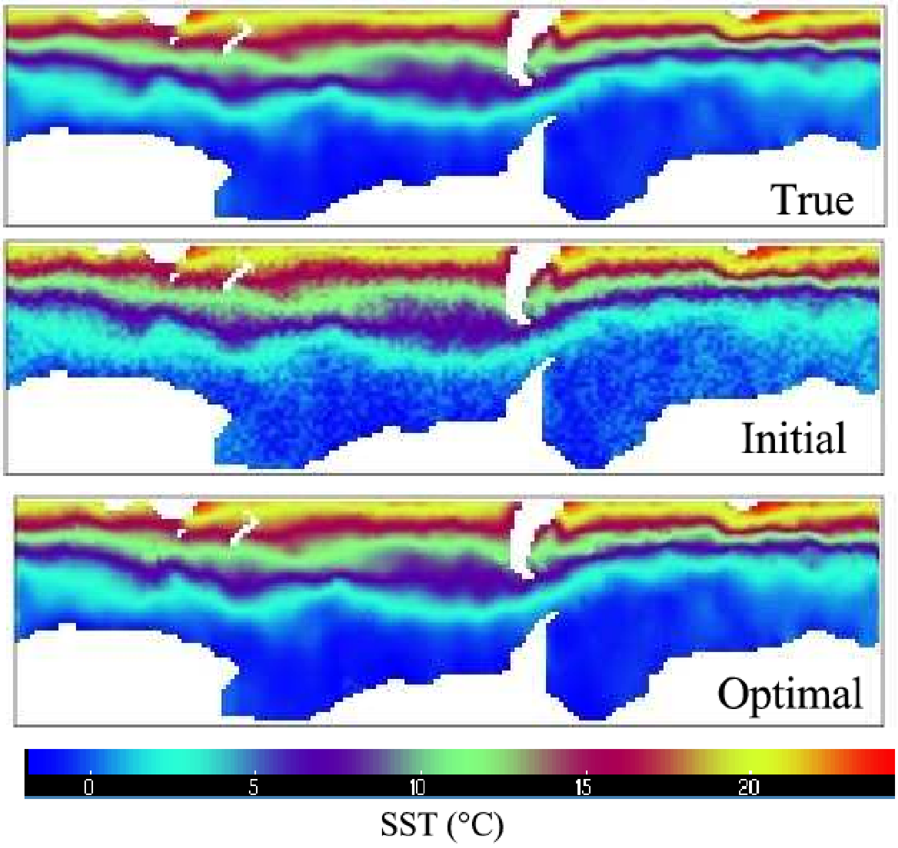

Figure 1. Twin experiment using the adjoint of OPA. Random noise, added to a simulation of the sea surface temperature around the Antarctic, is removed by minimizing the discrepancy with the physical model

One particular case of inverse problems is *data assimilation* [37] 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 [40]. Figure 1 shows an example of a data assimilation exercise using the oceanography code OPA [38] and its AD-adjoint produced by Tapenade.

The special case of *4Dvar* data assimilation is particularly challenging. The 4^{th} dimension in "4D" is time, as available measurements are distributed over a given assimilation period. Therefore the least squares mechanism must be applied to a simulation over time that follows the time evolution model. This process gives a much better estimation of the initial state, because both position and time of measurements are taken into account. On the other hand, the adjoint problem involved is more complex, because it must run (backwards) over many time steps. This demanding application of AD justifies our efforts in reducing the runtime and memory costs of AD adjoint codes.

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

Aironum is an experimental software that solves the unsteady compressible Navier-Stokes equations with k-, LES-VMS (Large Eddy Simulation - Variational Multi-Scale) and hybrid turbulence modelling on parallel platforms, using MPI. The mesh model is unstructured tetrahedrization, with possible mesh motion.

Aironum was developed by Inria and University of Montpellier. It is used by Inria, University of Montpellier and University of Pisa. Aironum is used as an experimental platform for:

- Numerical approximation of compressible flows, such as upwind mixed element volume approximation with superconvergence on regular meshes.
- Numerical solution algorithms for the implicit time advancing of the compressible Navier-Stokes equations, such as parallel scalable deflated additive Schwarz algorithms.
- Turbulence modelling such as the Variational Multiscale Large eddy Simulation and its hybridization with RANS (Reynolds Averaged Navier-Stokes) statistical models.
- Participant: Alain Dervieux
- Contact: Alain Dervieux
- URL: http://www-sop.inria.fr/tropics/aironum

5.2. TAPENADE

KEYWORDS: Static analysis - Optimization - Compilation - Gradients
Tapenade [10] is an Algorithmic Differentiation tool that transforms an original program into a new program that computes derivatives of the original program. Being an AD tool, Tapenade produces analytical derivatives exact up to machine precision, and in adjoint mode computes gradients at a cost independent of the number of input variables.

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 accepts source programs written in Fortran77, Fortran90, or C. It provides differentiation in the following modes: tangent, vector tangent, adjoint, and vector adjoint.

Tapenade performs sophisticated data-flow analysis, flow-sensitive and context-sensitive, on the complete source program to produce an efficient differentiated code. Analyses performed are Type-Checking, Read-Write analysis, Pointer analysis, and AD-specific analyses including Activity analysis, Adjoint Liveness analysis, and TBR analysis.

- Participants: Laurent Hascoët, Valérie Pascual
- Contact: Laurent Hascoët
- URL: http://www-sop.inria.fr/tropics/tapenade.html

6. New Results

6.1. AD-adjoints and C dynamic memory management

Participants: Laurent Hascoët, Sri Hari Krishna Narayanan [Argonne National Lab. (Illinois, USA)], Mathieu Morlighem [University of California at Irvine (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 in our ongoing effort towards adjoint AD of C, and more remotely towards 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 require 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, ADMM was instrumental in the successful generation of the adjoint code of “ALIF” (formerly called “SEISM”) by Tapenade. The “ALIF” code is developed by Mathieu Morlighem from UC Irvine, jointly with Eric Larour from JPL. This glaciology code is a C clone of the C++ “ISSM” code from JPL. One objective of this work is to clarify the C programming style that allows AD to perform better. Another objective is to make progress in the direction of generating adjoints of C++ code. Although ADMM has already been used with success for the adjoint of several small- to medium-size applications, and now on the large-size code “ALIF”, we are still considering alternative implementation strategies. This work was presented at the AD2016 conference in Oxford [16], and an article is submitted to journal “Optimization Methods and Software”.

6.2. AD-adjoints of MPI-parallel codes

Participants: Laurent Hascoët, Ala Taftaf, Georgios Ntanakas [Rolls-Royce, Dahlewitz, Germany], Sri Hari Krishna Narayanan [Argonne National Lab. (Illinois, USA)].

We have a long-standing collaboration with Argonne National Lab on the question of adjoint AD of message-passing parallel codes. We continued joint development of the Adjoinable-MPI library (AMPI) that provides efficient tangent and adjoint AD for MPI-parallel codes, independently of the AD tool used (now AdolC, dco, OpenAD, Tapenade).

Ala Taftaf considers the question of checkpointing applied to the AD-adjoint of an MPI-parallel code. Checkpointing is a memory/runtime tradeoff which is essential for adjoint AD of large codes, in particular parallel codes. However, for MPI codes this question has always been addressed by ad-hoc hand manipulations of the differentiated code, and with no formal assurance of correctness. Ala Taftaf studies these past experiments and proposes more general strategies. Ala Taftaf presented her results [20], [23] at the Eccomas 2016 conference (Crete) in June and at the NOED 2016 conference (Munich) in july [22].

During his secondment with our team, PhD student Georgios Ntanakas from Rolls-Royce studied possible extension of Tapenade to handle the parallel constructs in Rolls-Royce's “Hydra” code, which rely on a special parallel library named “OPlus”.

6.3. AD-adjoints of Iterative Processes

Participants: Laurent Hascoët, Ala Taftaf, Sri Hari Krishna Narayanan [Argonne National Lab. (Illinois, USA)], Daniel Goldberg [University of Edinburgh, UK].

Ala Taftaf continued her work on the adjoint of iterative Fixed-Point loops. This year she studied refinements of the AD-specific data-flow analyses to adapt them to the specific shape of this adjoint code, proposed by Bruce Christianson [27]. She also proposed an efficient “warm-start” mechanism, that provides a good initial guess for the fixed-point loop that computes the adjoint, in the case where this fixed-point loop is itself enclosed in another loop. These results are described in her PhD document, to be defended in January 2017.

We published a journal article [13] on our joint work with Krishna Narayanan from ANL and Dan Goldberg from University of Edinburgh (UK), which applies in particular this fixed-point adjoint strategy to a glaciology configuration of the MIT GCM code.

6.4. AD of mixed-language codes

Participants: Valérie Pascual, Tom Verstraete [VKI, Brussels, Belgium], Laurent Hascoët.

In collaboration with Tom Verstraete, Valérie Pascual is applying Tapenade to the library “Calculix”, whose implementation mixes Fortran and C. This library is well fit for Tapenade differentiation, as the internal representation that we use for codes is language-independent. We can thus load both Fortran and C source into Tapenade and differentiate the complete code transparently. Obviously, since this is the first application of Tapenade to a real-size mixed-language code, interesting problems arise mostly about parameter-passing strategies. Valérie Pascual presented her first results at the AD2016 conference in Oxford [21].

6.5. Multirate methods

Participants: Alain Dervieux, Bruno Koobus, Emmanuelle Itam, Stephen Wornom.

This study is performed in collaboration with IMAG-Montpellier II. It addresses an important complexity issue in unsteady mesh adaptation and takes place in the work done in the ANR Maidesc. 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 streched. 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 cooperation 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. The comparison with an implicit scheme shows that the implicit scheme is in some cases one order less accurate due to higher time steps and higher dissipation. A communication has been presented at ECCOMAS [17] and an article is submitted to a journal.

6.6. Application of AD to uncertainties and errors in CFD

Participants: Valérie Pascual, Laurent Hascoët, Alain Dervieux.

An important application of AD is the creation of uncertainty management tools, as first and second derivatives are used for the assembly of perturbation-based models for Uncertainty Quantification.

During the FP7 project UMRIDA, finished in september 2016, Inria has assisted Alenia-Aermacchi and WUT (Warsaw) in applying Tapenade to a CFD software for perturbation-based models.

We contributed the following chapters to the UMRIDA monography [24]:

- II.5.0 Introduction to Intrusive Perturbation Methods
- II.5.1 Algorithmic Differentiation for second derivatives
- III.a.4 Introduction to Intrusive Perturbation Methods and their range of applicability
- IV.3 Use of Automatic Differentiation tools at the example of Tapenade

6.7. Control of approximation errors

Participants: Gautier Brèthes, Eléonore Gauci, Alain Dervieux, Adrien Loseille [Gamma3 team, Inria-Rocquencourt], Frédéric Alauzet [Gamma3 team, Inria-Rocquencourt], Loïc Frazza [Gamma3 team, Inria-Saclay], Stephen Wornom, Anca Belme [university of Paris 6].

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.

Our theoretical studies in mesh adaptation are supported by the ANR project MAIDESC coordinated by ECUADOR and Gamma3, which deals with meshes for interfaces, third-order accuracy, meshes for boundary layers, and curved meshes.

The thesis of Éléonore Gauci on the goal-oriented criteria for CFD and coupled CSM-CFD systems is continuing. Éléonore Gauci gave a presentation at ECCOMAS in Crete.

Further studies of mesh adaptation for viscous flows are currently performed and a paper in collaboration with Gamma3 and university of Paris 6 (Anca Belme) is being written for a Journal.

An important novelty in mesh adaption is the norm-oriented AA method. The method relies on the definition of ad hoc correctors. It has been developed in the academic platform “FMG” for elliptic problems. Gautier Brèthes gave several presentations in conferences, a journal article has been published [12]. The introduction of the norm-oriented idea considerably amplifies the impact of adjoint-based AA. The applied mathematician and the engineer now have methods when faced to mesh adaptation for the simulation of a complex PDE system, since they can specify which error norm level they wish, and for which norm. Another version is developed jointly with Inria team Gamma3 for the compressible Euler model.

A work of extension of a different standpoint, the tensorial metric method was started during the thesis of Gautier Brèthes and has been been submitted to a journal.

CFD application are supported by the European FP7 project UMRIDA which deals with the application of AA to approximation error modelling and control.

This involves an extensive work on a series of RANS (Reynolds Averaged Navier-Stokes) adaptative computations relying on the multi-scale method on the one hand, and on the other hand on further development by Gamma3 and Ecuador of the novel norm-oriented method for the compressible Euler model. This will be first published as a chapter contributed to the UMRIDA monography [24]: II.1.4 Numerical uncertainties estimation and mitigation by mesh adaption Frédéric Alauzet, Alain Dervieux, Loïc Frazza and Adrien Loseille.

6.8. Turbulence models

Participants: Alain Dervieux, Bruno Koobus, Emmanuelle Itam, Marianna Braza [CNRS-IMFT at Toulouse], Stephen Wornom, Bruno Sainte-Rose [Lemma].

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 tenth millions, far too high for pure LES models. However, certain regions in the flow can be better predicted 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 model, 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.

This year, we have validated and experimented for various test cases the integration of the boundary layer by adding the so-called Menter correction imposing the Bradshaw law. We have studied these improvements on multiple-body flows. An emblematic case is the interaction between two parallel cylinders, one being in the wake of the other.

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. This year, 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. A little surprisingly, the prediction of vortical wakes needs some improvement. For this improvement, we propose a hybrid formulation involving locally a sophisticated LES-VMS (Large Eddy Simulation - Variational Multi-Scale) model combined with the dynamic local limitation of Germano-Piomelli. Several standard options together with the new model have been compared for a series of test cases: a communication has been presented in a conference [18] and an article is in preparation.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- Ecuador and Lemma share the results of Gautier Brèthes' thesis, which is partly supported by Lemma, the other part being supported by a PACA region fellowship.
- 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. National Initiatives

8.1.1. ANR

8.1.1.1. MAIDESC

Ecuador is coordinator of the ANR project MAIDESC, with Inria team Gamma3, University of Montpellier II, CEMEF-Ecole des Mines, Inria-Bordeaux, Lemma and Transvalor. MAIDESC concentrates on mesh adaptation and in particular meshes for interfaces, third-order accuracy, meshes for boundary layers, and curved meshes.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. AboutFlow

Type: PEOPLE

Instrument: Initial Training Network

Duration: 2012-2016

Coordinator: Jens-Dominik Mueller

Partner: Queen Mary University of London (UK)

Inria contact: Laurent Hascoët

Abstract: The aim of AboutFlow is to develop robust gradient-based optimisation methods using adjoint sensitivities for numerical optimisation of flows. http://aboutflow.sems.qmul.ac.uk/

8.2.1.2. UMRIDA

Type:AAT

Instrument:Aeronautics and Air Transport

Duration: 2013-2016

Coordinator: Charles Hirsch

Partner: Numeca S.A. (Belgium)

Inria contact: Alain Dervieux

Abstract: UMRIDA addresses major research challenges in Uncertainty Quantification and Robust Design: develop new methods that handle large numbers of simultaneous uncertainties and generalized geometrical uncertainties. Apply these methods to representative industrial configurations.

8.3. International Initiatives

8.3.1. Inria International Labs

Ecuador participates in the Joint Laboratory for Exascale Computing (JLESC) together with colleagues at Argonne National Laboratory. Laurent Hascoët attended the JLESC meeting in Lyon, France, june 27-29.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

- Krishna Narayanan from Argonne National Laboratory, june 29-july 1.

8.4.2. Internships

- Georgios Ntanakas from Rolls-Royce, Germany, january 18-30.
- Ala Taftaf to Rolls-Royce, Germany, may 6-27.

8.4.3. Visits to International Teams

- Laurent Hascoët visited Argonne National Laboratory, november 14-22.

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.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master : Laurent Hascoët, Optimisation avancée, 15 h, M2, University of Nice

9.2.2. Supervision

PhD in progress : Ala Taftaf, “Extensions of Algorithmic Differentiation by Source Transformation to meet some needs of Scientific Computing”, started july 2013, advisor L. Hascoët.

PhD in progress : Éléonore Gauci, “Norm-oriented criteria for CFD and coupled CSM-CFD systems”, started october 2014, advisor A. Dervieux

9.2.3. Juries

- Alain Dervieux, jury, PhD defense of Laure Billon, Mines Paristech, december 9.
- Laurent Hascoët, jury, PhD defense of Vladimir Groza, University of Nice, november 9.

9.3. Popularization

Laurent Hascoët wrote an article about AD for the blog “binaire”, hosted by ”Le Monde”. May 9.

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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

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2.1.7. - Distributed programming
2.4.3. - Proofs

Other Research Topics and Application Domains:

6.1. - Software industry
6.3. - Network functions
6.4. - Internet of things
9.4.1. - 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. 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.

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: for example, based on modern virtualization technologies, cloud computing offers the possibility to build sophisticated service systems on virtualized infrastructures accessible from everywhere and from any kind of computing device. Such infrastructures are usually examples of sophisticated service oriented architectures that, differently from traditional service systems, should also be capable to elastically adapt on demand to the user requests.

5. Highlights of the Year

5.1. Highlights of the Year

- Valeria Vignudelli has won the “Outstanding Master Thesis Award”, for best master thesis in logic in computer science. Awarded by the Vienna Center for Logic and Algorithms, as part of the VCLA International Student Awards (http://logic-cs.at/award/)

6. New Software and Platforms

6.1. AIOCJ

Adaptive Interaction-Oriented Choreographies in Jolie

SCIENTIFIC DESCRIPTION

AIOCJ is a framework for programming adaptive distributed systems based on message passing. AIOCJ comes as a plugin for Eclipse, AIOCJ-ecl, allowing one to edit descriptions of distributed systems 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 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.

FUNCTIONAL DESCRIPTION

AIOCJ is an open-source choreography programming language for developing adaptive systems.

- Participants: Saverio Giallorenzo, Mila Dalla Preda, Maurizio Gabbrielli, Ivan Lanese and Jacopo Mauro
- Contact: Saverio Giallorenzo
- URL: http://www.cs.unibo.it/projects/jolie/aiocj.html

6.2. DF4ABS

Deadlock Framework for ABS

SCIENTIFIC DESCRIPTION

We have prototyped a framework for statically detecting deadlocks in a concurrent object-oriented language with asynchronous method calls and cooperative scheduling of method activations (the language is ABS, which has been developed in the EU project HATS and is currently extended with primitives for cloud-computing in the EU project ENVISAGE. ABS is very similar to ASP, developed by the former OASIS team.). Since this language features recursion and dynamic resource creation, deadlock detection is extremely complex and state-of-the-art solutions either give imprecise answers or do not scale. In order to augment precision and scalability we propose a modular framework that allows several techniques to be combined. The basic component of the framework is a front-end inference algorithm that extracts abstract behavioural descriptions of methods that retain resource dependency information. Then these behavioural descriptions are analyzed by a back-end that uses a fix-point technique to derive in a deterministic way the deadlock information.

- Contact: Cosimo Laneve
- URL: http://df4abs.nws.cs.unibo.it/

6.3. HoCA

Higher-Order 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 analyzed 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. All these techniques have been specifically suited to the methods integrated in modern first-order complexity analyzers. 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), and call-by-value reductions of the PCF program are simulated by the ATRS step-by-step. On the ATRS, various complexity reflecting transformations are performed: inlining, dead-code-elimination, instantiation of higher-order variables through a call-flow-analysis and finally uncurrying. This results in a first-order rewrite system, whose runtime-complexity asymptotically reflects the complexity of the initial program.

- Participants: Ugo Dal Lago and Martin Avanzini
- Contact: Ugo Dal Lago
- URL: http://cbr.uibk.ac.at/tools/hoca/

6.4. JOLIE

Java Orchestration Language Interpreter Engine

KEYWORD: Microservices

SCIENTIFIC DESCRIPTION

Jolie is a service-oriented programming language. Jolie can be used to program services that interact over the Internet using different communication protocols.

Differently from other Web Services programming languages such as WS-BPEL, Jolie is based on a user-friendly C/Java-like syntax (more readable than the verbose XML syntax of WS-BPEL) and, moreover, the language is equipped with a formal operational semantics. This language is used for the *proof of concepts* developed around Focus activities. For instance, contract theories can be exploited for checking the conformance of a Jolie program with respect to a given contract.

DEVELOPMENTS IN 2016

Jolie has transitioned from version 1.4.1 to version 1.6. The last version of Jolie that supports Java 1.6 is Jolie 1.5. Jolie 1.6 transitions from Java 1.6 to Java 1.8 and makes use of the new features and libraries found in the new version of Java. Version 1.6 of Jolie features:

- general performance improvements and bug fixes, in particular regarding concurrent data structures using Java lambdas,
- improvements of the standard library of the language,
- better error messages and improved compatibility with the main operating systems,
- support for type choices (AKA type sums),
- support of for-loop construct to iterate over arrays without explicit indexes,
- improved support for the HTTP protocol (and, by extension, web applications).
- Participants: Claudio Guidi, Fabrizio Montesi, Saverio Giallorenzo and Maurizio Gabbrielli
- Contact: Fabrizio Montesi
- URL: http://www.jolie-lang.org/

6.5. SRA

Static Resource Analyzer for ABS

SCIENTIFIC DESCRIPTION

We prototype a static analysis technique that computes upper bounds of virtual machine usages in a concurrent language with explicit acquire and release operations of virtual machines. In our language it is possible to delegate other (ad-hoc or third party) concurrent code to release virtual machines (by passing them as arguments of invocations, a feature that is used by Amazon Elastic Cloud Computing or by the Docker FiWare). Our technique is modular and consists of (i) a type system associating programs with behavioural descriptions that record relevant information for resource usage (creations, releases, and concurrent operations), (ii) a translation function that takes behavioural types and returns cost equations, and (iii) an automatic off-the-shelf solver for the cost equations.

- Contact: Cosimo Laneve
- URL: http://sra.cs.unibo.it/

6.6. SUNNY-CP

SCIENTIFIC DESCRIPTION

Within the Constraint Programming paradigm, a portfolio solver combines different constraint solvers in order to create a globally better solver. Sunny-cp is a parallel portfolio solver that allows one to solve a Constraint (Satisfaction/Optimization) Problem defined in the MiniZinc language. It essentially implements the SUNNY algorithm introduced in the team. Sunny-cp is built on top of state-of-the-art constraint solvers, including: Choco, Chuffed, CPX, G12/LazyFD, G12/FD, G12/Gurobi, G12/CBC, Gecode, HaifaCSP, iZplus, MinisatID, Opturion, OR-Tools.

FUNCTIONAL DESCRIPTION

SUNNY-CP is a portfolio solver for solving both Constraint Satisfaction Problems and Constraint Optimization Problems. The goal of SUNNY-CP is to provide a flexible, configurable, and usable CP portfolio solver that can be set up and executed just like a regular individual CP solver.

- Contact: Maurizio Gabbrielli
- URL: https://github.com/CP-Unibo/sunny-cp

6.7. Blender

Aeolus Blender
KEYWORDS: Automatic deployment - Cloud applications management
SCIENTIFIC DESCRIPTION

The various tools developed in the Aeolus project (Zephyrus, Metis, Armonic) have been combined in this software which represents an integrated solution for the declarative specification of cloud applications, and its subsequent automatic deployment on an OpenStack cloud system. In particular, a web-based interface is used to specify the basic software artifacts to include in the application, indicate their level of replication, and specify co-installability conflicts (i.e. when two components cannot be installed on the same virtual machines). The tool Zephyrus is then used to synthesize the final architecture of the application, the tool Metis indicates the plan of configuration actions, and the Armonic platform provides the library of components and the low-level scripts to actually install and configure the entire application.

- Partners: IRILL - Mandriva
- Contact: Gianluigi Zavattaro
- URL: https://github.com/aeolus-project/blender

7. New Results

7.1. Service-oriented computing

Participants: Maurizio Gabbrielli, Elena Giachino, Saverio Giallorenzo, Claudio Guidi, Mario Bravetti, Cosimo Laneve, Ivan Lanese, Fabrizio Montesi, Gianluigi Zavattaro.

7.1.1. Microservices

Microservices is an emerging paradigm for the development of distributed systems that, originating from Service-Oriented Architecture, fosters the creation of an ecosystem of reusable components by focusing on the small dimension, the loose coupling, and the dynamic topology of services. Their dynamic nature calls for suitable techniques that support automatic deployment. In [40] we address this problem and we propose JRO (Jolie Redeployment Optimiser), a tool for the automatic and optimised deployment of microservices written in the Jolie language. The flexibility of microservices is their key advantage, yet it poses many security issues. In [39] we classify the most relevant vulnerabilities related to data reliability, integrity, and authenticity, and we investigate directions for their mitigation.

7.1.2. Orchestrations and choreographies

The practice of programming distributed systems is one of the most error-prone, due to the complexity in correctly implementing separate components that, put together, enact an agreed protocol. Theoretical and applied research is, therefore, fundamental, to explore new tools to assist the development of such systems. In particular, choreographies can be compiled to obtain projected systems that enjoy freedom from deadlocks and races by construction. In [10] we studied how to make choreographies, and extensions of them that allow one to perform dynamic updates, a suitable tool for real-world programming.

7.2. Models for reliability

Participants: Elena Giachino, Ivan Lanese.

7.2.1. Reversibility

We have continued the study of causal-consistent reversibility started in the past years. In particular, we concentrated on uncontrolled reversibility, where one specifies how a concurrent computation can go back to past states, without giving policies about when to do that. In [25] we thoroughly studied the problem for higher-order pi-calculus. In particular, we studied the causality structures needed to enable reversibility, and we related them with the causal semantics of Boreale and Sangiorgi. In [30] we proposed a modular approach that, given a formal model equipped with both an LTS semantics and an independence relation capturing causality, defines a causal-consistent reversible semantics for it. The approach is very general, capturing models as different as CCS and concurrent X-machines, but it is not fully automatic.

7.3. Cloud Computing and Deployment

Participants: Elena Giachino, Saverio Giallorenzo, Claudio Guidi, Cosimo Laneve, Gianluigi Zavattaro.

7.3.1. Static deployment

We have continued our foundational investigation of the Aeolus component model for the automatic deployment of a component-based application in a cloud environment. In [42] we have refined a previous Turing completeness result for the Aeolus model. In fact, a previous proof of undecidability of the deployment problem assumes the possibility of performing in a synchronized way atomic configuration actions on a set of interdependent components: this feature is usually not supported by actual deployment frameworks. To make the theoretical model used for our undecidability result closer to the real deployment infrastructures, in [42] we have proved that even without synchronized configuration actions the Aeolus component model is still Turing complete.

7.3.2. Dynamic deployment

We have analyzed linguistic mechanisms for expressing and managing dynamic aspects of deployment, in particular the possibility to dynamically modify the architecture of an application.

In [17] we propose a new mechanism for Dynamic Rebinding, a particular kind of Dynamic Software Updating that focuses on modifying the workflow of a program. This mechanism is built upon the model of Concurrent Object Groups, which is adopted in programming languages like Coboxes, Creol or ABS. Using this model, which extends and solves some of the limitations of Active Objects, it becomes possible for an update to wait for the program to reach a local quiescent state and then perform the update without creating any inconsistency in the program's state.

In [34] we show how deployment can be added as a first-class citizen in the object-oriented modeling language ABS. We follow a declarative approach: programmers specify deployment constraints and a solver synthesizes ABS classes exposing methods like deploy (resp. undeploy) that executes (resp. cancels) configuration actions changing the current deployment towards a new one satisfying the programmer's desiderata. Differently from previous works, this novel approach supports the specification of incremental modifications, thus supporting the declarative modeling of elastic applications.

7.4. Probabilistic Systems and Resource Control

Participants: Martin Avanzini, Flavien Breuvart, Alberto Cappai, Raphaelle Crubillé, Ugo Dal Lago, Francesco Gavazzo, Charles Grellois, Simone Martini, Alessandro Rioli, Davide Sangiorgi, Marco Solieri, Valeria Vignudelli.

7.4.1. Probabilistic Systems

7.4.1.1. Behavioural Equivalences and Metrics

Finding effective methodologies to check program equivalence is one of the oldest problems in the theory of programming languages, and has been studied also in the realm of probabilistic programming idioms. One particularly fruitful research direction consists in *characterising* context equivalence, the most natural way to *define* equivalence in higher-order languages, by way of *coinductive* notions of equivalence akin to bisimulation. In 2016, Focus has been involved in defining notions of *environmental* bisimulation for probabilistic lambda-calculi [37], proving them not only adequate, but also fully-abstract. Environmental bisimulation, contrarily to *applicative* bisimulation, is robust enough to be applicable to languages with local store. Moreover, the proof of adequacy of environmental bisimulation turns out to be simpler than that of applicative bisimulation, the latter requiring sophisticated arguments from linear programming. In a probabilistic setting, programs are more naturally compared through metrics rather than through equivalences, due to their intrinsic quantitative nature. Nicely, coinductive methodologies for program equivalence can be generalised to metrics by way of so-called *behavioural metrics*. This year, we have studied behavioural metrics in the context of concurrent processes, and defined enhancements of the proof method based on bisimulation metrics, by extending the theory of up-to techniques to premetrics on discrete probabilistic concurrent processes [32].

7.4.1.2. Programming Languages for Machine Learning

In recent years, higher-order functional programming languages like Church, Anglican, and Venture, have proved to be extremely effective as ways to specify not algorithms but rather bayesian models in the context of machine learning. The operational semantics of these languages, and learning algorithms when applied to programs in these languages, have been so far defined only informally. In 2016, we developed the operational semantics of an untyped probabilistic lambda-calculus with continuous distributions, as a foundation for universal probabilistic programming languages like those cited above [31]. Our first contribution was to adapt the classic operational semantics of lambda-calculus to a continuous setting. Our second contribution was to formalise the implementation technique of trace Markov chain Monte Carlo (MCMC) for our calculus and to show its correctness.

7.4.2. Resource Control

7.4.2.1. Complexity Analysis of Higher-Order Functional Programs

Complexity analysis of higher-order programs have been one of the main research themes inside Focus since its inception. It remains so today, although the emphasis is progressively shifting towards problems related to the *implementation* of complexity analysis methodologies rather than on their foundations. One issue with most existing complexity analysis methodologies is that they are insensitive to the sharing of computations among subprograms. We have studied how the interpretation method and dependency tuples, two prominent complexity analysis techniques can be adapted to graph-rewriting, thus accounting for the possible performance gains due to sharing [38]. We have also collaborated to the development of TCT, the Tyrolean Complexity Tool [29], a state-of-the-art complexity analyzer for term rewrite systems, making it capable to efficiently apply not one but *many* methodologies to the input program. Finally, we studied how the geometry of interaction can provide effective ways to compile higher-order functional programs into circuits, thus guaranteeing space efficiency [21].

7.4.2.2. On the Foundations of Complexity Analysis

One of the main foundational issues in complexity analysis is whether simple time cost models can be proved invariant, i.e., polynomially related to low-level models like those traditionally defined on Turing machines. We have solved a long-standing open problem, and proved that the unitary cost model, namely that attributing unitary cost to each beta-reduction step, is invariant for the pure lambda-calculus when evaluated leftmost-outermost [12]. We have also studied to which extent traditional methodologies like the interpretation method and light logics can be adapted to higher-order languages [16] and processes [20], respectively.

7.5. Verification techniques

Participants: Daniel Hirschkoff, Elena Giachino, Cosimo Laneve, Davide Sangiorgi.

7.5.1. Deadlock detection

In [22] we present a framework for statically detecting deadlocks in a concurrent object-oriented language with asynchronous method calls and cooperative scheduling of method activations. Since this language features recursion and dynamic resource creation, deadlock detection is extremely complex and state-of-the-art solutions either give imprecise answers or do not scale. In order to augment precision and scalability we propose a modular framework that allows several techniques to be combined. The basic component of the framework is a front-end inference algorithm that extracts abstract behavioural descriptions of methods, called contracts, which retain resource dependency information. This component is integrated with a number of possible different back-ends that analyze contracts and derive deadlock information. As a proof-of-concept, we discuss two such back-ends: (i) an evaluator that computes a fixpoint semantics and (ii) an evaluator using abstract model checking.

In [36] we study deadlock detection in an actor model with wait-by-necessity synchronizations, a lightweight technique that synchronizes invocations when the corresponding values are strictly needed. This approach relies on the use of futures that are not given an explicit Future type. The approach we adopt allows for the implicit synchronization on the availability of some value (where the producer of the value might be decided at runtime), whereas previous work allowed only explicit synchronization on the termination of a well-identified request. This way we are able to analyze the data-flow synchronization inherent to languages that feature wait-by-necessity. We provide a type-system and a solver inferring the type of a program so that deadlocks can be identified statically. As a consequence we can automatically verify the absence of deadlocks in actor programs with wait-by-necessity synchronizations.

7.5.2. Service Level Agreement

There is a gap between run-time service behaviours and the contracted quality expectations with the customers that is due to the informal nature of service level agreements. In [41] we explain how to bridge the gap by formalizing service level agreements with metric functions. We therefore discuss an end-to-end analysis flow that can either statically verify if a service code complies with a metric function or use run-time monitoring systems to report possible misbehaviours. In both cases, our approach provides a feedback loop to fix and improve the metrics and eventually the resource configurations of the service itself.

7.6. Type Systems

Participants: Daniel Hirschkoff, Simone Martini, Davide Sangiorgi.

7.6.1. Surveys

In [27], Martini elaborates the history of type systems, focusing on that fundamental period covering the seventies and the early eighties. It was then that types became the cornerstone of the programming language design, passing first from the abstract data type (ADT) movement and blossoming then into the object-oriented paradigm. The paper also discusses how it has been possible that a concept like ADTs, with its clear mathematical semantics, neat syntax, and straightforward implementation, can have given way to objects, a lot dirtier from any perspective the language theorist may take.

In another paper [45], the same author compares the notion of “type” as found in programming languages with that found in mathematical logic, pointing out also some important historical remarks such as the role of the Curry-Howard isomorphism. It is argued that there are three different characters at play in programming languages, all of them now called types: the technical concept used in language design to guide implementation; the general abstraction mechanism used as a modelling tool; the classifying tool inherited from mathematical logic.

Two further surveys concerns behavioural types. The successful application of behavioural types requires a solid understanding of several practical aspects, from their representation in a concrete programming language, to their integration with other programming constructs such as methods and functions, to design and monitoring methodologies that take behaviours into account. The survey [15] provides an overview of the state of the art of these aspects.

The behavioural type of a software component specifies its expected patterns of interaction using expressive type languages, so that types can be used to determine automatically whether the component interacts correctly with other components. Two related important notions of behavioural types are those of session types and behavioural contracts. The paper [24] surveys the main accomplishments of the last twenty years within these two approaches.

7.6.2. Subtyping and dualities in name-passing concurrency

The fusion calculi are simplifications of the π-calculus in which input and output are symmetric and restriction is the only binder. In [23], Hirschkoff et al. highlight a major difference between these calculi and the π-calculus from the point of view of types, proving some impossibility results for subtyping in fusion calculi. A modification of fusion calculi is then proposed that allows one to import subtype systems, and related results, from the π-calculus, and examine the consequences of such modifications on theory and expressiveness of the languages.

8. Partnerships and Cooperations

8.1. National Initiatives

- REVER (Programming Reversible Recoverable Systems) is an ANR project with a 4-year duration. REVER aims to study the possibility of defining semantically well-founded and composable abstractions for dependable computing on the basis of a reversible programming language substrate, where reversibility means the ability to undo any distributed program execution, possibly step by step. The critical assumption behind REVER is that by adopting a reversible model of computation, and by combining it with appropriate notions of compensation and modularity, one can develop systematic and composable abstractions for recoverable and dependable systems. Main persons involved: Giachino, Lanese, Laneve, Zavattaro.

- PACE (Processus non-standard: Analyse, Coinduction, et Expressivité) is an ANR project with a 4-year duration. The project targets three fundamental ingredients in theories of concurrent processes, namely coinduction, expressiveness, and analysis techniques. The project targets processes that are beyond the realm of "traditional" processes. Specifically, the models studied exhibit one or more of the following features: probabilities, higher-order, quantum, constraints, knowledge, and confidentiality. These models are becoming increasingly important for today's applications. Coinduction is intended to play a pivotal role. Indeed, the approaches to expressiveness and the analysis techniques considered in the project are based on coinductive equalities. Main persons involved: Hirschkoff (project coordinator), Dal Lago, Lanese, Sangiorgi, Zavattaro.
- ELICA (Expanding Logical Ideas for Complexity Analysis) is an ANR project that started on October 2014 and that will finish on September 2018. ELICA focuses on methodologies for the static analysis of programs and their resource consumption. The project's aim is 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, Cappai, Dal Lago, Hirschkoff, Martini, Sangiorgi.
- 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, Martini, 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.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

- ENVISAGE (Engineering Virtualized Services) is a EU FP7 project, with starting date October 1st, 2013, and with a 3-year duration. The project is about model-based development of virtualized services, including tool support for resource analysis. Most Focus members are involved.

8.2.2. Collaborations in European Programs, Except FP7 & H2020

- The ICT COST Action BETTY (Behavioural Types for Reliable Large-Scale Software Systems). initiated in October 2012 and with a 4-year duration, uses behavioural type theory as the basis for new foundations, programming languages, and software development methods for communication-intensive distributed systems. Behavioural type theory encompasses concepts such as interfaces, communication protocols, contracts, and choreographies. Main persons involved: Bravetti, Giachino, Hirschkoff, Lanese, Laneve, Mauro, Sangiorgi, Zavattaro.
- 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: Giachino, 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.
- SMAll (Smart Mobility for All) SMAll is an EIT project that runs during 2016.

  The aim of the project is to develop a service-oriented platform, called the SMAll platform [0], to support the creation of a liquid market for transportation, facilitating the publication, retrieval, and orchestration of functionalities for transportation, owned by different operators.

  Jolie plays a prominent part in the development of the SMAll platform: it is the main language for the development of both the platform — the architecture of services that support publishing, organisation, and interaction among the functionalities for transportation — and of the services for mobility.

8.2.3. Collaborations with Major European Organizations

Simone Martini is a member of the Executive Board of EQANIE (European Quality Assurance Network for Informatics Education), from October 2014.

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, Vignudelli. Some visit exchanges during the year, in both directions. A new joint PhD started in september 2016 (Adrien Durier).
- Inria EPI Spades (on models and languages for components, reversibility). 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. An Italian PhD student (Marco Solieri) is working on his PhD thesis with joint supervision (Martini, Guerrini).
- 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: Mauro, Zavattaro. Some short visits in both directions during the year.
- EPI Carte, Inria-Nancy Grand Est and LORIA (on implicit computational complexity). Contact person(s) in Focus: Dal Lago.
- LMU Munich (M. Hofmann) (on implicit computational complexity and IntML). Contact person(s) in Focus: Dal Lago.
- IMDEA Software, Madrid (G. Barthe) (on implicit computational complexity for cryptography). Contact person(s) in Focus: Dal Lago,Sangiorgi. 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.

[0] https://github.com/small-dev/SMAll.Wiki/wiki

8.3. International Initiatives

8.3.1. Inria Associate Teams Not Involved in an Inria International Labs

8.3.1.1. CRECOGI

Title: Concurrent, Resourceful and Effectful Computation, by Geometry of Interaction

International Partner (Institution - Laboratory - Researcher):

Tokyo (Japan) - Department of Computer Science, Graduate School of Information Science and Technology - Ichiro HASUO

Start year: 2015

See also: http://crecogi.cs.unibo.it

Game semantics and geometry of interaction (GoI) are two closely related frameworks whose strength is to have the characters of both a denotational and an operational semantics. They offer a high-level, mathematical (denotational) interpretation, but are interactive in nature. The formalization in terms of movements of tokens through which programs communicate with each other can actually be seen as a low-level program. The current limit of GoI is that the vast majority of the literature and of the software tools designed around it have a pure, sequential functional language as their source language. This project aims at investigating the application of GoI to concurrent, resourceful, and effectful computation, thus paving the way to the deployment of GoI-based correct-by-construction compilers in real-world software developments in fields like (massively parallel) high-performance computing, embedded and cyberphysical systems, and big data. The presence of both the japanese GoI community (whose skills are centered around effects and coalgebras) and the french GoI community (more focused on linear logic and complexity analysis) will bring essential, complementary, ingredients.

8.4. International Research Visitors

8.4.1. 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.

- Marco Bernardo: "Disjunctive Probabilistic Modal Logic is Enough for Bisimilarity on Reactive Probabilistic Systems."
- Guillermo Roman Diez: "Resource Analysis."
- Lukasz Mikulski: "On Concurrency Paradigms."
- Jean-Pierre Jouannaud: "Coq modulo theory."
- Paul Blain Levy: "Trace semantics of well-founded processes via commutativity."
- Akihisa Yamada: "Certifying Safety and Termination Proofs for Integer Transition Systems" (long visit).
- Ryo Tanaka: semantics of higher-order functional languages (long visit).
- Antonio Ravara: “Behavioural Type Inference for Object-Oriented Languages”.
- Lukasz Mikulski: "On concurrency paradigms".
- Ludovic Henrio, “Deadlock analysis in distributed object systems”.

8.4.2. Visits to International Teams

- Ugo Dal Lago: has spent two weeks in April at ENS Lyon, and 1 month at IRIF, Université Paris 7, in May/June.
- Charles Grellois has taken part in the programme "Automata, Logic and Games", 5 weeks (August-September), Singapore.
- Valeria Vignudelli has spent six months in the Inria Comète team, Inria Saclay/Ecole Polytechnique, Paris.
- Abel Garcia has spent 6 months at the Department of Computer Science, TUD Darmstadt.

8.4.2.1. Sabbatical programme

Maurizio Gabbrielli is, since 15 September 2014, Head of the EIT ICT Labs Doctoral School with Paris as his principal location.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

I. Lanese: Co-chair and local organizer for the 8th Conference on Reversible Computation (RC 2016), Bologna, July 7th-8th, 2016.

9.1.1.2. Chair of Conference Program Committees

I. Lanese: 36th IFIP International Conference on Formal Techniques for Distributed Objects, Components and Systems (FORTE 2016)

D. Sangiorgi: 43rd International Colloquium on Automata, Languages, and Programming (ICALP 2016), Rome, July 2016

9.1.1.3. Member of the Conference Program Committees

M. Bravetti: 5th European Conference on Service-Oriented and Cloud Computing (ESOCC 2016); 14th International Conference on Software Engineering and Formal Methods (SEFM 2016); 10th IEEE International Conference on Big Data Science and Engineering (IEEE BigDataSE 2016); 2016 IEEE International Conference on Big Data (IEEE BigData 2016) 32nd Symposium on Applied Computing, track on Software Verification and Testing (SAC-SVT 2016); 7th International Conference on Fundamentals of Software Engineering (FSEN 2017).

U. Dal Lago: 13th IFIP WG 1.3 International Workshop on Coalgebraic Methods in Computer Science (CMCS 2016); 1st International Conference on Formal Structures for Computation and Deduction (FSCD 2016); 15th International Workshop on Termination (WST 2016); 17th International Workshop on Logic and Computational Complexity (LCC 2016, Chair).

I. Lanese: 1st International Workshop on Pre- and Post-Deployment Verification Techniques (PrePost 2016); 9th Interaction and Concurrency Experience (ICE 2016); 25th European Symposium on Programming (ESOP 2016); Special Track on Microservices: Science and Engineering of the 9th IEEE International Conference on Service-Oriented Computing and Applications (MSE @ SOCA 2016).

S. Martini: DIDAMATICA - Informatica per la Didattica (DIDAMATICA 2016).

D. Sangiorgi: 10th International Conference on Language and Automata Theory and Applications (LATA'16).

V. Vignudelli: 9th Interaction and Concurrency Experience (ICE 2016).

G. Zavattaro: 21st International Symposium on Formal Methods (FM2016); 5th European Conference on Service-oriented and Cloud Computing (ESOCC'16); 27th International Conference on Concurrency Theory (CONCUR'16); 31st ACM/SIGAPP Symposium On Applied Computing - track on Software Verification and Testing (ACM-SAC 2016).

9.1.1.4. Member of the Editorial Boards

U. Dal Lago: Logical Methods 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).

The Scientific World Journal (Hindawi Publishing Corporation): editor till August 3, 2016

F. Montesi: Guest editor for "Special issue on Service-Oriented Architecture and Programming (SOAP 2013)". Science of Computer Programming.

D. Sangiorgi: Acta Informatica, Distributed Computing, RAIRO Theoretical Informatics and Applications.

9.1.2. Invited Talks

U. Dal Lago: gave an invited course "Implicit Complexity and the Curry-Howard Correspondence" at 'Days in Logic 2016', Lisboa, Portugal.

D. Hirschkoff: gave an invited course "Mechanised Coinductive Proofs" at East China Normal University (Shanghai, China), in november 2016 (a course mainly targeted towards master students).

S. Martini: gave the invited talk "Types in programming languages, between modelling, abstraction and correctness" at 'Computability in Europe' (Cie 2016), special session on History and Philosophy of Computing, Paris, June 2016.

G. Zavattaro: gave an invited course on cloud computing management at the 'Bertinoro International Spring School 2016' (BISS'16), Bertinoro, Italy, 6-11 March, 2016.

9.2. Teaching - Supervision - Juries

9.2.1. 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: “Cryptography”, 36 Hours, 2nd Year, University of Bologna, Italy.
- Daniel Hirschkoff

  Master: “Coinductive Methods in Computer Science”, 2nd year, Ecole Normale Supérieure de Lyon.
- Maurizio Gabbrielli

  Undergraduate: “Programming languages”, 40 hours, 2nd year, University of Bologna, Italy.

  Master: “Artificial Intelligence”, 60 hours, 2nd year, University of Bologna, Italy.
- Elena Giachino

  Undergraduate: “Programmazione”, 40 hours, 1st year, University of Bologna, Italy.
- Saverio Giallorenzo

  Undergraduate: “Laboratorio di Operating Systems”, 40 hours, 2nd year, University of Bologna, Italy.
- Ivan Lanese

  Undergraduate: “Programmazione”, 32 hours, 1st year, University of Bologna, Italy.

  Undergraduate: “Algoritmi e Strutture Dati”, 45 hours, 2nd 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: “Introduction to programming in Python”, 58 hours, 1st year, University of Bologna, Italy.

  Undergraduate: “Computer abilities for biologists”, 8 hours, 1st year, University of Bologna, Italy.

  Master: “Logical Foundations of Computer Science”, 48 hours, 2nd year, University of Bologna, Italy.
- Davide Sangiorgi

  Undergraduate: “Operating Systems”, 110 hours, 2nd year, University of Bologna, Italy.

  Master: “Models for concurrency”, 15 hours, 2nd year, University of Bologna, Italy.
- Marco Solieri

  Undergraduate: “UNIX system programming”, 48 hours, 3rd year, Université Paris Diderot

Undergraduate: “Network programming”, 48 hours, 3rd year, Université Paris Diderot

- Gianluigi Zavattaro

  Undergraduate: “Computer Architectures”, 60 hours, 1st year, University of Bologna, Italy

  Undergraduate: “Programming Languages”, 60 hours, 2nd year, University of Bologna, Italy

9.2.2. Supervision

PhD thesis completed in 2016:

- Alberto Cappai, " On Equivalences, Metrics, and Computational Indistinguishability", University of Bologna, April 2016.
- Alessandro Rioli, " Coinductive Techniques on a Linear Quantum λ-calculus", University of Bologna, April 2016.
- Marco Solieri, “Sharing, Superposition and Expansion — Geometrical Studies on the Semantics and Implementation of λ-calculi and Proof-Nets”, S. Guerrini (Paris Nord) and S. Martini. [11].
- Saverio Giallorenzo, “Real-World Choreographies”, University of Bologna, April 2016 [10].

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.

- 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.
- Abel Garcia, January 2014, “Analysis of Cloud Computing Systems”. Supervisor C. Laneve.
- Francesco Gavazzo, October 2015, “Coinductive Techniques for Effectful Lambda Calculi”. Supervisors U. Dal Lago and D. Sangiorgi.
- Raphaelle Crubillé, October 2015, “Bisimulation Metrics and Probabilistic Lambda Calculi”, Université Denis Diderot and University of Bologna. Supervisors Thomas Ehrhard and Ugo Dal Lago.
- Vincenzo Mastandrea, October 2015, “Deadlock analysis in ASP”. Supervisors Cosimo Laneve and Ludovic Henrio (CNRS Sophia Antipolis).
- Valeria Vignudelli, January 2014, “Probabilities in Higher-Order languages”. Supervisor D. Sangiorgi.

9.2.3. Juries

U. Dal Lago has been member of the PhD evaluation committee for Charles Grellois (April 2016, Université Paris 7), and Thomas Leventis (December 2016, Université Aix-Marseille).

D. Hirschkoff has been referee (rapporteur) for the Habilitation à Diriger les Recherches of Nicolas Tabareau, Université de Nantes), November 2016, and member of the PhD committee of Martin Bodin (Université Rennes 1), Nov. 25, 2016.

S. Martini has been supervisor and member of the PhD evaluation committee for Marco Solieri (Université Paris 13 and Università di Bologna).

G. Zavattaro: has been member of the PhD jury of Laura Nenzi and Andrea Morichetta, IMT Lucca, Italy, July 2016.

9.3. Popularization

Simone Martini has carried out extended work of scientific divulgation, including

- member of the technical committee of Olimpiadi del Problem Solving (at Italian Ministry of Education), http://www.olimpiadiproblemsolving.com;
- invited talks ("Il pensiero computazionale spiegato ai manager", given at 'Il codice del futuro', Teatro anatomico dell'Archiginnasio, Bologna, May 2016, and "Pensare computazionale: una quarta competenza dopo scrivere, leggere e far di conto", given at 'Trasformazioni sociali e trasmissione delle conoscenze nell'Università italiana', Bologna, November 2016);
- various talks at institutes and workshops on the teaching methods for Computer Science;
- coordinator of some initiatives for the 'Hour of Code', see https://italia.code.org/ and http://www.programmailfuturo.it.

D. Hirschkoff takes part in several popularization activities in schools, in Lyon (association "Maths en Jeans").

9.3.1. Other duties

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.

S. Martini has been elected Head of the Department of Computer Science and Engineering, University of Bologna, for the term 2015-2018.

D. Sangiorgi has been coordinator of undergraduate studies at the Department of Computer Science and Engineering, University of Bologna (Informatica per il Management), till October 2016, when G. Zavattaro has taken over from him.

10. 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, https://hal.inria.fr/hal-00906347/en.

[7] I. Lanese, C. A. Mezzina, A. Schmitt, J.-B. Stefani.*Controlling Reversibility in Higher-Order Pi*, in "Proc. of CONCUR 2011", J.-P. Katoen, B. König (editors), Lecture Notes in Computer Science, Springer, 2011, vol. 6901, p. 297-311, http://www.cs.unibo.it/~lanese/publications/fulltext/concur2011.pdf.gz.

[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

Doctoral Dissertations and Habilitation Theses

[10] S. GIALLORENZO.*Real-World Choreographies*, Università degli studi di Bologna, May 2016, https://hal.inria.fr/tel-01336757.

[11] M. SOLIERI.*Sharing, Superposition and Expansion: Geometrical Studies on the Semantics and Implementation of λ-calculi and Proof-nets*, Université Paris XIII, Sorbonne Paris Cité ; Università di Bologna, November 2016, https://hal.archives-ouvertes.fr/tel-01400369.

Articles in International Peer-Reviewed Journal

[12] B. ACCATTOLI, U. DAL LAGO.*(Leftmost-outermost) beta reduction is invariant, indeed*, in "Logical Methods in Computer Science", 2016 [*DOI :* 10.2168/LMCS-12(1:4)2016], https://hal.inria.fr/hal-01337712.

[13] R. AMADINI, M. GABBRIELLI, J. MAURO.*An Extensive Evaluation of Portfolio Approaches for Constraint Satisfaction Problems*, in "International Journal of Interactive Multimedia and Artificial Intelligence", 2016, https://hal.inria.fr/hal-01336684.

[14] R. AMADINI, M. GABBRIELLI, J. MAURO.*Portfolio Approaches for Constraint Optimization Problems*, in "Annals of Mathematics and Artificial Intelligence", 2016, https://hal.inria.fr/hal-01336686.

[15] D. ANCONA, V. BONO, M. BRAVETTI, J. CAMPOS, G. CASTAGNA, P.-M. DENIÉLOU, S. J. GAY, N. GESBERT, E. GIACHINO, R. HU, E. B. JOHNSEN, F. MARTINS, V. MASCARDI, F. MONTESI, R. NEYKOVA, N. NG, L. PADOVANI, V. T. VASCONCELOS, N. YOSHIDA.*Behavioral Types in Programming Languages*, in "Foundations and Trends in Programming Languages", July 2016, vol. 3, n^{o} 2-3, p. 95-230 [*DOI :* 10.1561/2500000031], https://hal.inria.fr/hal-01348054.

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[20] U. DAL LAGO, S. MARTINI, D. SANGIORGI.*Light Logics and Higher-Order Processes*, in "Mathematical Structures in Computer Science", 2016, vol. 26, n^{o} 06, p. 969 - 992 [*DOI :* 10.1017/S0960129514000310], https://hal.inria.fr/hal-01400903.

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[28] E. ALBERT, F. DE BOER, R. HÄHNLE, E. B. JOHNSEN, C. LANEVE.*Envisage: Developing SLA-aware Deployed Services with Formal Methods*, in "ESOCC 2016:Fifth European Conference on Service-Oriented and Cloud Computing", Wien, Austria, September 2016, https://hal.inria.fr/hal-01345020.

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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:

3.1.4. - Uncertain data
5. - Interaction, multimedia and robotics
5.1. - Human-Computer Interaction
5.1.1. - Engineering of interactive systems
5.1.2. - Evaluation of interactive systems
5.3.5. - Computational photography
5.4.4. - 3D and spatio-temporal reconstruction
5.5. - Computer graphics
5.5.1. - Geometrical modeling
5.5.2. - Rendering
5.5.3. - Computational photography
5.6. - Virtual reality, augmented reality
5.9.1. - Sampling, acquisition
6.3.5. - Uncertainty Quantification
7.5. - Geometry, Topology
8.2. - Machine learning
8.3. - Signal analysis

Other Research Topics and Application Domains:

5. - Industry of the future
5.2. - Design and manufacturing
5.7. - 3D printing
8. - Smart Cities and Territories
8.3. - Urbanism and urban planning
9. - Society and Knowledge
9.1.2. - Serious games
9.2. - Art
9.2.2. - Cinema, Television
9.2.3. - Video games
9.5. - Humanities
9.5.6. - Archeology, History

1. Members

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Adrien Bousseau [Inria, Research Scientist, HDR]

Technical Staff

Georgios Kopanas [Inria, until Aug 2016]
Sebastien Bonopera [Inria, from Sept 2015 to Sept 2016]

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Johanna Delanoy [Inria]
Valentin Deschaintre [Optis, from Nov 2016, CIFRE funding]
Rodrigo Ortiz Cayon [Inria, until Nov 2016]
Julien Philip [Inria, from Nov 2016, EU H2020 EMOTIVE funding]
Simon Rodriguez [UCA (University), from Nov 2016]
Theo Thonat [Inria]

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Abdelaziz Djelouah [Inria]
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Eugene Fiume [University of Toronto, from Jul 2016]
Miika Aittala [MIT/Aaalto University, from Nov 2016]

Administrative Assistant

Sophie Honnorat [Inria]

Others

Sai Praveen Bangaru [Inria, Intern, from May 2016 until Jul 2016]
Srinivasa Rao Gadhamchetty [Inria, Intern, from May 2016 until Jul 2016]
Amelie Fondevilla [Inria, Intern, from Feb 2016 to Jul 2016]

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.

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.

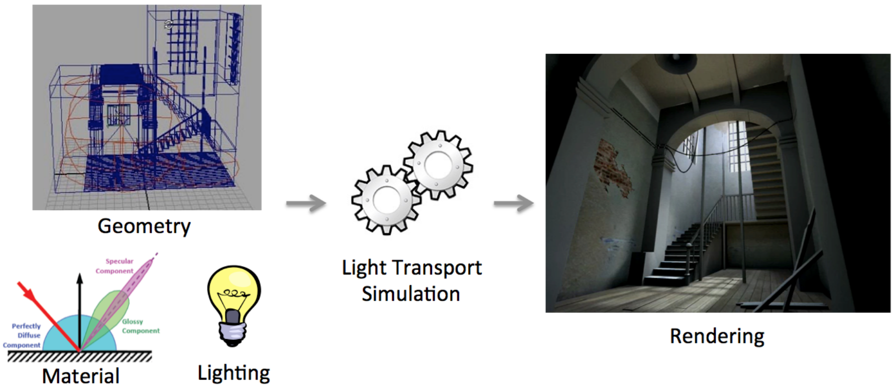


Figure 1. Traditional computer graphics pipeline. Rendering from www.thegnomonworkshop.com

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.

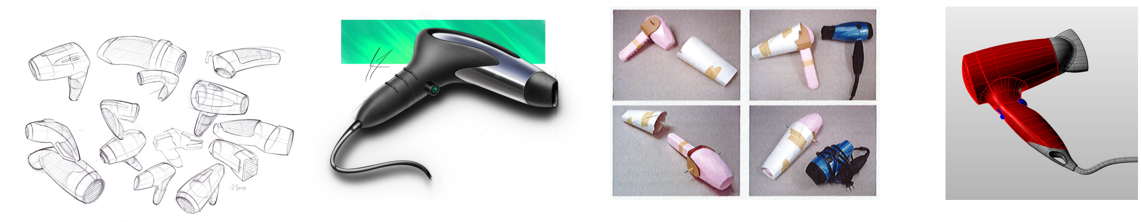
3. Research Program

3.1. Introduction

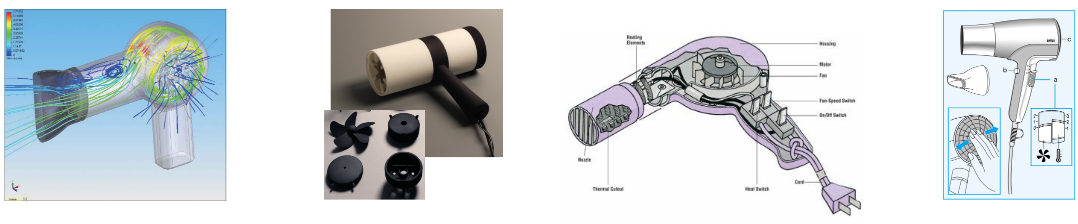
Our research program is oriented around two main axes: 1) Computer-Assisted Design with Heterogeneous Representations and 2) Graphics with Uncertainty and Heterogeneous Content. These two axes are governed by a set of common fundamental goals, share many common methodological tools and are deeply intertwined 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

In addition to publications in the leading conferences and journals in computer graphics (3 ACM Transactions on Graphics [5], [6], [8], 1 IEEE Virtual Reality), we made notable contributions to related fields such as human-computer interaction (1 ACM Conference on Human Factors in Computing Systems - CHI [9]) and computer vision (3 papers presented at the International Conference on 3DVision [13], [12], [10]). Several of these results were developed in the context of the CR-Play project, which was completed in November with excellent reviews.

4.1.1. Awards

Adrien Bousseau received a Young Researcher Award from the French National Research Agency (ANR) for the project ANR DRAO.

Adrien Bousseau obtained an ERC Starting Grant funding, the project will start in February 2017.

5. New Software and Platforms

5.1. SWARPI-Unity

SWARPI-Unity (for Superpixel Warp for Image-based rendering for Unity)
This is a software module developed in collaboration with Testaluna in the context of the CR-PLAY EU project. It involves an implementation of the Image-Based rendering algorithms of the group in the Unity3D framework. The software was improved this year to support mobile Android devices and was used in the evaluation step of the CR-PLAY project and for multiple demos.

- Participants: Sebastien Bonopera, Jerome Esnault, George Drettakis and Gaurav Chaurasia
- Contact: George Drettakis

5.2. SIBR

SIBR (for Simple Image-Based Rendering)
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. This new framework replaces the previously used IBR-COMMON tools.

- Participants: George Drettakis, Abdelaziz Djelouah, Rodrigo Ortiz Canyon, Theo Thonat, Sebastien Bonopera
- Contact: George Drettakis

5.3. MVIIR

MVIIR (for Multi-View Image Intrinsic Images and Relighting)
This package is the software implementation of the intrinsic image algorithm of Duchêne et al. It includes two libraries; one general-purpose that can be used to augment the functionalities of the previously mentioned SIBR framework, and another for specific logic concerning the relighting task. This package includes also programs to compute preprocess data required for the relighting of a dataset.

- Participants: George Drettakis, Sebastien Bonopera, Adrien Bousseau
- Contact: George Drettakis

5.4. SGTDGP

SGTDGP (for Synthetic Ground Truth Data Generation Platform)
We have started the development of a ground truth data generation platform based on complex and realistically rendered scenes built in 3D modelling packages such as 3DS Max. The platform includes an export module from 3DSMax with support for complex materials and shade trees such as those developed for the physically based rendering VRay platform. This module exports to the Mitsuba opensource renderer, and includes support for various operations using Mitsuba, as well as rendering on the Inria cluster. The platform is designed to generate ground truth data for learning as well as data for ground truth comparisons for image-based rendering projects in the group.

- Participants: George Drettakis, George Kopanas, Sai Bangaru
- Contact: George Drettakis

6. New Results

6.1. Computer-Assisted Design with Heterogeneous Representations

6.1.1. How Novices Sketch and Prototype Hand-Fabricated Objects

Participant: Adrien Bousseau.

We are interested in how to create digital tools to support informal sketching and prototyping of physical objects by novices. Achieving this goal first requires a deeper understanding of how non-professional designers generate, explore, and communicate design ideas with traditional tools, i.e., sketches on paper and hands-on prototyping materials. We conducted a study framed around two all-day design charrettes where participants perform a complete design process: ideation sketching, concept development and presentation, fabrication planning documentation and collaborative fabrication of hand-crafted prototypes (Figure 4). This structure allows us to control key aspects of the design process while collecting rich data about creative tasks, including sketches on paper, physical models, and videos of collaboration discussions. Participants used a variety of drawing techniques to convey 3D concepts. They also extensively manipulated physical materials, such as paper, foam, and cardboard, both to support concept exploration and communication with design partners. Based on these observations, we propose design guidelines for CAD tools targeted at novice crafters.

This work is a collaboration with Theophanis Tsandilas, Lora Oehlberg and Wendy Mackay from the ExSitu group, Inria Saclay. It has been published at ACM Conference on Human Factors in Computing Systems (CHI) 2016 [9].

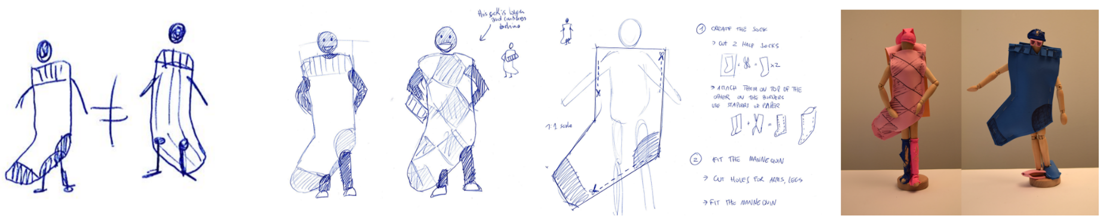


Figure 4. We asked participants to design a costume, from an initial sketch to a physical prototype.

6.1.2. Interactive Sketching of Urban Procedural Models

Participant: Adrien Bousseau.

3D modeling remains a notoriously difficult task for novices despite significant research effort to provide intuitive and automated systems. We tackle this problem by combining the strengths of two popular domains: sketch-based modeling and procedural modeling. On the one hand, sketch-based modeling exploits our ability to draw but requires detailed, unambiguous drawings to achieve complex models. On the other hand, procedural modeling automates the creation of precise and detailed geometry but requires the tedious definition and parameterization of procedural models. Our system uses a collection of simple procedural grammars, called snippets, as building blocks to turn sketches into realistic 3D models. We use a machine learning approach to solve the inverse problem of finding the procedural model that best explains a user sketch. We use non-photorealistic rendering to generate artificial data for training convolutional neural networks capable of quickly recognizing the procedural rule intended by a sketch and estimating its parameters. We integrate our algorithm in a coarse-to-fine urban modeling system that allows users to create rich buildings by successively sketching the building mass, roof, facades, windows, and ornaments (Figure 5). A user study shows that by using our approach non-expert users can generate complex buildings in just a few minutes.

This work is a collaboration with Gen Nishida, Ignacio Garcia-Dorado, Daniel G. Aliaga and Bedrich Benes from Purdue University. It has been published at ACM Transactions on Graphics (proc. SIGGRAPH) 2016 [8].

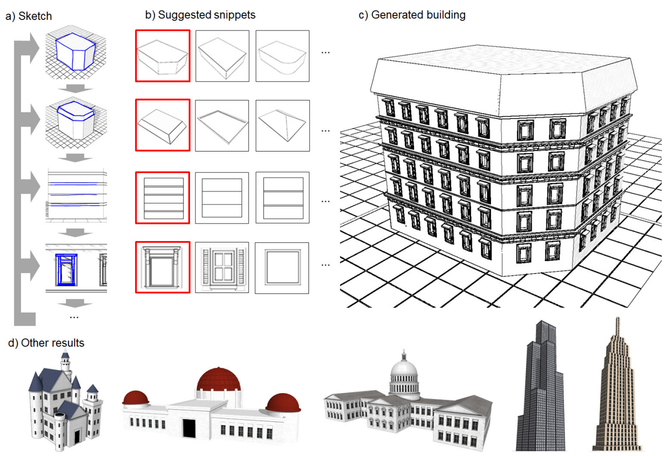


Figure 5. Our system allows novices to quickly create complex procedural 3D models of buildings by sketching.

6.1.3. Fidelity vs. Simplicity: a Global Approach to Line Drawing Vectorization

Participant: Adrien Bousseau.

Vector drawing is a popular representation in graphic design because of the precision, compactness and editability offered by parametric curves. However, prior work on line drawing vectorization focused solely on faithfully capturing input bitmaps, and largely overlooked the problem of producing a compact and editable curve network. As a result, existing algorithms tend to produce overly-complex drawings composed of many short curves and control points, especially in the presence of thick or sketchy lines that yield spurious curves at junctions. We propose the first vectorization algorithm that explicitly balances fidelity to the input bitmap with simplicity of the output, as measured by the number of curves and their degree. By casting this trade-off as a global optimization, our algorithm generates few yet accurate curves, and also disambiguates curve topology at junctions by favoring the simplest interpretations overall. We demonstrate the robustness of our algorithm on a variety of drawings, sketchy cartoons and rough design sketches (Figure 6).

The first author of this work, Jean-Dominique Favreau, is co-advised by Adrien Bousseau and Florent Lafarge (Titane team). The work was published at ACM Transactions on Graphics (proc. SIGGRAPH) 2016 [5].

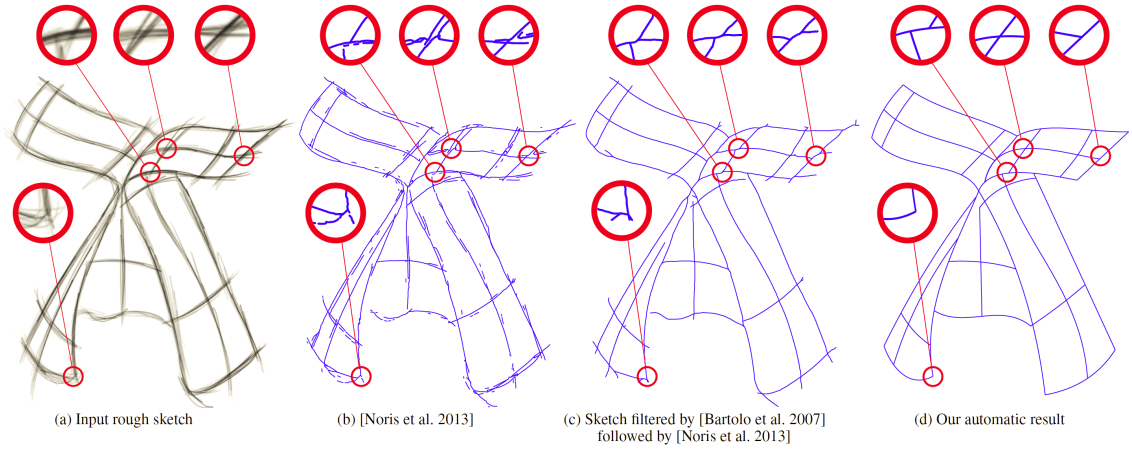


Figure 6. Rough sketches often contain overlapping strokes (a), which existing vectorization algorithms represent as multiple curves (b). Pre-filtering the drawing improves the vectorization, but produces spurious curve segments at junctions (c). Since existing algorithms analyze junctions locally, they cannot recover the proper topology of these seemingly similar line configurations. By adopting a global formulation that optimizes for both fidelity to the input sketch and simplicity of the output curve network, our algorithm recovers proper topology while significantly reducing the overall number of curves and control points. Design sketch after Sori Yanagi's "Butterfly" stool.

6.1.4. SketchSoup: Exploratory Ideation using Design Sketches

Participant: Adrien Bousseau.

A hallmark of early stage design is a number of quick-and-dirty sketches capturing design inspirations, model variations, and alternate viewpoints of a visual concept. We present SketchSoup, a workflow that allows designers to explore the design space induced by such sketches. We take an unstructured collection of drawings as input, register them using a multi-image matching algorithm, and present them as a 2D interpolation space (Figure 7). By morphing sketches in this space, our approach produces plausible visualizations of shape and viewpoint variations despite the presence of sketch distortions that would prevent standard camera calibration and 3D reconstruction. In addition, our interpolated sketches can serve as inspiration for further drawings, which feed back into the design space as additional image inputs. SketchSoup thus fills a significant gap in the early ideation stage of conceptual design by allowing designers to make better informed choices before proceeding to more expensive 3D modeling and prototyping. From a technical standpoint, we describe an end-to-end system that judiciously combines and adapts various image processing techniques to the drawing domain – where the images are dominated not by color, shading and texture, but by sketchy stroke contours.

This work is a collaboration with Rahul Arora and Karan Singh from University of Toronto and Vinay P. Namboodiri from IIT Kampur. The project was initiated while Rahul Arora was an intern in our group. It will be published in Computer Graphics Forum in 2017.

6.1.5. Modeling Symmetric Developable Surfaces from a Single Photo

Participants: Amelie Fondevilla, Adrien Bousseau.

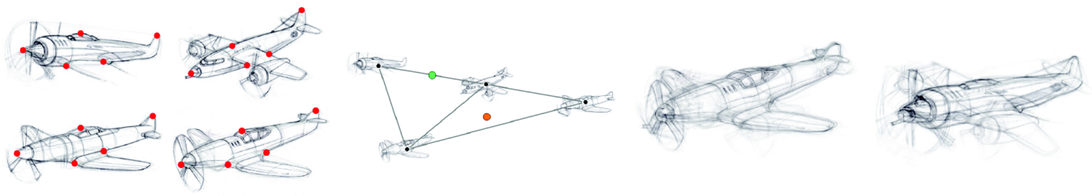


Figure 7. SketchSoup takes an unstructured set of sketches as input, along with a small number of correspondences (shown as red dots), registers the sketches and embeds them into a 2D interpolation space based on their shape differences. Users can explore the interpolation space to generate novel sketches.

We propose to reconstruct 3D developable surfaces from a single 2D drawing traced and annotated over a side-view photo of a partially symmetrical object (Figure 8). Our reconstruction algorithm combines symmetry and orthogonality shapes cues within a unified optimization framework that solves for the 3D position of the Bézier control points of the drawn curves while being tolerant to drawing inaccuracy and perspective distortions. We then rely on existing surface optimization methods to produce a developable surface that interpolates our 3D curves. Our method is particularly well suited for the modeling and fabrication of fashion items as it converts the input drawing into flattened developable patterns ready for sewing.

This work is a collaboration with Damien Rohmer, Stefanie Hahmann and Marie-Paule Cani from the Imagine team (LJK/ Inria Grenoble Rhône Alpes). This work was presented at the AFIG French conference in November 2016, where it received the 3rd price for best student work.

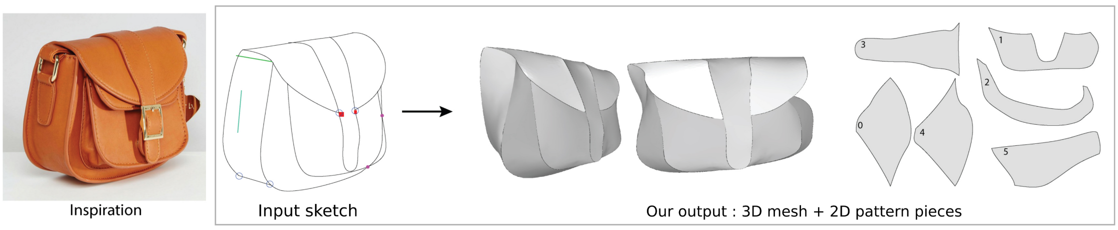


Figure 8. Our method reconstructs a 3D mesh and 2D pattern pieces of a sewed object from a single annotated drawing.

6.1.6. DeepSketch: Sketch-Based Modeling using 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. 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. It is supported by the CRISP Inria associate team.

6.2. Graphics with Uncertainty and Heterogeneous Content

6.2.1. Cotemporal Multi-View Video Segmentation

Participants: Abdelaziz Djelouah, George Drettakis.

We address the problem of multi-view video segmentation of dynamic scenes in general and outdoor environments with possibly moving cameras. Multi-view methods for dynamic scenes usually rely on geometric calibration to impose spatial shape constraints between viewpoints. In this work, we show that the calibration constraint can be relaxed while still getting competitive segmentation results using multi-view constraints. We introduce new multi-view cotemporality constraints through motion correlation cues, in addition to common appearance features used by cosegmentation methods to identify co-instances of objects. We also take advantage of learning based segmentation strategies by casting the problem as the selection of monocular proposals that satisfy multi-view constraints. This yields a fully automated method that can segment subjects of interest without any particular pre-processing stage (see Fig. 9). Results on several challenging outdoor datasets demonstrate the feasibility and robustness of our approach.

This work is a collaboration with Jean-Sébastien Franco and Edmond Boyer from Morpheo team at Inria Grenoble, and Patrick Pérez from Technicolor. The work has been published in the International Conference on 3D Vision (3DV) - 2016 [10].

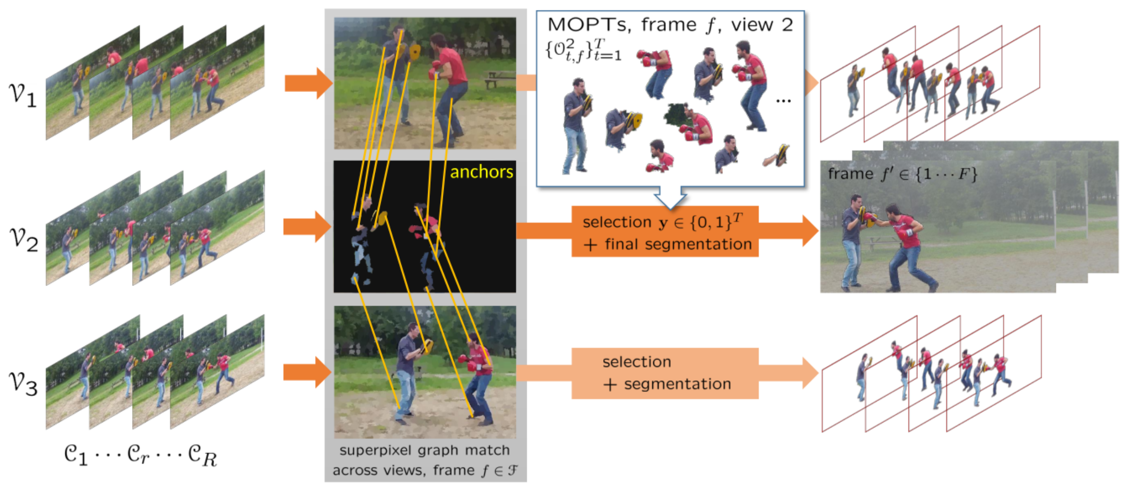


Figure 9. Synchronized videos of the same scene are partitioned into short clips. At a small number of instants where motion is sufficiently informative, cross-view correspondences between with similar appearance and motion are obtained by graph matching. In each view, matched superpixels, which are likely to lie on moving foreground objects, are used as sparse anchors to guide the selection process among a large pool of moving objects proposals extracted from all clips.

6.2.2. Automatic 3D Car Model Alignment for Mixed Image-Based Rendering

Participants: Rodrigo Ortiz Cayon, Abdelaziz Djelouah, George Drettakis.

We present a method that improves quality of Image-Based Rendering of poorly reconstructed objects. We focus on the case of reflective objects which are hard to reconstruct, such as cars. The key insight is to replace these poorly reconstructed objects with models from existing rich 3D CAD databases, and subsequently align them to the input images. We use deep learning-based algorithms to obtain the 3D model present in the databases which is closest to the object seen in the images. We formulate two optimizations using all available information to finely position and orient the model and adapt it to image contours (see Fig. 10(1.)). Our method provides much higher quality rendering results of such objects compared to previous solutions as seen in Fig. 10(2.(b)).

This work is a collaboration with Francisco Massa and Mathieu Aubry from École des Ponts ParisTech. The work was published in the International Conference in 3D Vision (3DV) - 2016 [12].

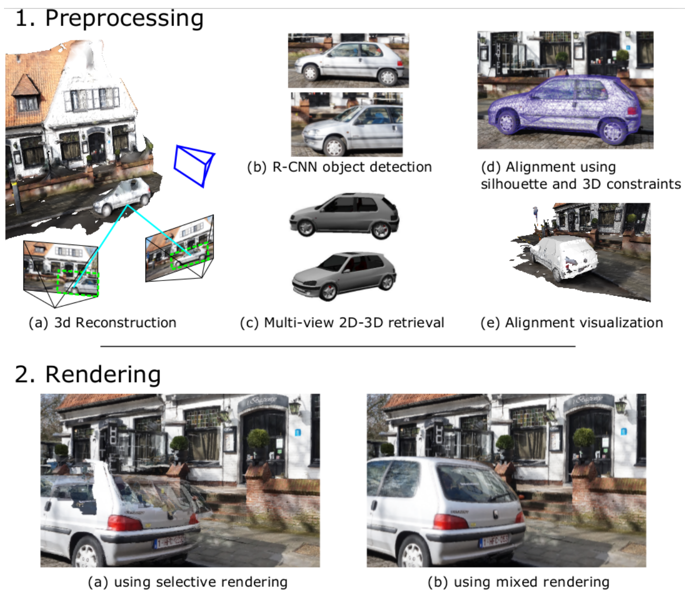


Figure 10. Overview of our pre-processing and rendering pipeline for Mixed Image-Based Rendering.

6.2.3. Multi-View Inpainting for Image-Based Scene Editing and Rendering

Participants: Theo Thonat, George Drettakis.

We propose a method to remove objects such as people and cars from multi-view urban image datasets (Figure 11), enabling free-viewpoint Image-Based Rendering (IBR) in the edited scenes. Our method combines information from multi-view 3D reconstruction with image inpainting techniques, by formulating the problem as an optimization of a global patch-based objective function. We use IBR techniques to reproject information from neighboring views, and 3D multi-view stereo reconstruction to perform multi-view coherent initialization for inpainting of pixels not filled by reprojection. Our algorithm performs multi-view consistent inpainting for color and 3D by blending reprojections with patch-based image inpainting. We run our algorithm on casually captured datasets, and Google Street View data, removing objects such as cars, people and pillars, showing that our approach produces results of sufficient quality for free-viewpoint IBR on "cleaned up" scenes, as well as IBR scene editing, such as limited displacement of real objects.

This work is a collaboration with Eli Shechtman and Sylvain Paris from Adobe Research. It has been published in the International Conference on 3D Vision (3DV) - 2016 [13].

Figure 11. Our system takes as input a set of images from the same scene (top row). The method then removes all the vehicules in a multi-view coherent way (bottom row).

6.2.4. Gaze Prediction using Machine Learning for Dynamic Stereo Manipulation in Games

Participants: George Koulieris, George Drettakis.

Comfortable, high-quality 3D stereo viewing has become a requirement for interactive applications. Previous research shows that manipulating disparity can alleviate some of the discomfort caused by 3D stereo, but it is best to do this locally, around the object the user is gazing at. The main challenge is thus to develop a gaze predictor in the demanding context of real-time, heavily task-oriented applications such as games. Our key observation is that player actions are highly correlated with the present state of a game, encoded by game variables. Based on this, we trained a classifier to learn these correlations using an eye-tracker which provides the ground-truth object being looked at. The classifier is used at runtime to predict object category – and thus gaze – during game play, based on the current state of game variables. We used this prediction to propose a dynamic disparity manipulation method, which provided rich and comfortable depth. We evaluated the quality of our gaze predictor numerically and experimentally, showing that it predicts gaze more accurately than previous approaches. A subjective rating study demonstrates that our localized disparity manipulation is preferred over previous methods.

This work is a collaboration with Katerina Mania from the Technical University of Crete and Douglas Cunningham from the Technical University of Cottbus. The work was presented at the IEEE conference for Virtual Reality (IEEE VR) 2016 [14].

6.2.5. A Feasibility Study with Image-Based Rendered Virtual Reality in Patients with Mild Cognitive Impairment

Participant: George Drettakis.

Figure 12. We propose a gaze predictor (a), used to perform localized stereo grading (b). We compare to no stereo grading (c) and prior work (d). We provide rich and comfortable depth. Please use red/cyan anaglyph glasses.

Virtual Reality (VR) has emerged as a promising tool in many domains of therapy and rehabilitation, and has recently attracted the attention of researchers and clinicians working with elderly people with MCI, Alzheimer's disease and related disorders. In this study we tested the feasibility of using highly realistic image-based rendered VR with patients with MCI and dementia. We designed an attentional task to train selective and sustained attention, and we tested a VR and a paper version of this task (see Fig. 13) in a single-session within-subjects design. Results showed that participants with MCI and dementia reported to be highly satisfied and interested in the task, and they reported high feelings of security, low discomfort, anxiety and fatigue. In addition, participants reported a preference for the VR condition compared to the paper condition, even if the task was more difficult. Interestingly, apathetic participants showed a preference for the VR condition stronger than that of non-apathetic participants. These findings suggest that VR-based training can be considered as an interesting tool to improve adherence to cognitive training for elderly people with cognitive impairment.

This work was a collaboration with EA CoBTek/IA, CMRR (memory center) of the CHU (University Hospital) of Nice, Disney Research and Trinity College Dublin, as part of the (completed) VERVE EU project. The work was published in the PLoS ONE journal [7].

6.2.6. Scalable Inside-Out Image-Based Rendering

Participant: George Drettakis.

The goal of this project was to provide high-quality free-viewpoing rendering of indoors environments. captured with off-the-shelf equipment such as a high-quality color camera and a commodity depth sensor. Image-based Rendering (IBR) can provide the realistic imagery required at real-time speed. For indoor scenes however, two challenges are especially prominent. First, the reconstructed 3D geometry must be compact, but faithful enough to respect occlusion relationships when viewed up close. Second, man-made materials call for view-dependent texturing, but using too many input photographs reduces performance.

We customize a typical RGB-D 3D surface reconstruction pipeline to produce a coarse global 3D surface, and local, per-view geometry for each input image. Our tiled IBR preserves quality by economizing on the expected contributions that entire groups of input pixels make to a final image. The two components are designed to work together, giving real-time performance, while hardly sacrificing quality. Testing on a variety of challenging scenes shows that our inside-out IBR scales favorably with the number of input images.

This work was a collaboration with P. Hedman, G. Brostow and T. Ritschel at UCL, as part of the CR-PLAY project. It was published in ACM Transactions on Graphics (Proc. SIGGRAPH Asia) [6].

6.2.7. Measuring Accommodation and Comfort in Head-Mounted Displays

Participants: George Koulieris, George Drettakis.

Head-mounted displays (HMDs) are rapidly becoming the preferred display for stereo viewing in virtual environments, but they often cause discomfort and even sickness. Previous studies have shown that a major cause of these adverse symptoms is the vergence-accommodation (VA) conflict. Specifically, the eyes use

Figure 13. The VR and paper conditions of the study

Figure 14. Images from our method rendered in 1080p at 55 Hz on an Nvidia Titan X GPU. Input is an RGB-D video and 298 high-quality photos of 'Dr Johnson's house', London. With no wheelchair access to this floor, curators were keen to have their rooms digitized.

the distance to the screen to accommodate, while they use the distance to the fixated virtual object to converge. The VA conflict is the difference between those distances. The magnitude of the conflict is well correlated with subjective reports of discomfort. Many methods have been proposed for reducing the VA conflict and thereby reducing discomfort by making accommodation more consistent with vergence. But no one has actually measured accommodation in HMDs to see how well a given method is able to drive it to the desired distance. We built the first device for measuring accommodation in an HMD, using a modular design with off-the-shelf components, focus-adjustable lenses, and an autorefractor. We conducted experiments using the device to determine how well accommodation is driven with various combinations of HMD properties and viewing conditions: focus-adjustable lenses, depth-of-field rendering, binocular viewing, and “monovision" (setting the two eyes’ focal distances to quite different values). We found that focus-adjustable lenses drive accommodation appropriately across many conditions. The other techniques were much less effective in driving accommodation. We also investigated whether the ability to drive accommodation predicts viewer comfort. We did this by conducting a discomfort study with most of the conditions in the accommodation study. We found that the ability to drive accommodation did in fact predict the amount of discomfort. Specifically, the most comfortable conditions were the ones that generated accommodation consistent with vergence. Together, these results illustrate the potential benefit of focus-adjustable lenses: They enable stimulation of accommodation and thereby comfortable viewing. In contrast, monovision neither enable accurate accommodation nor comfortable viewing.

This work is an ongoing collaboration with Martin S. Banks from UC Berkeley, in the context of the CRISP Inria associate team.

6.2.8. Beyond Gaussian Noise-Based Texture Synthesis

Participants: Kenneth Vanhoey, Georgios Kopanas, George Drettakis.

Texture synthesis methods based on noise functions have many nice properties: they are continuous (thus resolution-independent), infinite (can be evaluated at any point) and compact (only functional parameters need to be stored). A good method is also non-repetitive and aperiodic. Current techniques, like Gabor Noise, fail to produce structured content. They are limited to so-called “Gaussian textures”, characterized by second-order statistics like mean and variance only. This is suitable for noise-like patterns (e.g., marble, wood veins, sand) but not for structured ones (e.g., brick wall, mountain rocks, woven yarn). Other techniques, like Local Random-Phase noise, leverage some structure but as a trade-off with repetitiveness and periodicity.

In this project, we model higher-order statistics produced by noise functions in a parametric model. Then we define an algorithm for sampling of the noise functions’ parameters so as to produce a texture that meets prescribed statistics. This sampling ensures both the reproduction of higher-order visual features with high probability, like edges and ridges, and non-repetitiveness plus aperiodicity thanks to the stochastic sampling method. Moreover a (deep) learning algorithm has been established to infer the prescribed statistics from an input examplar image.

This project is a collaboration with Ian H. Jermyn (Durham University, UK, former Inria) and Mathieu Aubry (ENPC, France).

6.2.9. Fences in Image Based Rendering

Participants: Abdelaziz Djelouah, Frederic Durand, George Drettakis.

One of the key problem in Image Based Rendering (IBR) methods is the rendering of regions with incorrect 3D reconstruction. Some methods try to overcome the issue in the case of reflections and transparencies trough the estimation of two planes or the usage of 3D stock models. Fences with their thin repetitive structures are another important common source of 3D reconstruction errors but have received very little attention in the context of image based rendering. They are present in most urban pictures and represent a standard failure case for reconstruction algorithms, and state of the art rendering methods exhibit strong artifacts.

In this project, we propose to detect and segment fences in urban pictures for IBR applications. Similarly to related methods in image *de-fencing*, we use the assumptions that fences are thin repetitive structures lying on a 3D plane. To address this problem we consider the following steps: First we propose a multi-view approach to estimate the plane supporting the fences using repetition candidates. Second, we estimate image matting taking advantage of the multi-view constraints and the repetitive patterns. Finally, the estimated 3D plane and matting masks are used in a new rendering algorithm.

6.2.10. Handling reflections in Image-Based Rendering

Participants: Theo Thonat, Frederic Durand, George Drettakis.

In order to render new viewpoints, current Image Based Rendering techniques (IBR) use an approximate geometry to warp and blend photographs from close viewpoints. They assume the scene materials are diffuse, so geometry colors are independent of the viewpoint, an assumption that fails in the case of specular surfaces such as windows. Dealing with reflections in an IBR context first requires identifying what are the diffuse and the specular color layers in the input images. The challenge is then to correctly warp the specular layers since their associated geometry is not available and since the normals of the reflective surfaces might be not reliable.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. Optis

Participants: Valentin Deschaintre, Adrien Bousseau, George Drettakis.

Valentin Deschaintre is starting a CIFRE PhD in collaboration with Optis, a company specialized in material acquisition and rendering.

7.2. Bilateral Grants with Industry

7.2.1. Technicolor

Participants: George Drettakis, Adrien Bousseau.

We have initiated a collaboration with Technicolor on the use of deep learning for computational photography and video tasks. This will involve the use of our synthetic ground truth data generation platform (see Sec. 5.4) to tasks such as color grading and white balance. This is a collaboration with P. Pérez and E. Reinhard of Technicolor.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

8.1.1.1. ANR DRAO

Participant: Adrien Bousseau.

https://www-sop.inria.fr/members/Adrien.Bousseau/drao/

The ANR DRAO is a young researcher project coordinated by Adrien Bousseau, in collaboration with the InSitu project team at Inria Saclay - Ile de France (W. Mackay and T. Tsandilas) and the MANAO project team (P. Barla and G. Guennebaud) and POTIOC project team (M. Hachet) at Inria Bordeaux - Sud Ouest. The goal of this collaboration is to develop novel drawing tools for amateurs as well as for expert designers and illustrators, combining expertise in Computer Graphics (REVES and MANAO) and Human-Computer Interaction (InSitu, POTIOC). This ANR project funds the PhD of Emmanuel Iarussi.

While the ANR DRAO ended in 2015, it has resulted in a publication at ACM Conference on Human Factors in Computing Systems (CHI) 2016 [9]. Adrien Bousseau received an ANR Young Researcher Award for coordinating this project.

8.1.1.2. ANR SEMAPOLIS

Participants: George Drettakis, Abdelaziz Djelouah, Theo Thonat.

This ANR project started in October 2013. The goal is to use semantic information to improve urban reconstruction and rendering. The consortium is led by ENPC (R. Marlet) and includes the Inria Willow team and the GREY-C laboratory on image processing. Our contribution will be in the rendering of urban models, in particular using image-based rendering algorithms.

This year, the ANR SEMAPOLIS resulted in five publications on multi-view segmentation [10], multi-view inpainting [13], image-based rendering of cars [12] and interiors [6], and procedural modeling of buildings [8]. Two of these projects rely on a deep learning method from the ENPC group to identify semantic object categories in images (e.g., cars, people etc.) [13], [12]. In [12] we also collaborated with the ENPC group to use a deep learning method to allow the use of rendered images to identify objects in photographs. These collaborations have been extremely fruitful for our group, and have opened the way to several new collaborations with ENPC.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. CR-PLAY – Capture Reconstruct Play

http://www.cr-play.eu

Type: COOPERATION (ICT)

Instrument: Specific Targeted Research Project

Objectif: Creativity

Duration: November 2013 - October 2016

Coordinator: Testaluna SA (IT)

Partner: TU Darmstadt (DE), UC London (UK), U. Patras (GR), Miniclip UK, Cursor Oy (FI)

Inria contact: George Drettakis

Abstract: The goal of this project is to use image- and video-based rendering and relighting techniques in the context of games and in particular mobile or casual games. The computer graphics and vision partners (UCL, TUD) are leaders in their fields, and have developed algorithms allowing easy capture of scenes using images and video, and reconstruction using vision algorithms. UCL and Inria have developed image- and video-based rendering algorithms which can be useful for games. These tools need to be perfected, reducing artifacts and difficulty of use so that they can be useful and productive for games companies. For evaluation, the HCI lab of the University of Patras will provide cutting-edge methodologies to make the resulting systems useable. The consortium is led by the games company Testaluna, based in Genova Italy. Other industrial partners include Cursor Oy (a regional group of games companies in Finland, which is a leader in Europe in Casual games) and Miniclip, which is one of the major players in the online game market.

This year we had four results related to CR-PLAY on multi-view segmentation [10], multi-view inpainting [13], image-based rendering of cars [12] and indoors [6]. The work on indoors rendering was led by the CR-PLAY partner UCL. The CR-PLAY project ended in October, and was successfully evaluated in November. The project has resulted in a number of technological developments related to the Ph.D. work of R. Ortiz-Cayon and T. Thonat, as well as the postdoc of A. Djelouah which will be the object of a market study in the goal of a technology transfer.

8.2.1.2. EMOTIVE

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 will contribute by developing novel image-based rendering techniques to help museum curators and archeologists provide more engaging experiences.

8.3. International Initiatives

8.3.1. Inria Associate Teams Not Involved in an Inria International Labs

8.3.1.1. CRISP2

Title: Creating and Rendering Images based on the Study of Perception

International Partner (Institution - Laboratory - Researcher):

University of California Berkeley (United States) - Electrical Engineering and Computer Science Department (EECS) - Maneesh Agrawala

Start year: 2014

See also: http://www-sop.inria.fr/reves/crisp/

The CRISP collaboration aims at developing novel techniques to create and manipulate effective numerical imagery. We adopt a multidisciplinary approach, focusing on understanding how people create and perceive images, on developing new rendering algorithms based on this understanding, and on building interactive tools that enable users to efficiently produce the images they have in mind. The participants of CRISP share complementary expertise in computer graphics, human computer interaction and human visual perception. In 2016, the CRISP collaboration supported the postdoc of George Koulieris, who spent 6 months at UC Berkeley and is now at Inria. Johanna Delanoy also spent 2 weeks at UC Berkeley to collaborate with Alexei Efros.

8.3.2. Inria International Partners

8.3.2.1. Informal International Partners

Canada. A. Bousseau collaborates regularly with the University of Toronto (K. Singh) and the University of British Columbia (A. Sheffer).

India. A. Bousseau collaborates with Vinay Namboodiri from IIT Kanpur and hosted several of his students for internships (Rahul Arora and Srinivasa Rao Gadhamchetty).

UK. G. Drettakis collaborates with UCL in the context of the CR-PLAY projects, resulting in a publication on indoor image-based rendering [6].

United States. We regularly collaborate with Adobe Research. Most recently, G. Drettakis worked with Eli Shechtman and Sylvain Paris on multi-view inpainting [13]. We also collaborate with Daniel Aliaga from Purdue University on sketch-based procedural modeling [8].

8.4. International Research Visitors

8.4.1. Visits of International Scientists

Martin Banks (UC Berkeley) visited our group for two weeks in the context of the Associate Team CRISP (Sec. 8.3.1.1). We also hosted Philip Isola, Richard Zhang and Alexei Efros (UC Berkeley) for two days, also in the context of CRISP. Several international researchers made short visits and talks: Elena Garces (University of Zaragoza), Yulia Gryditskaya (MPI), Jan Jermyn (Durham University) , Christian Lessig (Otto-von-Guericke Universitat Magdeburg), Marc Stamminger (Erlangen University). Finally, we hosted Frédo Durand from MIT (10 months) and Eugene Fiume from university of Toronto (6 months) for their sabbatical.

8.4.1.1. Internships

Sai Praveen Bangaru and Srinivasa Rao Gadhamchetty were master interns from IIT Madras and IIT Kampur respectively.

8.4.2. Visits to International Teams

8.4.2.1. Research Stays Abroad

George Koulieris spent 6 months at UC Berkeley (Feb. 1 - Jul. 31) to work with Martin S. Banks in the context of the CRISP Inria associate team. Johanna Delanoy also visited UC Berkeley for two weeks to work with Alexei Efros.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

George Drettakis chairs the Eurographics working group on Rendering.

9.1.2. Scientific Events Selection

9.1.2.1. Chair of Conference Program Committees

Adrien Bousseau is co-chair of the Tutorial program of Eurographics 2017.

9.1.2.2. Member of Conference Program Committees

Adrien Bousseau was on the program committee of Eurographics 2017 and of SIGGRAPH Asia 2016 technical briefs and posters.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

Adrien Bousseau is Associate Editor of The Visual Computer journal (Springer)

George Drettakis is Associate Editor of ACM Transactions on Graphics (TOG) and of Computational Visual Media (CVM).

9.1.3.2. Reviewer - Reviewing Activities

Adrien Bousseau was reviewer for ACM TOG, IEEE TVCG, SIGGRAPH, SIGGRAPH Asia, Computers & Graphics, ACM CHI, ACM UIST, AFIG.

George Drettakis was reviewer for SIGGRAPH, Computer Graphics Forum.

9.1.4. Leadership within the Scientific Community

George Drettakis chairs the local "Jacques Morgenstern" Colloquium organizing committee.

9.1.5. Scientific Expertise

G. Drettakis is a member of the Scientific Advisory Board (SAB) of Aalto University, Finland, and participated in the SAB meeting at Aalto in October.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence : Abdelaziz Djelouah, TP système d'information, niveau L1, Université Nice Sophia Antipolis, 24h

Licence : Johanna Delanoy, TP Bases de données and personal project, niveau L1, IUT - Université Nice Sophia Antipolis, 64h

Masters II: G. Drettakis, A. Bousseau: Foundations of Image Synthesis, CentralSupelec, Paris, 28h

Masters I: A. Bousseau, G. Drettakis: Image Synthesis International Masters I, University of Nice Sophia-Antipolis, 12h

Masters I: G. Drettakis, A. Bousseau: Image Synthesis, Masters MAPI Cannes, University of Nice Sophia-Antipolis, 12h

9.2.2. Supervision

PhD in progress : Rodrigo Ortiz-Cayon, Mixed image-based rendering, Nice Sophia Antipolis University, started Dec. 2013, to be defended in Feb. 2017, advisor: G. Drettakis

PhD in progress : Théo Thonat, Multi-view image processing for image-based rendering, Nice Sophia Antipolis University, started Oct. 2015, advisor: G. Drettakis

PhD in progress : Johanna Delanoy, Data-driven sketch-based modeling, Nice Sophia Antipolis University, started Oct. 2015, advisor: A. Bousseau

PhD in progress : Jean-Dominique Favreau, geometric analysis of line drawings, Nice Sophia Antipolis University, started Oct. 2014, advisor: A. Bousseau and F. Lafarge (Titane)

PhD in progress : Valentin Deschaintre, lightweight material capture, Nice Sophia Antipolis University, started Nov. 2016, advisor: A. Bousseau and G. Drettakis

PhD in progress : Julien Philip, Mixed rendering for cultural heritage, Nice Sophia Antipolis University, started Nov. 2016, advisor: G. Drettakis

PhD in progress : Simon Rodriguez, Combining image-based and procedural modeling, Nice Sophia Antipolis University, started Nov. 2016, advisor: G. Drettakis

9.2.3. Juries

Adrien Bousseau was in the PhD committees of Boris Raymond (Inria Bordeaux) and Elena Garces (University of Zaragoza)

George Drettakis was in the PhD committees Oriel Frigo (Paris Descartes) and was an evaluator (rapporteur) for Kaan Yucer (ETH Zurich) and Yitzchak Lockerman (Yale).

9.3. Popularization

George Koulieris described his research in an interview for the Inria@SiliconValley Newsletter [0].

[0] https://project.inria.fr/siliconvalley/2016/06/21/post-doc-george-koulieris/

Adrien Bousseau described his research in two interviews for the Inria website [0][0].

Adrien Bousseau gave demos of his tool to help people practice drawing-by-observation techniques during the “Rencontres du numérique” organized by ANR (Nov. 16th) and during the “Rencontres Inria-Industrie” on e-learning (Dec. 1st).

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[2] S. DUCHÊNE, C. RIANT, G. CHAURASIA, J. LOPEZ-MORENO, P.-Y. LAFFONT, S. POPOV, A. BOUSSEAU, G. DRETTAKIS.*Multi-View Intrinsic Images of Outdoors Scenes with an Application to Relighting*, in "ACM Transactions on Graphics", 2015, http://www-sop.inria.fr/reves/Basilic/2015/DRCLLPD15.

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Articles in International Peer-Reviewed Journal

[5] J.-D. FAVREAU, F. LAFARGE, A. BOUSSEAU.*Fidelity vs. Simplicity: a Global Approach to Line Drawing Vectorization*, in "ACM Transactions on Graphics", 2016 [*DOI :* 10.1145/2897824.2925946], https://hal.inria.fr/hal-01309271.

[6] P. HEDMAN, T. RITSCHEL, G. DRETTAKIS, G. BROSTOW.*Scalable Inside-Out Image-Based Rendering*, in "ACM Transactions on Graphics", December 2016, vol. 35, n^o 6, https://hal.inria.fr/hal-01369382.

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[0] https://www.inria.fr/en/centre/sophia/news/adrien-bousseau-receives-an-erc-starting-grant
[0] https://www.inria.fr/centre/sophia/actualites/adrien-bousseau-laureat-du-prix-jeune-chercheur

International Conferences with Proceedings

[9] A. Bousseau, T. Tsandilas, L. Oehlberg, W. E. Mackay.*How Novices Sketch and Prototype Hand-Fabricated Objects*, in "Conference on Human Factors in Computing Systems (CHI)", San Jose, United States, ACM, May 2016 [*DOI :* 10.1145/2858036.2858159], https://hal.inria.fr/hal-01272187.

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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

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Project-Team GRAPHIK

Creation of the Project-Team: 2010 January 01

Keywords:

Computer Science and Digital Science:

3.1.1. - Modeling, representation
3.2.1. - Knowledge bases
3.2.3. - Inference
3.2.5. - Ontologies
7.4. - Logic in Computer Science
8.1. - Knowledge
8.6. - Decision support
8.7. - AI algorithmics

Other Research Topics and Application Domains:

3.1. - Sustainable development
9.4.5. - Data science
9.5.10. - Digital humanities
9.7.2. - Open data

1. Members

Research Scientists

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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, in the field of logic-based KR, we distinguish ourselves by also using 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 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 on graph-theoretic notions), with homomorphism as a core notion, 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 with "imperfect knowledge" (*i.e.*, vague, uncertain, partially inconsistent, multi-viewpoints and/or with multi-granularity).

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 for agronomy, the final objective being a knowledge-based system to aid decision-making for the quality control in food processing.
- data integration and quality improvement, specifically for document metadata.

3. Research Program

3.1. Logic-based Knowledge Representation and Reasoning

We follow the mainstream *logic-based* approach to the KR domain. 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 some 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. See Section 6.1 for details on the results obtained.

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. Imperfect Information and Priorities

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 in the agronomy domain.

1. to cope with vague and uncertain information and preferences in queries;
2. to cope with multi-granularity knowledge;
3. to take into account different and potentially conflicting viewpoints ;
4. to integrate decision notions (priorities, gravity, risk, benefit);
5. to integrate argumentation-based reasoning.

Although the solutions we develop need 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. Highlights of the Year

4.1. Highlights of the Year

- M. Bienvenu was awarded the Bronze CNRS medal 2016 http://www.cnrs.fr/ins2i/spip.php?article2197. She was an invited speaker at IJCAI 2016 (International Joint Conference in Artificial Intelligence), Early Career Spotlight track http://ijcai-16.org/index.php/welcome/view/early_career_spotlight
- Theoretical and algorithmic results on ontology-mediated query answering recognized at the best international level (10 articles in the major conferences in Artificial Intelligence and Knowledge Representation and Reasoning: IJCAI, AAAI, ECAI and KR)
- Sudoqual prototype for the evaluation of link quality in document bases considered to be used in production conditions by ABES (French Agency for Academic Libraries).
- CoGui-Capex prototype linking food descriptors to actions considered to be used in production conditions by Régilait in its milk powder factory in Macon.

4.1.1. Best papers

BEST PAPERS AWARDS :

[29] **10th International Conference on Web Reasoning and Rule Systems**. M. BIENVENU, M. THOMAZO.

5. New Software and Platforms

5.1. SudoQual

Participants: Michel Leclère, Michel Chein, Alain Gutierrez, Clément Sipieter, Brett Choquet.

Contact: Michel Leclère

SudoQual is a software suite that allows discovering and evaluating coreference links between individual entities references. It has been developed during the ANR project Qualinca. This software suite comprises:

- a generic API allowing to implement (thanks to a graphical interface) applications computing "same-as" and "different-from" links in knowledge bases;
- a generic application (whose specific parameters are defined in a configuration file) evaluating the quality of a knowledge base; it is available either as a standalone client or as a web service;
- a library dedicated to the comparison of individual entities' attributes;
- the specific configuration file dedicated to evaluating the quality of links in ABES' Sudoc catalogue.

Main developments this year are:

- adapting the API's architecture to the NetBeans IDE in order to benefit from its better edition functionalities;
- finalizing, testing and optimizing the linkage application;
- specifying and implementing the quality evaluation application;
- implementing this latter application as a web service.

5.2. GRAAL

Participants: Clément Sipieter, Jean-François Baget, Michel Leclère, Marie-Laure Mugnier, Swan Rocher.

Contact: Marie-Laure Mugnier (scientific contact), Clément Sipieter (technical contact)

Keywords: Data management - Ontologies - Query Answering

Web site: https://graphik-team.github.io/graal/

Scientific Description Graal is a generic platform for ontological query answering with existential rules. It implements various paradigms that fall into that framework. It is an open source software written in Java.

Functional Description See last year's report for a description of GRAAL's features http://raweb.inria.fr/rapportsactivite/RA2015/graphik/uid49.html.

New Features The main features developed in 2016 are:

- improvement of the semi-saturation algorithm with compilable rules;
- implementation of mappings allowing to query an existing database as it is, without prior loading it in GRAAL;
- design and implementation of classes that manage a knowledge base (i.e., the rules and the data). In particular, the results of the rule analyser Kiabora (that has been integrated within GRAAL) are used to automatically select the most appropriate algorithms for querying the knowledge base.

5.3. Cogui

Participants: Alain Gutierrez, Marie-Laure Mugnier, Michel Leclère, Michel Chein.

Contact: Marie-Laure Mugnier (scientific contact), Alain Gutierrez (technical contact)

Keywords: Graphical knowledge bases - Ontology Editor - Conceptual Graphs

Web site: http://www.lirmm.fr/cogui/

Scientific Description Cogui is a tool for building and verifying graphical knowledge bases. It is a freeware written in Java.

Functional Description See last year's report for a description of CoGui's features http://raweb.inria.fr/rapportsactivite/RA2015/graphik/uid41.html.

New features Cogui is currently under heavy refactoring to benefit from NetBeans graphical libraries.

5.4. CoGui-Capex

CoGui-Capex is a decision support tool dedicated to food industry. Its knowledge base represents the causal links between food descriptors and actions which can be undertaken by operators to control food quality on the line. The new version of CoGui-Capex developed in 2016 in a Neatbeans environnement is coupled with the so-called "Knowledge book" developed by INRA I2M team in Bordeaux [49]. This collaboration will be extended in the CASDAR Docamex national project (funded by the French Ministry of Agriculture), which will begin in January 2017 for 4 years with several cheese makers.

5.5. @Web

An extension of the 5 stars/FAIRS scientific data annotation platform called @Web (http://www6.inra.fr/cati-icat-atweb), managed by INRA, has been developped by Leandro Lovisolo (UBA master student) co-supervised by Federico Ulliana and Patrice Buche using semantic web languages (OWL, SPARQL, RDF). This extension permits to represent negative constraints expressed on annotated data and will be used in data curation phase.

6. New Results

6.1. Logics and Graph-Based Languages for Ontology-Mediated Query Answering

Participants: Jean-François Baget, Meghyn Bienvenu, Efstathios Delivorias, Michel Leclère, Marie-Laure Mugnier, Swan Rocher, Federico Ulliana.

Ontolology-mediated query answering (and more generally *Ontology-Based Data Access*, *OBDA*) is a recent paradigm in data management, which takes into account inferences enabled by an ontology when querying data. In other words, the notion of a database is replaced by that of a knowledge base, composed of data (also called facts) and of an ontology. Two families of formalisms for representing and reasoning with the ontological component are considered in this context: *description logics* and the more recent *existential rule* framework. Until last year, the team has mainly investigated existential rules. This expressive formalism generalizes most lightweight description logics used in OBDA (such as $\mathcal{EL}$ and DL-Lite, on which OWL 2 tractable profiles are based) on the one hand, and Datalog, the language of deductive databases, on the other hand. With the arrival of Meghyn Bienvenu, description logics have joined the core formalisms studied by the team. Compared to existential rules, the description logics considered for OBDA lead to lower complexity classes and specific algorithmic techniques. Studying both formalisms is scientifically highly relevant, specially in the context of OBDA.

We have also broadened this research line by starting investigating ontological languages for non-relational data, an issue that has barely been considered yet.

Before presenting this year' results, we recall 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 initial facts 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 rules). The backward chaining process can be divided into two steps: first, the initial query is rewritten using the rules into a first-order query (typically a union of conjunctive queries, UCQ); then the rewritten query is evaluated against the initial factbase (again, as in a classical database system). Note that forward and backward processes do not halt for all kinds of existential rules nor all lightweight description logics.

6.1.1. New Results in the Description Logics Framework

When using Description Logics (DL) ontologies to access relational data, mappings are used to link the relational schema to the vocabulary of the ontology (which uses only unary and binary predicates). In order to debug and optimize DL-based OBDA systems, it is important to be able to analyze and compare ontology-mapping pairs, called OBDA specifications. Prior work in this direction compared specifications using classical notions of equivalence and entailment.

- We have explored an alternative approach in which two specifications are deemed equivalent if they give the same answers to the considered query or class of queries for all possible data sources. After formally defining such query-based notions of entailment and equivalence of OBDA specifications, we investigated the complexity of the resulting analysis tasks when the ontology is formulated in (fragments of) DL-Lite$_R$, which forms the basis for the Semantic Web ontological language OWL 2 QL.
  - *KR'16 [28]*
- We consider a range of Horn DLs for which query answering has polynomial data complexity, but which do not guarantee the existence of First-Order(FO)-rewritings of all queries. In order to extend the applicability of the FO-rewriting technique, a key task is to be able to identify specific ontology-query pairs that admit an FO-rewriting. This led us to study FO-rewritability of conjunctive queries in the presence of ontologies formulated in DLs ranging between $\mathcal{EL}$ and Horn-$\mathcal{SHIF}$, along with related query containment problems. Apart from providing characterizations, we established complexity results ranging from EXPTIME via NEXPTIME to 2EXPTIME, pointing out several interesting effects. In particular, FO-rewriting is more complex for conjunctive queries than for atomic queries when inverse roles are present, but not otherwise.
  - *IJCAI'16 [27]*

6.1.2. New Results in the Existential Rule Framework

Several new theoretical results have been obtained on ontology-mediated query answering with existential rules:

- While most work in the area of ontology-mediated query answering focuses on conjunctive queries, navigational queries are gaining increasing attention. In collaboration with Michael Thomazo (Inria CEDAR), we took a step towards a better understanding of the combination of navigational query languages and existential rules by pinpointing the (data and combined) complexities of evaluating path queries (more precisely, two-way regular path queries) over knowledge bases whose ontology is composed of linear existential rules (a class of rules that can be seen as a natural generalisation of the description logic DL-Lite$_{\mathcal{R}}$). We extended an algorithm tailored for DL-Lite$_{\mathcal{R}}$ and showed that, despite an exponential blow-up with respect to the maximum predicate arity, our algorithm was worst-case optimal.
  - *RR'16 (Best paper award) [29]*
- Boundedness is an important notion for optimizing the processing of rule languages, as it ensures that materialisation can be performed in a predefined number of steps, independently from the size of any factbase. We are currently studying several boundedness notions for existential rules that extend the well-known boundedness notion of Datalog, and investigate their relationships with properties ensuring the finiteness of the chase or query rewriting. One of our first results is that, for a natural notion of boundedness, bounded existential rules are exactly those at the intersection of finite expansion sets (which ensure that any factbase has a finite sound and complete saturation) and finite unification sets (which ensure that any conjunctive query can be finitely rewritten into a sound and complete union of conjunctive queries).
  - *DL'16 [36]*
- Finally, Swan Rocher's PhD thesis deepened the study of the decidability and complexity of conjunctive query answering for classes of existential rules added with transitivity rules (previous results were presented at IJCAI 2015 [48])

6.1.3. Querying NoSQL databases (Key-value stores)

Over the last decade, research efforts to develop algorithms for OBDA have built on the assumption that data conforms to relational structures (including RDF) and that the paradigm can be deployed on top of relational databases with conjunctive queries at the core (e.g., in SQL or SPARQL). However, this is not the prominent way on which data is today stored and exchanged, especially in the Web. Whether OBDA can be developed for non-relational structures, like those shared by increasingly popular NOSQL languages sustaining Big-Data analytics, is still an open question. In collaboration with Marie-Christine Rousset (University of Grenoble, LIG), we proposed the first framework for studying the problem of answering ontology-mediated queries on top of NOSQL key-value stores. More precisely, we formalized the core data model and basic queries of these systems and introduced a rule language (NO-RL) to express lightweight ontologies on top of data. We defined a sound and complete query rewriting technique and studied the decidability and data complexity of answering ontology-mediated queries depending on considered the rule fragment.

- *AAAI'16 [39]; DL'16 [40]*

6.2. Representing and Processing Imperfect Information

Participants: Abdallah Arioua, Jean-François Baget, Meghyn Bienvenu, Pierre Bisquert, Patrice Buche, Madalina Croitoru, Jérôme Fortin, Fabien Garreau, Abdelraouf Hecham, Marie-Laure Mugnier, Odile Papini, Swan Rocher, Rallou Thomopoulos, Bruno Yun.

Inconsistency-Tolerant Query Answering is one of the challenging problems that received a lot of attention in recent years as inconsistency may arise in practical applications due to several reasons: merging, integration, revision. In the context of Ontology-Based Data Access (OBDA), where the ontological knowledge is assumed to be coherent and fully reliable, inconsistency comes from the data, i.e., occurs when some assertional facts contradict some constraints imposed by the ontological knowledge. Existing works in this area have studied different inconsistency-tolerant query answering techniques, called “semantics”: some examples include Brave, IAR, ICR, AR etc..These proposals are closely related to works on querying inconsistent databases, or inference from inconsistent propositional logic knowledge bases.

The work of this year on inconsistency-tolerant query answering techniques for Ontology Based Data Access focused on (i) new results about different kinds of semantics or (ii) the user interaction with such semantics (we investigated the notion of repair based explanation or argumentation based explanation). We have investigated the interest of inconsistency-tolerant semantics in general and argumentation techniques for the agrifood chain in particular.

6.2.1. Inconsistency-Tolerant Semantics for Query Answering

In all approaches considered here, a knowledge base can have, in opposition to the logics studied in 6.1, several incompatible "minimal" models. Those models can correspond to possible repairs of an inconsistent knowledge base or can be the models generated by a non-monotonic logic. The questions we address here are linked to the semantics (how to define those models, how to define preferences on those models), while trying to preserve a satisfying trade-off between expressivity and computational complexity of the querying mechanism.

- We proposed a new inconsistency-tolerant inference relation, called non-objection inference, where a query is considered as valid if it is entailed by at least one repair and it is consistent with all the other repairs. The main salient points of the newly introduced semantics is its efficiency (query answering with non-objection inference is achieved in polynomial time) and the fact that the inferences are strictly more productive than universal inference while preserving the consistency of its set of conclusions. The intuition behind is that no repair has an objection veto to the acceptance of the query. If query entailment from repairs is seen as posing a vote for, against or abstaining to a query then, in this semantics, some repairs are "voting" for a query (i.e., the query is entailed) and the rest of the repairs are not against (i.e., the query body atoms together with the atoms in the repair are consistent with the terminology) then the query is accepted without any objection. In addition, two variants of non-objection inference based on a selection of repairs (that can be against a query) are also considered.
  - *IJCAI'16 [31]*
- We provided a dialectical characterization of the Brave and IAR semantics. We proposed an argumentation dialogue system that considers a turn taking game between a proponent and an opponent. We defined the concept of participant's profile and depending on these profiles we were able to give necessary and sufficient conditions for the Brave and IAR semantics. We further proposed a new TPI-like dialectical proof theory (a procedure where two players exchange arguments (moves) until one of them cannot play) for universal acceptance (i.e.,AR semantics). We limit the scope of the work to finite and coherent logic-based argumentation frameworks that correspond to the OBDA instantiation we consider in practical applications.
  - *ECAI'16 [18]; FLAIRS'16 [19]*
- We proposed a unifying framework for inconsistency-tolerant query answering within existential rule setting. In this framework, an inconsistency-tolerant semantics is seen as a pair composed of a modifier, which produces consistent subsets of the data, and an inference strategy, which evaluates queries on the selected subsets. We systematically compared the productivity and the complexity of the obtained semantics.
  - *KR'16 [22]; JELIA'16 [23]*
- We studied the relationships between our unifying repair framework and stable model semantics. In particular, we provided a generic encoding for most semantics defined in that framework using Answer Set Programming.
  - *SUM'16 [24]*

6.2.2. Practical Applicability of Inconsistency-Tolerant Semantics and Argumentation

- Several inconsistency-tolerant semantics have been introduced for querying inconsistent knowledge bases. In order for users to be able to understand the query results, it is crucial to be able to explain why a tuple is a (non-)answer to a query under such semantics. We defined explanations for positive and negative answers under the brave, AR and IAR semantics. We then studied the computational properties of explanations in the lightweight description logic DL-Lite$_R$. For each type of explanation, we analyzed the data complexity of recognizing (preferred) explanations and deciding if a given assertion is relevant or necessary. We established tight connections between intractable explanation problems and variants of propositional satisfiability (SAT), enabling us to generate explanations by exploiting solvers for Boolean satisfaction and optimization problems. Finally, we empirically studied the efficiency of our explanation framework using the well-established LUBM benchmark.

  – *AAAI'16 [25]*

- We considered the problem of query-driven repairing of inconsistent DL-Lite knowledge bases: query answers are computed under inconsistency-tolerant semantics, and the user provides feedback about which answers are erroneous or missing. The aim is to find a set of data modifications (deletions and additions), called a repair plan, that addresses as many of the defects as possible. After formalizing this problem and introducing different notions of optimality, we investigated the computational complexity of reasoning about optimal repair plans and proposed interactive algorithms for computing such plans. For deletion-only repair plans, we also presented a prototype implementation of the core components of the algorithm.

  – *IJCAI'16 [26]*

- Based on the equivalent use of inconsistency-tolerant semantics for OBDA and logical instantiation of argumentation with existential rules, we highlighted some of the practical advantages that come from the interplay of the two techniques. More generally, we focussed on the generic problem of dealing with the uncertain knowledge (elicitation, representation and reasoning) involved at different levels of the food chain that model complex processes relying on numerous criteria, using various granularity of knowledge, most often inconsistent (due to the fact that complementary points of view can be expressed).

  – *IPMU'16 [32]*

  Beside, regarding the various granularity of knowledge, inspired from a hierarchical graph-based definition, we introduced the possibility of representing hierarchical knowledge using existential rules.

  – *ICCS'16 [33]*

- Agent technology and notably argumentation can optimise food supply chain operation in presence of inconsistency by employing intelligent agent applications (as shown in supply chain management case) but also facilitate reasoning with incomplete, inconsistent and missing knowledge as shown in the results presented in the previous sections. We considered two main methods of handling inconsistency: repair-based techniques and argumentation techniques. We demonstrated how to benefit from structured argumentation frameworks in practice by means of their implementations. Such implementations provide reasoning capabilities under inconsistency-tolerant semantics by means of a workflow that will enable Datalog frameworks to handle inconsistencies in knowledge bases using existing structured argumentation implementations.

  – *COMMA'16 [46]*

- We provided a first implementation of the explanation based techniques using argumentation that can be used for inconsistent tolerant semantics. Such implementation served as a proof of concept of the usefulness of the interplay of the two techniques.

  – *COMMA'16 [17]*

  Furthermore, we provided an existential rule benchmark inspired from a real practical setting in the DURDUR project.

  – *MTSR'16 [16]*

To refine this approach, we presented a generic framework of capturing reasoning errors by the interplay of strict logical rules and associative rules in knowledge bases (with the latter being elicited using a game with a purpose). We showed that such model can capture certain reasoning biases and could be eventually used as a predictive model for interacting with domain experts. We also showed empirically the difference of associations agronomy experts exhibit with respect to a random control population validated in the context of the DURDUR ANR project.

  – *ECAI'16 [18]; ICCS'16 [20]*

6.2.3. Decision Support in Agronomy

- We addressed a crucial problem for decision-making tools that are using inconsistency-handling methods (either argumentation frameworks or inconsistency-tolerant semantics) and namely the existence of multiple extensions / repairs. We placed ourselves in an applicative scenario, in the Pack4Fresh project, that investigates the best packaging for strawberries. We showed that being given a set of preferences on the initial set of facts in the existential rule knowledge base we can output meaningful (i.e., agrifood chain expert validated) extensions / repairs that will assist the decision maker.
  – *MTSR'16 [45]*
- We proposed a novel approach for decision-making that allows not only to handle symbolic data but also handle numerical RDF datasets. To deal with the numerical data, a preprocessing step is applied to convert numerical data into symbolic data. Based on the obtained symbolic classes we discover keys that are valid in this preprocessed data. We tested this approach on a dataset that describes wines with the set of numerical values representing different chemical components that give the flavour of wines. In this application setting, the discovered keys can be used to discover flavour complementarity, unknown from the experts, that allow to distinguish various wine sorts amongst themselves. We then validated the keys obtained with domain experts and discussed their interest with respect to the statistical analysis.
  – *ICCS'16 [43]*
- We presented a decision support system (DSS) which permits to compare, in a multi-criteria approach, innovative biomass transformation processes for biorefinery. Considered criteria are process extraction rate and green indicators. This DSS implements a pipeline which permits to annotate in a RDF knowledge heterogeneous textual data sources using a OWL/SKOS termino-ontological resource, to assess data source reliabilty and to compute several green indicators taking into account data reliability.
  – *CEA [13]; FUSS-IEEE'16 [37]*

6.3. Quality and interoperability of large document catalogues

Participants: Michel Chein, Madalina Croitoru, Alain Gutierrez, Michel Leclère, Clément Sipieter.

The work in this research line mainly takes place in the ANR project Qualinca (see Section 8.1), devoted to methods and tools to repair linkage errors in bibliographical databases. Within this project, we specially work with our applicative partner ABES (French Agency for Academic Libraries, http://www.abes.fr/). ABES manages several catalogues and authority bases, in particular the Sudoc, the collective catalogue of French academic libraries. ABES also provides services to libraries and end-users, as well as to other catalogue managers (e.g., OCLC for Worldcat and, in France, Adonis for the Isidore platform).

6.3.1. Evaluating the Quality of a Bibliographic Database

This year, we have focused on the specification, development and test of the application allowing to evaluate reference quality in a bibliographic database. The goal is to evaluate "same-as" links between contextual references (references to named entities provided in the context of a bibliographic notice) and authority references (references establishing an identifier for a given named entity). Our approach to solve this problem consists in two successive steps:

1. use the linkage API developed last years to compute automatically weighted links between contextual references and authority references;
2. compare those weighted links with those present in the bibliographic database in order to produce an evaluation of those links quality.

The evaluation output considers 12 different cases split in 5 major link categories: valid, almost valid, erroneous, missing, doubtful. For the 3 latter categories, we can often provide a correction or completion proposal.

We have initially implemented this application as a standalone client written in Java (see Section 5.1). We have tested it on a benchmark comprising 550 links, for which the evaluation has been done by experts. Our application has obtained very good results, since more than 70% of the links are evaluated correctly, less than 1% wrongly, and the rest consists of links for which data is insufficient to provide an evaluation.

To allow professionals from ABES to use this application, we have developed an interactive web service: the user first asks for the evaluation output on the set of links induced by a subset of contextual references; then he can validate or invalidate the proposed correction/completion. The tool can be restarted after each correction/completion to improve the evaluation with this new data. Our ABES partner is currently developing an enhanced graphical interface for Sudoc users, that will communicate with that web service, in order to use the software in production conditions.

Finally, an evaluation of the time required by our application led to numerous optimizations. We have for now concluded that the time is essentially spent by the library functions computing similarities between attributes. We consider now using map/reduce techniques to parallelize those computations.

6.3.2. Argumentation for Quality Evaluation

Beside, we studied the use of the `owl:sameAs` property (expressing that two URIs actually refer to the same thing) in practice. Many existing identity links do not reflect genuine real identity and therefore might lead to inconsistencies. We formalized explanation dialogues that use argument-based explanation based on inconsistency-tolerant semantics, and showed how to support a domain expert in discovering inconsistencies due to erroneous `SameAs` links. We implemented a prototype of the explanation dialogue that communicates with our tool Graal and provided an example of `sameAs` invalidation over real data explaining what has been obtained while running dialogues and how such results might benefit domain experts.

- *SUM'16 [21], ECAI'16 [18]*

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. UMR IATE / UMR STLO / Régilait

Participants: Patrice Buche, Jérôme Fortin, Alain Gutierrez.

In the framework of a contract between INRA IATE and STLO (Rennes) research units and Régilait, two master students have been recruited in 2016. Marine Damblon, food engineer from Polytech Montpellier, has created a knowledge base which represents the causal links between a food descriptor (mouillabilité des poudres de lait) and actions which can be undertaken by operators to control food quality on the line. Justine Flore Tchouanguem participated to the development of the new CoGui-Capex version presented in section 5.4. CoGui-Capex prototype has been successfully evaluated by Régilait and is considered to be used in production conditions in its milk powder factory in Macon. Marine Damblon has been recruited by Régilait for that. This collaboration will be extended in 2017 and a new master student should be recruited.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

8.1.1.1. ASPIQ

Participants: Jean-François Baget, Madalina Croitoru, Fabien Garreau, Marie-Laure Mugnier, Jérôme Fortin, Michel Leclère, Odile Papini, Swan Rocher.

ASPIQ (ASP technologIes for Querying large scale multisource heterogeneous web information), is an ANR white project that started in January 2013 (duration: 4 years, extended to July 2017). It involves partners from CRIL, LERIA and LSIS. The project coordinator is Odile Papini (LSIS). http://aspiq.lsis.org/

The main objective of this project is to propose:

- extensions of standard ASP for representing OWL2 tractable sublanguages;
- new operations for merging conflicting information in this extended ASP;
- the identification of subclasses of this extended ASP allowing for efficient query answering mechanisms;
- an implementation of a prototype reasoning system.
- *See Section 6.1 and 6.2 for this year's results.*

8.1.1.2. Pagoda

Participants: Meghyn Bienvenu, Jean-François Baget, Marie-Laure Mugnier, Swan Rocher, Federico Ulliana.

Pagoda (Practical Algorithms for Ontology-based Data Access) is an ANR JCJC (young researchers) project that started in Jan. 2013 (duration: 4 years, extended to August 2017). The project coordinator is Meghyn Bienvenu (initially in LRI, now member of GraphIK). It involves partners from the EPI LEO, the LIG, and the Anatomy Laboratory of Grenoble. http://pagoda.lri.fr/

The primary aim of this project is to address challenges brought by scalability and the handling of data inconsistencies by developing novel OBDA (Ontology Based Data Access) query answering algorithms and practical methods for handling inconsistent data.

- *See Section 6.1 and 6.2 for this year's results.*

8.1.1.3. Qualinca

Participants: Michel Leclère, Michel Chein, Madalina Croitoru, Rallou Thomopoulos, Alain Gutierrez, Swan Rocher, Clément Sipieter, Marie-Laure Mugnier.

Qualinca is an ANR Contint project that started in Apr. 2012 (duration: 4 years, extended to September 2016). The project coordinator is Michel Leclère (GraphIK). It involves partners from LRI, LIG, ABES and INA. http://www.lirmm.fr/qualinca/index8ece.html?q=en/en/home

The main objective is to elaborate mechanisms allowing to:

- evaluate the quality of an existing document base;
- maintain a given level of quality by controlling updating operations;
- increase the quality of a given base;
- develop generic methods that take into account the quality of a given base (for instance for searching documents or interconnecting bases).
- *See Section 6.3 for this year's results.*

8.1.1.4. Dur-Dur

Participants: Abdallah Arioua, Pierre Bisquert, Patrice Buche, Madalina Croitoru, Jérôme Fortin, Abdelraouf Hecham, Rallou Thomopoulos.

Dur-Dur (Innovations agronomiques, techniques et organisationnelles pour accroître la DURabilité de la filière blé DUR) is an ANR project that started in March 2014 (duration: 3 years). It is led by IATE Laboratory. http://umr-iate.cirad.fr/projets/dur-dur

The Dur-Dur project develops a systematic approach to investigate the questions related to the management of the nitrogen, energy and contaminants, to guarantee a global quality of products throughout the production and the processing chain. The knowledge representation task of Dur-Dur proposes to map the stakeholders' objectives into a multicriteria cartography, as well as possible means to reach them, and computes the compatibility / incompatibility of these objectives on the basis of argumentation methods. The research methods used are qualitative and based both on argumentation theory and on Social Multi- Criteria Evaluation (SMCE) theory. They will be extended and adapted to the needs of the project to provide a formal framework of assessment of the various orientations considered for the durum wheat chain.

- *See Section 6.2 for this year's results.*

8.1.2. Other projects

8.1.2.1. Pack4Fresh

Participants: Patrice Buche, Pierre Bisquert, Madalina Croitoru, Bruno Yun.

Pack4Fresh (Sept. 2015 - Sept. 2017) is a project selected in the framework of the GloFood INRA-CIRAD metaprogramme. The multi-year metaprogramme GloFoodS (Transitions to global food security) is dedicated to the investigation of pathways to worldwide food security in a context of competition for land and natural resources, and is jointly conducted by INRA and Cirad, the two leading French research institutions for agriculture. Involving research on crop yield and livestock systems, land use changes, food processing and waste, nutrition and governance, GloFoodS aims at articulating global modeling of food supply and demand, with local issues of production and access to food.

In this context, Pack4Fresh focuses on the big fragility of fresh foods which generates enormous post-harvest wastes, short shelf-life, and constitutes a major lock to their consumption and health benefit. This project aims at initiating an eco-design approach of the post-harvest phase of fresh foods working on the interdependency relation between environmental impact (1) positive for waste reduction, et (2) negative for technologies, which aims at reducing the waste, in order to minimize the ratio between those two parameters.

- *See Section 6.2 for this year's results.*

8.1.2.2. OBDA-KeyVal: Ontology-Based Data Access for NoSQL Databases

Participants: Federico Ulliana, Marie-Laure Mugnier.

OBDA-KeyVal is a one-year PEPS project (JCJC INS2I 2016, funded by CNRS-INS2I) dedicated to Ontology Based Data Access for NOSQL Databases. Its goal is to study the problem of answering ontology-mediated queries on top of non-relational databases, and more precisely Key-Value stores. These are a family of NOSQL databases dealing with data represented as nested-structures (JSON records), processed on distributed systems but also increasingly exchanged on the Web, slowly replacing XML and RDF formats. Key-value stores have been designed with performance and scalability in mind, and this opens the possibility to implement OBDA in a novel and efficient distributed setting. The work carried out in this project builds on our first results published at AAAI 2016 [39], see also Sect. 6.1. We addressed both practical and theoretical aspects of OBDA for key-value stores. First, a prototype of the reasoning framework for key-value stores has been developed by master students (https://github.com/OBDA-KEYVAL/graal-keyval). Second, a novel first-order logic semantics for the setting (in contrast to the former operational semantics) has been defined and investigated from a decidability viewpoint. This still ongoing work is a necessary step towards bridging this setting with the relational OBDA.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. NoAW (No Agricultural Waste)

Participants: Patrice Buche, Pierre Bisquert, Madalina Croitoru, Nikolaos Karanikolas, Rallou Thomopoulos.

Website: http://cordis.europa.eu/project/rcn/203384_en.html

NoAW (No Agricultural Waste) is an H2020 european project led by INRA-IATE, started in Oct. 2016. 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 will contribute on two aspects. On one hand we will participate in the annotation effort of knowledge bases (using the @Web tool). On the other hand we will further investigate the interplay of argumentation with logically instantiated frameworks and its relation with social choice in the context of decision making.

8.2.2. Collaborations in European Programs, Except FP7 & H2020

8.2.2.1. COST FoodMC.

Participants: Madalina Croitoru, Rallou Thomopoulos.

Website: http://www6.inra.fr/foodmc

Rallou Thomopoulos is involved as Co-coordinator (together with Alberto Tonda and Kamal Kansou) in the European COST Action "FoodMC" (Mathematical and Computer Science Methods for Food Science and Industry) started in 2016. Both Madalina Croitoru and Rallou Thomopoulos are Members of the Management Committee, representing France.

8.3. International Initiatives

8.3.1. Inria International Partners

8.3.1.1. Informal International Partners

- University of Buenos Aires, Ricardo Rodriguez, since 2013. Work in progress.
- University of Aberdeen, Nir Oren, since 2010. Work in progress.
- Technical University of Dresden, Sebastian Rudolph, since 2012. [34], co-organizer for GKR@IJCAI 2017.
- University of Liverpool, Frank Wolter, since 2009. [11], [27]
- Sapienza University (Rome), Riccardo Rosati, since 2012. [28]
- University of Bremen, Carsten Lutz, since 2009. [27], [11]
- Technical University of Vienna, Magdalena Ortiz and Mantas Simkus, since 2010. Work in progress.
- Laval University (Quebec), Irène Abi-Zeid, since 2015, and Bernard Moulin, since 2012. [44], [38]
- University of Amsterdam, Ulle Endriss, since 2015. Work in progress.

8.3.2. Participation in Other International Programs

Patrice Buche is involved in the RDA AgriSemantics working group (https://www.rd-alliance.org/groups/agrisemantics-wg.html). The goal of the Agrisemantics WG is to gather community-based requirements and use cases for an infrastructure that supports appropriate use of semantics for data interoperability, with special focus on agriculture.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

- Nov. 2016 (1 week). Visit of Elena Botoeva (Univ. of Bolzano), Stanislav Kikot (London Univ.), Roman Kontchakov (London Univ.) Vladislav Rhyzhikov (Univ. of Bolzano), and Michael Zakharyaschev (London Univ.) to work on the complexity on ontology-mediated query answering with description logics and linear existential rules. Seminars: "Query Inseparability of Description Logic Knowledge Bases and TBoxes" by Elena Botoeva and "The Complexity of Ontology-Based Data Access with OWL 2 QL and Bounded Treewidth Queries" by Stanislav Kikot.
- Nov. 2016 (2 days). Visit of Sebastian Rudolph (TU Dresden) in the context of Swan Rocher's PhD defense. Seminar: "The Curse of Finiteness: Undecidability of Database-Inspired Reasoning Problems in Very Expressive Description Logics".
- Sept. 2016 (1 week) Visit of Ricardo Rodriguez (Univ. of Buenos Aires) to work on belief revision for inconsistent tolerant semantics.

8.4.2. Visits to International Teams

8.4.2.1. Research Stays Abroad

Pierre Bisquert was an invited researcher at the University of Amsterdam from May 2015 to Apr. 2016.

- In collaboration with Ulle Endriss (Institute for Logic, Language and Computation), he worked on the link between argumentation theory and social choice. The aim of this work was to study and understand how Arrow's Impossibility Theorem (stating that there is no democratic voting rule) could be avoided thanks to deliberation and argumentation. More precisely, the favored approach was to define a formal framework of the deliberation process predating a vote, and to establish conditions under which deliberation may help to output a democratic and collectively rational choice through the notion of preference structuration, i.e.,the changes in preferences that the agents may undergo after discussion.

Rallou Thomopoulos was invited at Laval University (Québec, Canada) for one year until July 2016. She worked on two projects dealing with decision support:

- An academic project conducted with the Computer Science Division of Laval University. It aimed at conceiving a systematic approach to assess several scenarios in agriculture, by combining a qualitative model based on argumentation and a quantitative simulation technique based on system dynamics.
- The second project was conducted both with a private partner and with the Operation and Decision Division of Laval University. It aimed to provide explanations for automatically-computed instructions, to improve human understanding of the situation. These instructions were the results of a commercial software used for real-time decision support for the flow management of a combined and sanitary wastewater system.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

9.1.1.1.1. 2016 Events

- We were local co-organizers (with the Coconut team at LIRMM) of the French workshop JIAF (Journées d'Intelligence Artificielle Fondamentale), held in Montpellier in June 2016, in conjunction with the JFPC, the Journées de Programmation par Contraintes (JFPC). https://www.supagro.fr/jfpc_jiaf_2016/index_jiaf.php

- Still with Coconut team at LIRMM, we also welcomed the opening days of the National CNRS Group on theoretical and algorithmic aspects of Artificial Intelligence (pre-GDR IA) in Jun. 2016.
- Marie-Laure Mugnier co-organized the workshop "Ontologies and logic programming for query answering" co-located with IJCAI 2016 http://ontolp.lsis.org/

9.1.1.1.2. 2017 Events

- We are organizing the 30th Workshop on Description Logics, to be held in July 2017 in Montpellier. The general chairs are Meghyn Bienvenu and Marie-Laure Mugnier. https://project.inria.fr/dl2017/
- Madalina Croitou will co-organise the 5th International Workshop of Graph Based Knowledge Representation and Reasoning collocated with IJCAI 2017 in Melbourne Australia. The organiser list is the same as GKR 2015. More information about past editions can be found at: https://www.lirmm.fr/~croitoru/GKR/
- Madalina Croitoru and Pierre Bisquert will organize a special session "Agronomy and AI" at IEA-AIE 2017 (30th International Conference on Industrial, Engineering and Other Applications of Applied Intelligent Systems) http://www.cril.univ-artois.fr/ieaaie2017/main/specialtracks/

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

We are regularly members of the program committees of the main generalist conferences in AI (i.e., IJCAI, AAAI, ECAI) and more specialized conferences and workshops (KR, the main conference in knowledge representation and reasoning, RR —Web reasoning and Rule Systems, SUM — International Conference on Scalable Uncertainty Management, COMMA — International Conference on Computational Models of Argument, Metadata and Semantics Research Conference, etc.)

For 2016, we served in the following program committees:

- IJCAI 2016 (21st International Conference on Artificial Intelligence): 1 senior PC + 3 PC
- ECAI 2016 (22nd European Conference on Artificial Intelligence): 2 PC
- ISWC 2016 (15th International Semantic Web Conference): 1 PC
- AAAI 2016 (30th AAAI Conference on Artificial Intelligence): 2 PC
- DL 2016 (29th International Workshop on Description Logics): 2 PC
- RR 2016 (10th International Conference on Web Reasoning and Rule Systems): 2 PC
- FOIS 2016 (9th International Conference on Formal Ontology in Information Systems): 1 PC
- BDA 2016 (Gestion de Données — Principes, Technologies et Applications): 1 PC
- FoIKS 2016 (9th International Symposium on Foundations of Information and Knowledge Systems): 1 PC
- CARI 2016 (13ème Colloque Africain sur la Recherche en Informatique et Mathématiques Appliquées): 1 PC
- IC 2016 (27es journées francophones d'Ingénierie des Connaissances): 1 PC
- MTSR 2016, AgroSEM Special track (10th Metadata and Semantics Research Conference): 1 PC
- LFA 2016 (25ème Conférence sur la Logique Floue et ses Applications): 1 PC

For 2017, we will serve in the following program committees (list not exhaustive yet):

- IJCAI 2017 (22nd International Conference on Artificial Intelligence): 1 senior PC, 1 PC
- AAAI 2017 (31st AAAI Conference on Artificial Intelligence): 2 PC
- PODS 2017 (36th International Conference on the Principles of Database Systems): 1 PC
- ICDT 2017 (20th International Conference on Database Theory): 1 PC
- SIGMOD 2017 (ACM SIGMOD International Conference on Management of Data): 1 PC
- EGC 2017 (Extraction et Gestion des Connaissances): 1 PC
- IC 2017 (28èmes journées francophones d'Ingénierie des Connaissances): 1 PC

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

Patrice Buche Member of the ARIMA Editorial Board (http://arima.inria.fr/docs/04redaction.html)

Rallou Thomopoulos is chapter coordinator in 2016 special issue of the IFSET journal, and member of the proposal committee of the special issue 2011 of the RNTI journal (Revue des Nouvelles Technologies de l'Information) on the topic of the evaluation of methods in EKD (Extraction of Knowledge from Data).

9.1.3.2. Reviewer - Reviewing Activities

Reviews for *Artificial Intelligence* and *Journal of Artificial Intelligence Research* (JAIR).

9.1.4. Invited Talks

- Meghyn Bienvenu was invited speaker at IJCAI 2016 (International Joint Conference in Artificial Intelligence), Early Career Spotlight track: "Ontology-mediated query answering : Harnessing knowledge to get more from data"
- Meghyn Bienvenu was keynote speaker at RR 2016 (International Conference on Web Reasoning and Rule Systems): "Query rewriting : Limits and possibilities"
- Meghyn Bienvenu was invited speaker at Reasoning Web (RW) Summer School 2016: "Inconsistency-Tolerant Querying of Inconsistent Description Logic Knowledge Bases"
- Meghyn Bienvenu (with Magdalena Ortiz)) was invited speaker at ESSLLI 2016 (European Summer School in Logic, Language and information): "Ontology- Mediated Query Answering with Horn Description Logics"

9.1.5. Invited Seminars

- Efstathios Delivorias gave a talk at the Computational Logic Group Seminar Dresden 2016.
- Meghyn Bienvenu gave a talk at the Séminaire Inria CEDAR 2016.
- Marie-Laure Mugnier, Rallou Thomopoulos, Bruno Yun and Patrice Buche gave talks at the INRA research school "intégration de connaissances et modèles", Nantes, Nov. 2016

9.1.6. Leadership within the Scientific Community

- **Scientific animation at INRA**: Patrice Buche co-animates the national network INRA IN-OVIVE, devoted to methods and tools for big data management in life sciences, agronomy and food processing http://www6.inra.fr/reseau-in-ovive
  In particular, he co-organized three editions of the IN-OVIVE workshop dedicated to heterogeneous data sources integration in life sciences during the French conference IC (ingénierie des connaissances) from 2013 to 2016 https://workshop.inra.fr/in_ovive_2016/Programme
  Patrice Buche is also co-animator (2012-2017) at the national level of the INRA CATI ICAT "Ingénierie des connaissances et analyse textuelle" http://www6.inra.fr/cati-icat/Presentation. Moreover, he co-animates the regional seminar MIAD (Mathematical models for decision making in environment, agronomy and processing of agricultural resources).
- **Scientific animation at the national level**: Marie-Laure Mugnier is member of the animating committee of the pre-GDR "Aspects algorithmiques de l'Intelligence Artificielle" http://www.gdria.fr and of the organizing committee of the workshop "Journées d'Intelligence Artificielle Fondamentale" (JIAF, the annual meeting of the French community on the foundations of AI) http://icube-web.unistra.fr/gdri3/index.php/Thème_1_:_Intelligence_Artificielle_Fondamentale

  Rallou Thomopoulos is co-leader (together with César Acéves, INSA Toulouse) of the trans-unit program "InCom" (Knowledge and Model Integration) of the CEPIA Division of INRA.

9.1.7. Scientific expertise

- Rallou Thomopoulos and Madalina Croitoru are members of the management committee of the European cooperation network (COST) "Mathematical and Computer Science Methods for Food Science and Industry", accepted in Nov. 2105. http://www.cost.eu/COST_Actions/ca/CA15118http://www.cost.eu/COST_Actions/ca/CA15118?management
- Marie-Laure Mugnier is member of the scientific advisory board of the Food and Bioproducts department (CEPIA) at INRA (2011-2016).
- Michel Chein is member of the scientific advisory board of ABES (French Agency for Academic Libraries), (2010-2016)
- Patrice Buche participates to the Wheat Data initiative of Research Data Alliance, whose objective is to propose recommandations for wheat and other cereals data http://ist.blogs.inra.fr/wdi/ (2015-2016)
- Marie-Laure Mugnier was member of the HCERES 2016 evaluation committee for IRISA.
- We also participate to punctual expertise tasks, as experts for ANR, INRA and Inria.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

The six faculty members teach at all university levels (IUT, Licence, Master). The main courses they are in charge of are: Logics (L), Web Technologies (IUT), Artificial Intelligence (M), Knowledge Representation and Reasoning (M), Social and Semantic Web (M). Some full-time researchers give Master courses (J.-F. Baget 40H; M. Bienvenu 15H).

In addition, Rallou Thomopoulos has been lecturer in the 2015-2016 “Multicriteria Decision Methods” training session, and instructor in the “Companion Modeling” and “Data, Knowledge and Model Integration” 2016 training programs of Laval University (Quebec).

Moreover, faculty members have some specific responsibilities in the Computer Science Licence and Master:

- Michel Leclère (Faculty): since 2011, he manages the program “Data, Knowledge and Natural Language Processing” (DECOL), part of the Master of Computer Science (about 30 students). This program is co-managed by Federico Ulliana (Faculty) since 2016.
- Marie-Laure Mugnier (Faculty): since 2011, she is (co)-director of the Master in Computer Science, which gathers 6 programs (about 250 students). She also led the Master project for the next four years (LMD4, from 2015/16 to 2018/2019).
- Madalina Croitoru (IUT): since Sept. 2014, she manages the “année spéciale” (about 25 students).

9.2.2. Involvement in University Structures

- Michel Leclère: since Sept. 2015, he is deputy manager of the Computer Science teaching Department from the Science Faculty, Univeristy of Montpellier.
- Marie-Laure Mugnier: since 2016, she is member of the “pôle de formation et de recherche” MIPS (Mathématiques, Informatique, Physique et Systèmes) of the University of Montpellier.

9.2.3. Supervision

9.2.3.1. Thesis defended in 2016

- Namarata Patel defended her PhD thesis “Mise en oeuvre de préférences dans les problèmes de décision” on Oct., 7 2016 in Montpellier. Advisor: Souhila Kaci (Univ. Montpellier), co-advisor: Roland Ducournau (Univ. Montpellier), reviewers: Jérôme Lang (CNRS, LAMASADE) and Nic Wilson (Univ. College Cork), jury members: Farid Nouioua (Univ. Aix-Marseille) and Nadjib Lazaar (Univ. Montpellier).

- Abdallah Arioua defended his PhD thesis “"Formalizing and Studying Dialectical Explanations in Inconsistent Knowledge Bases” on Oct., 17 2016 in Montpellier. Advisors: Patrice Buche (UMR IATE) and Madalina Croitoru (Univ. Montpellier), reviewers: Anthony Hunter (Univ. College London) and Nicolas Maudet (Univ. Pierre et Marie Curie), jury members: Juliette Dibie (AgroParisTech), Leila Amgoud (IRIT), Bernard Cuq (Montpellier SupAgro) and Jérôme Fortin (Univ. Montpellier).
- Fabien Garreau defended his PhD thesis “Extension d’ASP pour couvrir des fragments DL traitables : étude théorique et implémentation” on Nov., 24 2016 in Angers. Advisor: Igor Stephan (Univ. Angers), co-advisors: Jean-François Baget (Inria) and Laurent Garcia (Univ. Angers), reviewers: Andreas Herzig (IRIT) and Philippe Lamarre (INSA Lyon), jury members: Odile Papini (Univ. Aix-Marseille), Claire Lefevre (Univ. Angers) and Marie-Laure Mugnier (Univ. Montpellier).
- Swan Rocher defended his PhD thesis “Querying Existential Rule Knowledge Bases: Decidability and Complexity” on Nov., 25 2016 in Montpellier. Advisor: Marie-Laure Mugnier (Univ. Montpellier), co-advisor: Jean-François Baget (Inria), reviewers: Marie-Christine Rousset (Univ. Grenoble) and Sebastian Rudolph (TU Dresden), jury members: Andreas Pieris (Univ. Edinburgh) and Christophe Paul (CNRS, LIRMM).

9.2.3.2. Ongoing thesis

PhD in progress are:

- Stathis Delivorias. Supervisors: Federico Ulliana, Michel Leclère and Marie-Laure Mugnier. “Boundedness and Module extraction in Existential Rules KBs”. Started Oct. 2015.
- Abdelraouf Hecham. Supervisors: Madalina Croitoru and Pierre Bisquert. “Logical argumentation with dual cognitive systems”. Algerian National Ministry Grant 2015-2018.
- Bruno Yun. Supervisors: Madalina Croitoru, Rallou Thomopolous, Srdjan Vesic. “Decision Making and Ranking Semantics in Logical Argumentation Frameworks”. French National Ministry Grant 2016-2019.

9.2.4. Juries

In the following list, we exclude our participation in the PhD juries of GraphIK PhD Students.

- Marie-Laure Mugnier was PhD jury president - Christopher Beatrix - University of Nantes /LERIA - November 2016
- Meghyn Bienvenu was PhD co-supervisor - Camille Bourgaux - University of Orsay / LRI - September 2016
- Mare-Laure Mugnier was PhD reviewer - Camille Bourgaux - University of Orsay / LRI - September 2016
- Marie-Laure Mugnier was HDR reviewer - Nathalie Pernelle - University of Orsay / LRI - June 2016
- Patrice Buche was PhD reviewer - Fatma Chamekh - University of Jean Moulin / Lyon 3- December 2016
- Patrice Buche was HDR examiner - Nathalie Pernelle - University of Orsay / LRI - June 2016
- Federico Ulliana was member of the selection committee for a “Maître de conférence” position in Paris Dauphine

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Major publications by the team in recent years

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Invited Conferences

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Project-Team HEPHAISTOS

HExapode, PHysiology, AssISTance and RobOtics

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Robotics and Smart environments

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Project-Team HEPHAISTOS

Creation of the Team: 2014 January 01, updated into Project-Team: 2015 July 01

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Computer Science and Digital Science:

2.3. - Embedded and cyber-physical systems
5.1. - Human-Computer Interaction
5.6. - Virtual reality, augmented reality
5.10. - Robotics
5.11. - Smart spaces
6.1. - Mathematical Modeling
6.2. - Scientific Computing, Numerical Analysis & Optimization
6.4. - Automatic control
7.6. - Computer Algebra
7.14. - Game Theory
8.5. - Robotics

Other Research Topics and Application Domains:

2.1. - Well being
2.5. - Handicap and personal assistances
2.7. - Medical devices
2.8. - Sports, performance, motor skills
3.1. - Sustainable development
5.2. - Design and manufacturing
5.6. - Robotic systems
8.1. - Smart building/home
8.4. - Security and personal assistance
9.1. - Education
9.2. - Art
9.10. - Ethics

1. Members

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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 [19]
- 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.

Experimental work and the development of our own prototypes are strategic for the project as they allow us to validate our theoretical work and to discover new problems that will feed in the long term the theoretical analysis developed by the team members.

Dissemination is also an essential goal of our activity as its background both on the assistance side and on the theoretical activities as our approaches are not sufficiently known in the medical, engineering and academic communities.

In summary HEPHAISTOS has as major research axes assistance robotics, modeling (see section 7.3.2), 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 [1], [8], [5]:

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 componant** 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 ...).

3.2. Robotics

HEPHAISTOS, as a follow-up of COPRIN, has a long-standing tradition of robotics studies, especially for closed-loop robots [4], 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 [15]. 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. Domain 1

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 robotics
- strong collaboration with the medical community on walking analysis, rehabilitation (section 7.2.3) and activities detection (section 7.2.1)

5.1.2. Experimentation

- extensive test period for our walkers in clinical environment (section 7.2.3)
- start of the daily activities monitoring in a retirement house (section 7.2.1)

5.1.3. Transfer

- contract with Ellcie-Healthy for the evaluation of connected objects

5.1.3.1. Awards

- J-P. Merlet has been a finalist for the best paper award of the Eucomes conference and of the IROS conference

BEST PAPERS AWARDS :
[14] **Eucomes**. J.-P. MERLET.
[10] **IEEE Int. Conf. on Intelligent Robots and Systems (IROS)**. J.-P. MERLET.

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: Odile Pourtallier and Jean-Pierre Merlet
- Contact: Jean-Pierre Merlet
- URL: http://www-sop.inria.fr/hephaistos/developpements/main.html

6.2. Platforms

We describe here only the new platforms that have been developed in 2016 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).

6.2.1. GMSIVE ADT: virtual reality and rehabilitation

Inria has agreed to fund us for developing the platform GMSIVE 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 will 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 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 motion base are effective while the robot has been installed but not tested yet and we have started to study the coupling between the motion generators and the 3D visualization.

6.2.2. Activities detection platform

For non intrusive activities detection we use low cost distance and motion sensors that are incorporated in a 3D printed box (figure 1) and constitute a detection station. Several such station are implemented at appropriate place in the location that has to be monitored (e.g. the Valrose EHPAD where 15 such stations has been deployed at the end of 2016 while 17 stations will be deployed at Institut Claude Pompidou at the very beginning of 2017). Although the information provided by each station is relatively poor an appropriate network of such station allow us to provide the information requested by the medical community.

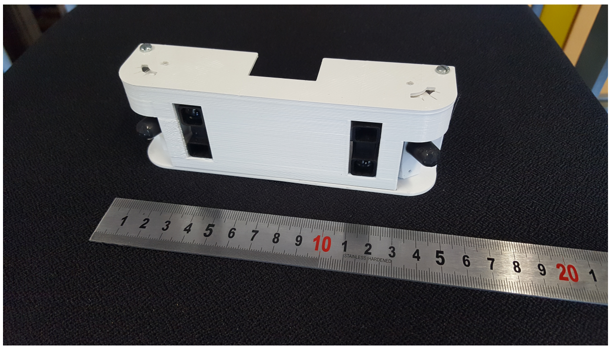

Figure 1. A station for activities detection. The 4 sensors allow to determine the presence of the subject in a given zone, his/her direction of motion and speed even at night

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[12]. For control it is essential to determine the current pose of the robot for given cable lengths (forward kinematics, FK) and to be able to calculate the cable lengths for a given pose of the platform (inverse kinematics, IK). If the cables are supposed to be non-deformable the IK problem is trivial and has a single solution but the FK is complex, admits several solutions and raises several issues. We have shown in the past that to get all FK solutions for a CDPR with m cables we have to consider not only the case where all cables are under tension but also have to solve the FK for all combinations of cables under tension with 1 to m cables. Surprisingly the FK is more difficult if the CDPR has less than 6 cables under tension. Our team, in collaboration with M. Carricato of Bologna University, is the first to have designed a solving algorithm that allow to compute in a guaranteed manner all FK solutions while a theoretical approach has allowed us to provide a bound for the maximal number of solutions according to the number of cables under tension (respectively 24, 156, 216, 140 and 40 for 2, 3, 4, 5, 6 cables).

Even more complex kinematic problems are involved if we assume that the cable are catenary-like, which is valid for large dimension robot, and involves inverse hyperbolic functions and square root, prohibiting to use algebraic geometry tools for estimating the maximal number of solutions and for the solving. In that case both the IK and FK may have multiple solutions and we have exhibited last year interval analysis-based solving algorithms for the IK and FK based on our interval analysis library `ALIAS`, that is the only existing algorithm for managing such complex cables. However such algorithm has the drawback, beside being computer intensive, to provide only solution(s) within a given search space for the unknowns. In our IK and FK problems two unknowns for each cable are the horizontal and vertical components F_x, F_z of the force exerted by the cables on the platform. In our case we have only the constraint $F_x > 0$ and F_z lower than half the mass of the cable but have no upper bound for F_x and lower bound for F_z. We may choose arbitrary large values for these bounds at the expense of an exponentially increasing computation time. As for the IK, beside F_x, F_z, the length of the cable at rest L_0 is an unknown with $L_0 > 0$ but no known upper bound. This year we have both improved the interval analysis algorithms but have also explored an original continuation scheme that be used both for the IK and FK whatever is the cable model. The idea is to assume that the cable model includes a set of physical parameters $\mathcal{P}$ which describe the elastic and deformation behavior of the cable material. We assume that their are limit values $\mathcal{P}_r$ for these parameters such that the cable behave like a non-deformable, non-elastic cable while the real cable parameter is $\mathcal{P}_d$. For example for catenary cables elasticity is defined by the Young modulus E of the cable material while the cable deformations is conditioned by its linear density μ. If E goes to infinity and μ to 0, then the cable is non-deformable, non-elastic. Now let us assume that we have a robot state for which the IK or FK are satisfied with the parameters $\mathcal{P}$. Assume that we modify $\mathcal{P}_d$ by a sufficient small amount ϵ toward $\mathcal{P}_r$ so that the Newton scheme allow us to determine the new robot state for $\mathcal{P} = \mathcal{P}_d + \epsilon$. Proceeding iteratively along this way will lead us to a robot state that must be very close to one obtained for non deformable, non elastic cables. Now we may revert the process: starting from all the IK or FK solutions obtained for non deformable cables (corresponding to $\mathcal{P} = \mathcal{P}_r$) we use Newton to compute a new robot state with $\mathcal{P}$ closer to $\mathcal{P}_d$ and doing that iteratively will lead to the solution(s) for $\mathcal{P} = \mathcal{P}_d$). We have also shown that a safe value of ϵ (ie. one that guarantee to obtain continuous solution without jump) may be calculated at each step by using the Kantorovitch theorem. We have implemented this principle for both the IK and FK problems (for 6 cables for the IK) and have found new IK and FK solutions which not been found previously because they were outside the search space of the interval analysis algorithms. A side benefit of this principle is that it has allowed us to be the first to provide an upper bound on the maximal number of solutions (63 for the IK of a robot with 6 cables, 33383 for the FK of a robot with 8 cables) whatever is the cable model. These new algorithms are much faster than the previous one (around one minute for the IK and 10 mn for the FK instead of several hours). However they raise a theoretical issue as the continuation scheme may lead to a solution that is close to be singular in which case the scheme cannot work. Understanding the singularity of the kinematics of CDPR is therefore a major problem. For the time being we mix the continuation scheme with the interval one that is basically used to solve the kinematic problem when the continuation scheme detect a singularity. As a test example we have considered a difficult CDPR with 8 cables and have shown a case with up to 41 solutions for the FK [10],[14],[11]. Figure 2 shows two of these solutions.

We have also investigated the calculation of cross-section of the workspace of CDPR [13]. We have shown that the border of this workspace for non deformable of purely elastic cables may be calculated rigorously by using an algorithm mixing a theoretical approach and numerical calculation. For catenary cables we have proposed a method that calculates a set of boxes that are guaranteed to lie in the workspace, getting smaller and smaller as soon as they are close to the border. Unfortunately this algorithm is highly computer intensive.

7.1.2. Cable-Driven Parallel Robots for additive manufacturing in architecture

Participant: Yves Papegay.

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 scale 1 and seems to be a good alternative to crane and industrial manipulators in the area of additive manufacturing.

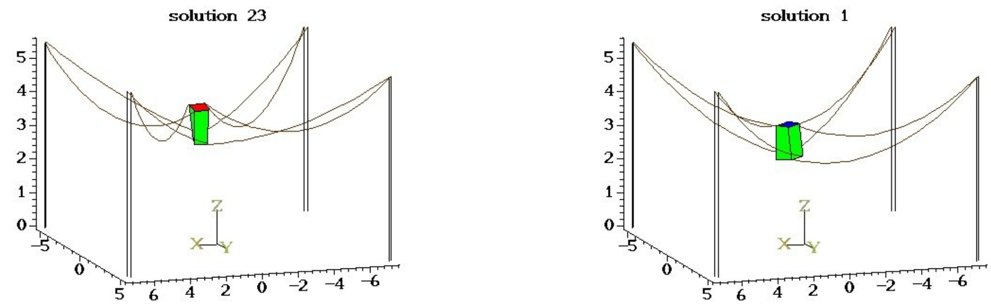

Figure 2. Two poses that are solutions of the forward kinematics, the left one being unstable while the right one is stable.

Based on the proof of concept developed during the previous collaboration with CNAM and Ecole Nationale Supérieure d'Architecture Paris-Malaquais, the design of a new large scale CDPR for additive manufacturing of building based on ultra-high performance concrete has started under our supervision.

A new partnership with the the XtreeE start-up company aiming at developing a real size industrial 3D-printer of concrete has been established.

7.2. Assistance

7.2.1. Smart Environment for Human Behaviour Recognition

Participants: Mohamed Hedi Amri, Alain Coulbois, Artem Melnyk, Aurélien Massein, Yves Papegay, Odile Pourtallier [correspondante].

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.

This year we have concentrated our effort on the first step of this research that consists in being able to locate the person in his/her indoor environment.

A natural way of being able to adapt the accuracy of localization (and consequently accuracy of monitoring), is to use a partition of the monitoring area in a finite number of elementary zones ; the number of zones together with their geometry being closely related with the pursued level of monitoring. In practice these zones will be materialized by sensors barriers that detect the passage of a person from one zone to the other. Henceforth each zone are polygonal.

Several directions have been followed this year.

- monitoring system design,
- material development,
- data gathering and analysis,
- experimentation.

7.2.1.1. Monitoring system design

We aim at designing the partition of the monitoring space. Given the geometry of the monitoring area, the admissible position of the sensors barriers and a set of points of interest, the objective is to determine the positions of a minimal number of barriers such that each zone therefore defined includes at most one point of interest. The crossing of a given secession of barriers therefore allows to determine the trajectory of a person from one point of interest to another. An algorithm for solving this problem has been developed.

7.2.1.2. Material development

We initially used commercialized Infra Red barriers to detect the crossing time from one zone to an other. Nevertheless although the collected data is sufficient for the monitoring of a single person it prove not to be sufficient in a environment where there may be several persons, which is typically the case when considering retirement home for example.

Hence we have developed a multi-sensor barrier, a box containing two infra red distance sensors and two motion sensors (passive infrared type). It has been designed and created by 3D fast prototyping printer. The box is light, cheap and discreet. In addition to detecting the crossing time, it also gives the direction of crossing together with information about the speed and the size of the crossing person or object. This last information is helpful to differentiate for example a person using a wheelchair, a valid person (e.g medical staff), or an elderly.

We use phidget interface kits connected to a fit-pc for data acquisition and recording.

7.2.1.3. Data gathering and analysis

The aim of this data processing is to transform the raw data provided by the sensor barriers in a higher level data composed by the time and direction of crossing and rough estimation of the speed and size of the object or person crossing the barrier. This information can be deduced using only the data given by the distance sensors after processing. Nevertheless in real situations the barrier may be hidden by an object (food or cleaning trolley for example), and the redundant information from PIR sensors of an other closed barrier may be useful to recover the missing information.

The data are intended to be collected on large period of time (typically months). Inline filtering and averaging techniques were used to transform large and noisy raw data to get reasonable dataset size. Figure 3 shows in blue or red the general direction of the measurement of the stations (that create detection zones) and in each zone the current estimation of the number of people in each zone (a cross indicates 0, a black circle represents one person). For example the lower left zone has between 1 and 2 people.

7.2.1.4. Experimentation

A monitoring system has been installed in the first floor of EHPAD Valrose in Nice. The area of monitoring was restricted to the hallway that leads to the individual rooms of six residents. Residents are proposed several activities (social or cultural activities, physical activities, meals) and have to use the hallway when participating to those activities. In addition to residents medical and service staff also use this hallway. The aim of this experiment is to determine an activity measure for each resident and to study its evolution with time. In that case the sensor placement is designed in such way that individual information may be obtained (e.g. by having stations on both side of the door of the individual room).

The installed system is composed of 10 multi sensor barriers installed on the wall of the hallway and 7 additional PIR sensors installed on the ceiling of the hallway. The data are transmitted by phidget interface kits and are processed by a fit-PC that store the daily data sets. A similar setup will be installed at the very beginning of 2017 in the Institut Claude Pompidou to monitor the activity in the corridors and in the waiting room. Here the medical community is more interested in statistical analysis than in individual analysis.

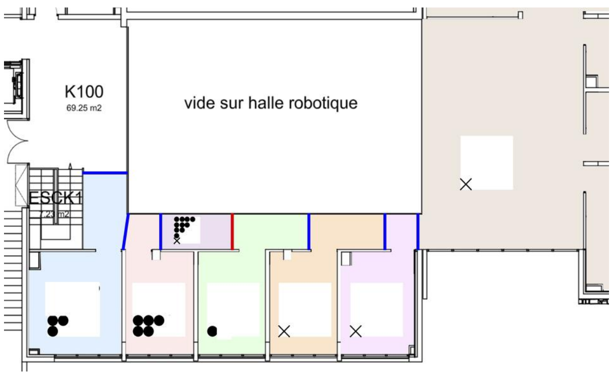

Figure 3. Occupancy of zone in a complex environment as measured by several stations

7.2.2. Sensors placement

Both economic motivations due to demographic evolution and willingness of people to live independently at home when aging, facing physical impairment or recovering from injuries has raised the need for activity monitoring at home, in rehabilitation center or in retirement home. Monitoring systems provide informations that can range from a broad measure of the daily activity to a precise analysis of the ability of a person performing a task (cooking, dressing, ...) and its evolution.

The broad range of needs and contexts, together with the large variety of available sensors implies the necessity to carefully think the design of the monitoring system. An appropriate system should be inexpensive and forgettable for the monitored person, should respect privacy but collect necessary data, and should easily adapt to stick to new needs. We aim to provide an assisting tool for designing appropriate monitoring systems.

As a second year of a PhD work, metrics have been defined to evaluate quality of sensors solutions and placement to infer people behaviors inside a smart environments. Based on these metrics, a methodology for optimal design of smart environments has been developed.

7.2.3. Rehabilitation

Participants: Alain Coulbois, Artem Melnyk, Jean-Pierre Merlet [correspondant].

We have developed the specific walking aid `ANG-med` to be used to monitor rehabilitation exercises beside performing analysis of walking pattern as any walker of the `ANG` family. The main addition for this walker are two rear looking distance sensors and two of such sensor mounted on a pan-tilt head (figure 4). These sensors have been placed under the guidance of the medical community in order to monitor and assess rehabilitation exercise such as leg flexion/extension/abduction and plantar flexion.

The walker is since on year in test in the MATIA fundation in Spain. The software that is used to for this walker has been developed with the European RAPP project (see section 9.3.1.1) so that new exercise may easily be programmed and downloaded through a message passing system [9].

7.3. Miscellaneous results

7.3.1. Analysis of multi unit uniform price auction

Participant: Odile Pourtallier [correspondante].

From previous works on CO2 and electricity market we have identified relevant auction mechanism. This mechanism is strongly related with multi unit uniform price auction. In collaboration with M. Tidball (Lameta INRA) we study this mechanism using game theory models such as optimal stopping time game. The first results have been presented to the 17th ISDG conference (Urbino, Italy July 12-15 2016).

Figure 4. Rear view of the `ANG-med` walker with the 4 distance sensors that are used to monitor and assess rehabilitation exercises

7.3.2. 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, and ease the integration of our environment into the airbus toolbox.

In 2016, we have studied how to map modeling concepts used by other Airbus tools into our modeling concepts to allow import in MOSELA of existing models, and perform corresponding C generation [17].

8. Bilateral Contracts and Grants with Industry

8.1. Airbus

8.1.1. Airbus

Participant: Yves Papegay.

Research activities on MOSELA environment, section 7.3.2, have been covered by a contract with Airbus company.

8.1.2. *GénérationRobot*

Participant: Jean-Pierre Merlet.

- we have got a grant from the company GénérationRobot to develop a pedagogical cable-driven parallel robot as a direct consequence from our research work, see section 7.1.1.

8.1.3. *Ellcie-Healthy*

Participants: Alain Coulbois, Jean-Pierre Merlet.

- we have got a grant from the company Ellcie-Healthy to evaluate connect objects that are developed by this company.

9. Partnerships and Cooperations

9.1. Regional Initiatives

- CPER project MADORSON for the assistance to elderly people (with the STARS project)
- we have submitted several projects to the local IDEX without success but we are preparing several projects for the next year

9.2. National Initiatives

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

9.3. European Initiatives

9.3.1. *FP7 & H2020 Projects*

9.3.1.1. RAPP

Type: COOPERATION

Instrument: Specific Targeted Research Project

Objective: Robotic Applications for Delivering Smart User Empowering Applications

Duration: December 2013-December 2016

Coordinator: CERTH/ITI

Partner: CERTH/ITI(Greece), Inria, WUT (Poland), ORTELIO (UK), ORMYLIA (Greece), INGEMA (Spain)

Inria contact: David Daney, Jean-Pierre Merlet, Manuel Serrano

Abstract: our societies are affected by a dramatic demographic change, in the near future elderly and people requiring support in their daily life will increase and caregivers will not be enough to assist and support them. Socially interactive robots can help to confront this situation not only by physically assisting people but also functioning as a companion. The increasing sales figures of robots are pointing that we are in front of a trend break for robotics. To lower the cost for developers and to increase their interest on developing robotic applications, the RAPP introduces the idea of robots as platforms. RAPP (Robotic Applications for Delivering Smart User Empowering Applications) will provide a software platform in order to support the creation and delivery of robotics applications (RAPPs) targeted to people at risk of exclusion, especially older people. The open-source software platform will provide an API that contains the functionalities for implementing RAPPs and accessing the robot's sensors and actuators using higher level commands, by adding a middleware stack with added functionalities suitable for different kinds of robots. RAPP will expand the computational and storage capabilities of robots and enable machine learning operations, distributed data collection and processing, and knowledge sharing among robots in order to provide personalized applications based on adaptation to individuals. The use of a common API will assist developers is creating improved applications for different types of robots that target to people with different needs, capabilities and expectations, while at the same time respect their privacy and autonomy, thus the proposed RAPP Store will have a profound effect in the robotic application market. The results of RAPP will be evaluated through the development and benchmarking of social assistive RAPPs, which exploit the innovative features (RAPP API, RAPP Store, knowledge reuse, etc.) introduced by the proposed paradigm.

9.4. International Initiatives

9.4.1. 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

9.5. International Research Visitors

9.5.1. Visits of International Scientists

We have received for an extended stay our joint PhD student J. Pickard from University of New Brunswick together with his canadian supervisor J.A Carretero. We have received the Associate Professor Martin Pfurner from Innsbruck University for an extended stay and and Cuong Trinh Duc, PhD student from University Genova while several other scientists from other domains have visited our robotics flat.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

- J-P. Merlet was General Chair of ARK 2016, organized by the team in Grasse (70 attendees), [16]

10.1.1.2. Member of the Organizing Committees

- J-P. Merlet is a member of the scientific committee of the European Conference on Mechanism Science (EUCOMES), chairman of the scientific Committee of the Computational Kinematics workshop, a member of the steering Committee of IROS
- Y. Papegay is a permanent member of the International Steering Committee of the International Mathematica Symposium conferences series.

10.1.2. Scientific Events Selection

10.1.2.1. Reviewer

- J-P. Merlet has been reviewing Editor for IROS 2016.
- The members of the team reviewed numerous papers for numerous international conferences.

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

10.1.4. Invited Talks

- J-P. Merlet has given a talk during the Scientific days of Inria and the Human Robot Interaction workshop

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 has be re-elected as one of the 10 members of IFToMM Executive Council, the board of this federation. He is a member of the scientific committee of the CNRS GDR robotique.

10.1.6. Scientific Expertise

- J-P. Merlet was involved in project evaluations for several foreign funding agencies (Israel, Austria, Finland). He was also appointed as *Nominator* for the Japan's Prize. He was a member of the jury of the PhD Award of GDR robotique.

10.1.7. Research Administration

- J-P. Merlet is an elected member of Inria Scientific Council. and member of the CAC of UCA COMUE.
- O. Pourtallier is a board member of SeaTech, an Engineering School of University of Toulon. She is a member of the Inria CSD (doctoral students monitoring), and is responsible of the Inria NICE committee (long term invited scientists and post-doctoral student selection).
- Y. Papegay is a member of the Inria CUMIR and of the ADT committee

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master: J-P. Merlet lectured 8 hours on robotics and connected objects to Master NeuroMoteur (M2) at University Paris Est. He has participated to the Parallel Kinematic Machine summer school organized by LIRMM (6h)

Master : O. Pourtallier lectured 6 hours on game theory to Master OSE (M2), at École des Mines de Paris, Sophia Antipolis, France.

E-learning

Mooc ICN : J-P. Merlet and Y. Papegay have contributed to this MOOC which is intended top introduce the numerical world to teacher. '

10.2.2. Supervision

- PhD in Progress : A. Massein, Design of Smart Environment for Human Behaviour Recognition, 2013-2016, supervisors: D.Daney, Y. Papegay

10.2.3. Juries

- J-P. Merlet has been a member of 5 PhD and 3 HDR juries, and for 6 of them has been the president of the jury.

10.3. Popularization

- J-P. Merlet has participated to a meeting "Future of robotics" organized by the Académie of Sciences. As a member of Executive Council of IFToMM he has contributed to the organization of the third Students International Olympiad on Mechanism and Machine Science held in Madrid. He is also a regular reviewer for Interstices and a contributor [18]
- Y.Papegay is actively participating to the Math.en.Jeans initiative for Mathematics teaching for undergraduate students. He has organized and animated summer schools in experimental mathematics and computer sciences. A three weeks session has been held at the University of Western Australia in Perth in July and three other one week sessions have been held in Oxford in June and August gathering around 50 high-school students - most of them were awardees in Mathematics Olympiads.

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Project-Team INDES

Secure Diffuse Programming

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Distributed programming and Software engineering

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Project-Team INDES

Creation of the Team: 2009 January 01, updated into Project-Team: 2010 July 01

Keywords:

Computer Science and Digital Science:

1.3. - Distributed Systems
2. - Software
2.1. - Programming Languages
2.1.3. - Functional programming
2.1.7. - Distributed programming
2.1.8. - Synchronous languages
2.1.9. - Dynamic languages
2.2.1. - Static analysis
2.2.3. - Run-time systems
4. - Security and privacy
4.3.3. - Cryptographic protocols
4.6. - Authentication
4.7. - Access control
4.8. - Privacy-enhancing technologies

Other Research Topics and Application Domains:

6.3.1. - Web
6.4. - Internet of things
9.4.1. - Computer science
9.8. - Privacy

1. Members

Research Scientists

Manuel Serrano [Team leader, Inria, Senior Researcher, HDR]
Nataliia Bielova [Inria, Researcher]
Gérard Boudol [Inria, Senior Researcher, until Jun 2016, HDR]
Ilaria Castellani [Inria, Researcher]
Tamara Rezk [Inria, Researcher]
Bernard Serpette [Inria, Researcher]

Technical Staff

Cédric Duminy [Inria]
Vincent Prunet [Inria, granted by FP7 RAPP project]

PhD Students

Yoann Couillec [Inria, until June 2016]
Dolière Francis Some [Inria]
Colin Vidal [Inria]

Post-Doctoral Fellow

Nguyen Nhat Minh Ngo [Inria, from October 2016]

Administrative Assistant

Nathalie Bellesso [Inria]

Other

Raimil Cruz Concepcion [University of Chile, Visiting Scientist, from May 2016 until July 2016]

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 [8]. 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 [9]. 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 [2], [1]. 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 [6]. 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. Hop

KEYWORDS: Domotique - Web 2.0 - Iot - Functional language - Programming
SCIENTIFIC DESCRIPTION

Hop.js is a platform for web, cloud, and IoT applications. Its development environment is composed of:

- a programming language named HopScript, which is based on ECMAScript 262, //aka// JavaScript;
- an optimized web server;
- on-the-fly compilers for generating HTML, CSS, and client-side JavaScript;
- an ahead-of-time compiler for compiling JavaScript to native code;
- numerous APIs for networking, multimedia, robotics, IoT, etc.

The HopScript language extends JavaScript to consistently define the server and client part of web applications and IoT applications. HopScript supports syntactic forms that help creating HTML elements. It supports services that enable function calls over HTTP. Being at higher level than traditional Ajax programming, Hop.js services avoid the burden and pitfalls of URL management and explicit data marshalling. They combine the benefits of a high level RPC mechanism and low level HTTP compatibility.

Although Hop.js can be used to develop traditional web servers, it is particularly adapted to the development of web applications embedded into devices, where the server and client part of the application are intimately interoperating with each other. The programing model of Hop.js fosters the joint specification of server and client code, and allows the rapid development of web user interfaces, on the client, controlling the execution of the distributed application. By defining a single data model, providing functions that can run indifferently on both sides, and almost forgetting about client-server protocols, Hop.js seems well suited for agile development of web applications for this class of applications.

- Participants: Manuel Serrano and Vincent Prunet
- Contact: Manuel Serrano
- URL: http://hop.inria.fr

4.2. Mashic

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

4.3. Webstats

Webstats is a follow-up of the internship on JavaScript constructs used in top Alexa sites, started in summer 2015 by Dolière Francis Some. He analyzed the top 10,000 Alexa sites, and provided statistics about them. Among those statistics, their are:

- the most popular JavaScript libraries
- the most recurrent JavaScript constructs
- the adoption of security features such as:
  - The Content Security Policy, a policy for defending against Cross-Site-Script attacks
  - HttpOnly and Secure cookies, that prevents attacks like session hijacking.

Starting from April, 2016, this study is performed periodically, at the end of each month. The results are accessible online at https://webstats.inria.fr.

- Contact: Francis Some
- URL: https://webstats.inria.fr

5. New Results

5.1. Web programming

Participants: Cédric Duminy, Vincent Prunet, Bernard Serpette, Manuel Serrano [correspondant], Colin Vidal.

Hop.js [20], [22] is a new platform for web applications, potentially involving interconnected servers. The server-side execution is compatible with Node.js. Programmers then benefit from numerous existing libraries and applications. Hop.js also introduces distinctive programming features that are expressed in the HopScript programming language, a multitier extension of JavaScript. The Hop.js runtime embeds a multi-backends HopScript compiler.

The HopScript language extends JavaScript to consistently define the server and client part of a web application. HopScript supports syntactic forms that help creating HTML elements. It supports services that enable function calls over HTTP. Being at higher level than traditional Ajax programming, Hop.js services avoid the burden and pitfalls of URL management and explicit data marshalling. They combine the benefits of a high level RPC mechanism and low level HTTP compatibility.

Hop.js supports server-side and client-side parallelism. On the server, it first relies on its built-in pipelining architecture that automatically decodes HTTP requests in parallel. It also relies on server-side web workers that programs may explicitly launch to perform background tasks (functions and services). Each worker runs its own system thread. The service invocation and execution API fully integrates with the JavaScript execution flow, allowing synchronous and asynchronous operations on both client and server processes. The asynchronous response API can be combined with the worker API, allowing processing and asynchronous service responses to be delegated between workers. On the browser client-side parallelism relies on standard web workers.

Although Hop.js can be used to develop traditional web servers, it is particularly adapted to the development of web applications embedded into devices, where the server and client part of the application are intimately interoperating with each other. The programing model of Hop.js fosters the joint specification of server and client code, and allows the rapid development of web user interfaces, on the client, controlling the execution of the distributed application. By defining a single data model, providing functions that can run indifferently on both sides, and almost forgetting about client-server protocols, Hop.js seems well suited for agile development of web applications for this class of applications.

As an example, Hop.js has already been successfully used as the core framework to develop embedded and cloud applications for connected robots and IoT devices. In the context of a European industrial collaborative project, it has been used by various categories of programmers (mostly undergraduate internships, robotic experts, and professional engineers familiar with web development techniques) to build complex distributed applications, where various sort of digital equipments (computers, robots, small devices) communicate with each other, discover themselves, and collaborate. In all cases we have observed an easy adoption from everyone. The tons of JavaScript resources and examples available on the web helped internship students to rapidly become productive. Robotic experts were instantly able to start implementing Hop.js applications. Web experts seemed to feel at home with Hop.js as it let them build working applications with Hop.js core features and then extend them with existing JavaScript third party modules, typically npm modules.

In 2016, we first version of Hop.js as been completed and released. It is available from the Web site http://hop.inria.fr.

5.1.1. Web Reactive Programming

Web UI interfaces are specified as HTML documents. When instantiated in a browser these documents are accessible from JavaScript as abstract data structures conforming to the Document Object Model (*aka* the DOM). Modifying these structures, for instance for applying updates, involves fine surgery for isolating the concerned elements and for applying the intended modifications. As these operations are generally triggered after asynchronous events that may come in response to earlier network requests or a user actions, the programming is complex and error prone. Improving on that situation has been the subject of many previous studies that propose alternative models for helping programming Web UI. Our work constitutes yet another contribution to that problem. It differs from the other solutions by the followings.

- It addresses exclusively the problem of programming the Web UI updates.
- It does not introduce a new programming model and it is fully compatible with traditional JavaScript programming.
- On the client, it only requires a very thin implementation layer whose weight is almost unnoticed in a Web browser.
- It does not impact the rest of the execution, leaving the performances unchanged.

Our proposal consists in introducing a zest of reactive programming used only for denoting the parts of the DOM that need updates. For that, we introduce two new constructs: i) reactive values, called *reactors*, that have the appearance of any regular JavaScript value, and ii) *reactive nodes*, which are DOM nodes that are automatically updated upon reactors changes. Reactors and reactive nodes can be used in pure JavaScript programs but that have been designed to complement other facilities Hop.js. To justify their design and to advocate their benefit, we show how they simplify the programming of classical Web patterns. Let us consider a classical example already detailed in the literature, a timer example, which consists in a simple Web page defined by:

```
var elapsedTime = 0;

function doEverySecond() {
   elapsedTime++;
   document.getElementById( "curTime" )
           .innerHTML = elapsedTime; }

<html>
  <script>setInterval( doEverySecond, 1000 )</script>
  <button onclick="elapsedTime = 0">reset</button>
  <div id="curTime"></div>
</html>
```

Although simple and innocuous at first glance, this program suffers from two major problems. First, the lack of modularity. The function doEverySecond, that implements the timer, increments the wall clock *and* updates the UI (via innterHTML attribute assignment). Hence, it must be aware of all the elements that needs update. This is problematic as a UI may evolve over time with some elements removed and new elements added. Each evolution of the specification will then impact doEverySecond implementation. The second problem we address is the plumbing needed for extracting and modifying the curTime element. In the pure JavaScript this involves assigning and looking up unique identifiers (curTime identifier). The reactors and reactive nodes we propose solve these two problems.

```
<html> ~{
     const T = hop.reactProxy( { elapsedTime: 0 } );
     setInterval( () => { T.elapsedTime++ }, 1000 );
  }
  <button onclick=~{T.elapsedTime=0}>reset</button>
  <div><react>~{T.elapsedTime}</react></div>
</html>
```

This Hop.js program solves the two problems previously mentioned. It is modular as new reactive elements depending on the elapsedTime can be added without modifying existing code. It avoids tedious surgery of the HTML DOM as the react node designates the node that need updates and its positioning in the UI.

We have built a first operational prototypes of reactors and reactive nodes. This work will be pursued in 2017. We will complete the implementation in Hop.js by including them in Hop-3.1.0. We will write a scientific paper describing their design and implementation.

5.1.2. Hiphop.js

Modern Web applications are rich in interactions between users and servers. Those interactions are from different nature: search and play music, book train or airplane tickets, query database or use an interactive map. From the programmer point-of-view, those interactions are handled by asynchronous events from multiple sources. Management of those events, which is called orchestration, is done by using event handlers. It is a mechanism that will call a specific function when a specific event raises. This kind of orchestration doesn't scale well since the behavior of the application has to be deduced by the programmer. Synchronous languages like Esterel, which are used in the industrial area, provides syntactic constructs that allow ordering the temporal behavior of the application. Then, reading the program source gives a precise idea of the behavior of the program at runtime.

The HipHop.js contribution is to adapt the reactive constructs of Esterel to the Web. The goal is to design a high-level tool that simplifies the orchestration of Web applications. In the traditional Esterel setting, the reactive program is written in a different source file of the host program. It is compiled independently of the host program. Therefore, the programmer must make explicit bindings between the reactive program and the host program in order to allow both of them to interact. This is inadequate for Web developments. So, HipHop.js adopts a radically different point of view: the reactive program is written in the same source code with the host program and the interaction between the reactive program and the host program is direct, thanks to a JavaScript API which is offered by the compilation output of the reactive program. HipHop.js uses a XML syntax, where each node corresponds to an Esterel instruction. This syntax has pros and cons but we think its advantages dominate. First, it is familiar to all Web developers, which do not have to learn a new syntax. Second, it is overly simple to implement as Hop.js natively supports XML parsing. Third, it gives macros for free as the XML syntax can be mixed with standard JavaScript that can create and return XML objects.

The classical Esterel example of the synchronous community is "ABRO": a program which is waiting for two events in parallel. When both events are raised, the host program is notified (here it pops a window up). At any moment, the reactive program state can be reset, in which case, the reactive program waits again for both events. For the sake of illustration, we show here how to implement ABRO in HipHop.js inside a Web page:

```
<html> ~{
     var abro =
```

```
        <hh.module A B R O>
          <hh.loopeach R>
            <hh.parallel>
                <hh.await A/>
                <hh.await B/>
            </hh.parallel>
            <hh.atom apply=${function() {alert("ABRO")}}/>
          </hh.loopeach>
        </hh.module>

    var m = new hh.ReactiveMachine(abro);
 }
 <button onclick=~{m.inputAndReact("A")}>A</button>
 <button onclick=~{m.inputAndReact("B")}>B</button>
 <button onclick=~{m.inputAndReact("R")}>R</button>
</html>
```

Pushing the buttons “A” and “B” triggers the popup message which contains "ABRO" in the browser page. In spite of its simplicity, the ABRO example is representative of a wide class of real programs. For instance, a program behaviorally similar to ABRO can be used to download a file in several parts of different sources, and merge them when all downloads are completed.

The first HipHop.js version has been released this year. It is available at the following URL http://www-sop.inria.fr/members/Colin.Vidal/hiphop/.

5.1.3. Garbage Collection with non ambiguous roots

Hop uses lot of objets with short time life.

Some Hop programs allocate many temporary objects whose lifetimes are very short. These objects are unefficiently handled by this *Mark&Sweep* garbage collector that Hop currently uses. We expect a speed-up by switching from a *Mark&Sweep* garbage collector to a generational *Stop&Copy* one. *Stop&Copy* collectors demand that all roots of the accessibility graph have to be precisely known (non ambiguous root). We have changed the code generation of the compiler in order to maintain a precise map of the pointers living in the stack.

5.1.4. Event calculus

We have studied functions over streams of events (timed values) and more precisely those which have a temporal causality property: at every instant, current outputs only depends on inputs that have already been received [24]. We have found a clear characterization of causal functions and made some proofs with the Coq system [21].

5.2. Privacy

Participant: Nataliia Bielova.

5.2.1. Hybrid Monitoring of Attacker knowledge

Enforcement of noninterference requires proving that an attacker’s knowledge about the initial state remains the same after observing a program’s public output. We have proposed a hybrid monitoring mechanism which dynamically evaluates the knowledge that is contained in program variables [14]. To get a precise estimate of the knowledge, the monitor statically analyses non-executed branches. We show that our knowledge-based monitor can be combined with existing dynamic monitors for non-interference. A distinguishing feature of such a combination is that the combined monitor is provably more permissive than each mechanism taken separately. We demonstrate this by proposing a knowledge-enhanced version of a no-sensitive-upgrade (NSU) monitor. The monitor and its static analysis have been formalized and proved correct within the Coq proof assistant.

5.3. Security

Participants: Nataliia Bielova, Ilaria Castellani, Tamara Rezk, Dolière Francis Some.

5.3.1. Security for multiparty session calculi

In our previous work, we investigated two security properties for multiparty session calculi: *access control* and *information flow security*. We proposed a type system ensuring both these properties. We also defined a monitored semantics inducing a property that is strictly included between typability and information flow security, which we called *information flow safety*.

The article [5] is an extended version of a previous workshop paper, which introduces refined versions of the safety and security properties examined in that paper and provides two additional results: compositionality of the refined safety property, and the proof that this property is ensured by a simplified version of the type system of [4].

In [18], we argue that the security requirements considered in previous work could be overly restrictive in some cases. In particular, a party is not allowed to communicate any kind of public information after receiving a secret information. The aim of [18] is to overcome this restriction, by proposing a new type discipline for a multiparty session calculus, which classifies messages according to their topics and allows unrestricted sequencing of messages on independent topics.

5.3.2. Security for dynamic and adaptable systems

We have started to study security issues in the context of dynamically evolving communicating systems, namely systems which are able to adapt themselves in reaction to particular events, arising in the system itself or in its environment. When focussing on security, examples of such events are security attacks or changes in security policies.

The paper [11] investigates a simple session calculus in which self-adaptation and security concerns may be jointly addressed. In this calculus, security violations occur when processes attempt to read or write messages of inappropriate security level within a session. Such violations trigger adaptation mechanisms that prevent the violations to propagate their effect in the remainder of the session, while allowing the computation to proceed. More specifically, our calculus is equipped with a monitored semantics based on session types, which activates local and global adaptation mechanisms for reacting respectively to soft and hard security violations. We present type soundness results that ensure that the overall protocol is still correctly executed after the application of these mechanisms.

5.3.3. Information Flow Monitoring

The dynamic aspects of JavaScript make the security analysis of web applications very challenging. Purely static analysis is prohibitively restrictive in practice since it must exclude JavaScript dynamic aspects or over-approximate them. In recent years, several dynamic enforcement mechanisms in the form of information flow monitors have been proposed. In order to better evaluate the currently available information flow monitors trade-offs, our contribution is to rigorously compare them [16]. We compare them with respect to two important dimensions according to the runtime monitor literature: soundness and transparency. We analyse five widely explored information flow monitor techniques: no-sensitive-upgrade, permissive-upgrade, hybrid monitors, secure multi execution, and multiple facets. Furthermore, we formally prove that the generalised belief in the equivalence of two of these approaches, secure multi-execution and multiple facets, is false [17].

5.3.4. Quantitative information flow measures

A number of measures for quantifying information leakage of a program have been proposed. Most of these measures evaluate a program *as a whole* by quantifying how much information can be leaked *on average* by different program outputs. While these measures perfectly fit for static program analyses, they cannot be used by dynamic analyses since they do not specify what information an attacker learns through observing one concrete program output.

In this work, we study the existing definitions of quantitative information flow [15]. Our goal is to find the definition of *dynamic leakage* – it should evaluate how much information an attacker learns when she observes *one program output*. Surprisingly, we find out that none of the existing definitions provide a suitable measure for dynamic leakage. We hence open a new research question in quantitative information flow area: which definition of dynamic leakage is suitable?

5.3.5. Access control and capability systems

Motivated by the problem of understanding the difference between practical access control and capability systems formally, we distill the essence of both in a language-based setting [19]. We first prove that access control systems and (object) capabilities are fundamentally different. We further study capabilities as an enforcement mechanism for confused deputy attacks (CDAs), since CDAs may have been the primary motivation for the invention of capabilities. To do this, we develop the first formal characterization of CDA-freedom in a language-based setting and describe its relation to standard information flow integrity. We show that, perhaps suprisingly, capabilities cannot prevent all CDAs. Next, we stipulate restrictions on programs under which capabilities ensure CDA- freedom and prove that the restrictions are sufficient. To relax those restrictions, we examine provenance semantics as sound CDA-freedom enforcement mechanisms.

6. Partnerships and Cooperations

6.1. National Initiatives

6.1.1. ANR AJACS

The AJACS project (Analyses of JavaScript Applications: Certification & Security) is by the ANR for 42 months, starting December 2014. The goal of AJACS project is to provide strong security and privacy guarantees on the client side for web application scripts. The Indes members 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.

6.1.2. 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.

6.1.2.1. Actions marquante

Inria Sophia-Antipolis Actions Marquante is a special funding for 2 postdocs during one year to explore a new research direction. The joint project with DIANA team "User discrimination on the Web: measurement, causation and prevention" has obtained this funding. The goal of this project is to detect when users get discriminated on the Web, what are the technologies used to discriminate users and how we can prevent it without breaking the functionality and sometimes useful personalisation within Web applications.

6.2. European Initiatives

6.2.1. FP7 & H2020 Projects

6.2.1.1. RAPP

Program: http://rapp-project.eu

Title: Robot App Store

Collaborator: Inria Hephaistos

Abstract: RAPP is a 36 months pan-european FP7 project, started in December 2013. Hop.js technology is used by partner academic and SME R&D teams to develop a distributed software platform and applications for assistive robotics.

6.2.2. Collaborations in European Programs, Except FP7 & H2020

6.2.2.1. ICT Cost Action IC1201 BETTY

Program:BETTY

Project acronym: BETTY

Project title: Behavioural Types for Reliable Large-Scale Software Systems

Duration: October 2012 - October 2016

Coordinator:Simon Gay, University of Glasgow

Other partners: several research groups, belonging to 22 european countries

Abstract: The aim of BETTY is to investigate and promote behavioural type theory as the basis for new foundations, programming languages, and software development methods for communication-intensive distributed systems. Behavioural type theory encompasses concepts such as interfaces, communication protocols, contracts, and choreography.

6.2.2.2. ICT Cost Action IC1405 on Reversible Computation

Program: COST

Project acronym: RC

Project title: Reversible computation - extending horizons of computing

Duration: November 2014 - November 2018

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.

6.2.2.3. Bilateral PICS project SuCCeSS

Program: PICS

Project acronym: SuCCeSS

Project title: Security, Adaptability and time in Communication

Duration: June 2016 - June 2019

Coordinator: Cinzia Di Giusto, I3S, Sophia Antipolis

Other partners: I3S, University of Gröningen

Abstract: The project SuCCeSS is a CNRS-funded "Projet coopératif" (PICS 07313), involving 2 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 Gröningen. 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.

6.3. International Research Visitors

6.3.1. Visits of International Scientists

6.3.1.1. Internships

Raimil Cruz

Date: 01/05/16 - 30/07/16

Institution: University of Chile

7. Dissemination

7.1. Promoting Scientific Activities

7.1.1. Scientific Events Organisation

7.1.1.1. General Chair, Scientific Chair

- Ilaria Castellani co-organised (with Mohammad Reza Mousavi) the workshop TRENDS 2016, which took place in Québec City in association with the CONCUR conference.

7.1.1.2. Member of the Organizing Committees

- Ilaria Castellani participated in the organisation of the 2nd Summer School of the BETTY project, which took place in Cyprus.

7.1.2. Scientific Events Selection

7.1.2.1. Member of the Conference Program Committees

- Ilaria Castellani served in the programme committee of the workshop EXPRESS/SOS 2016.
- Tamara Rezk served in the programme committee of POST, SEC@SAC, PLAS, IEEE SecDev, and APLAS 2016.

7.1.2.2. Reviewer

The team members have been reviewers for FSTJCS conference, SEC@SAC conference, USENIX Security 2016, POST 2016, NDSS 2016, and CCS 2016.

7.1.3. Journal

7.1.3.1. Member of the Editorial Boards

- Ilaria Castellani is a member of the editorial board of the french journal *Technique et Science Informatiques*.
- Tamara Rezk is a member of the editorial board of the french journal *Interstices*.

7.1.3.2. Reviewer - Reviewing Activities

The team members have been reviewers for the international journals JLAMP (*Journal of of Logical and Algebraic Methods in Programming*), LMCS (*Logical Methods in Computer Science*), International Journal of Information Security (IJIS), EEE TDCS, and ACM TISSEC.

7.1.4. Invited Talks

Manuel Serrano gave a presentation on "Diffuse Web programming" at The Open Source Innovation Spring 2016 (http://open-source-innovation-spring.org/techniques-de-programmation-web-letat-de-lart-date-conf/).

Nataliia Bielova has been invited to give a talk on Price discrimination of Online Airline Tickets at the Collaborative Action on the Protection of Privacy Rights in the Information Society (CAPRIS) project meeting, Sophia Antipolis, France.

7.1.5. Leadership within the Scientific Community

- Ilaria Castellani is the chair of the IFIP TC1 WG 1.8 on Concurrency Theory since May 2014. In this quality, she co-organises every year (together with the WG Secretary Mohammad Reza Mousavi) the annual business meeting of the working group as well as the workshop TRENDS, which is always affiliated with the CONCUR conference. Ilaria Castellani was a member of the european COST Action IC1201 BETTY on Behavioural Types (October 2012-October 2016). She also belonged to the Management Committee of BETTY and was the chair of its working group on security. Ilaria Castellani is a member of the COST Action IC1405 on Reversible Computation (November 2014-November 2018). She is also a deputy Management Committee member of this action.
- Nataliia Bielova has co-organised a Dagstuhl Seminar on Online Privacy and Web Transparency [0] with researchers from Telefonica (Spain), Stony Brook University (USA) and Princeton University (USA).
- Nataliia Bielova is a member of the W3C Tracking Protection Working Group. This group works towards creating a "DoNotTrack" specification. Its goal is to help users express their preferences on third-party tracking and help companies ensure their compliance with the specification.

7.1.6. Scientific Expertise

During 2016, Tamara Rezk has been an international research proposal evaluator for the following research agencies: Ministerio de Ciencia y Tecnología e Innovación Productiva (Foncyt, Argentina), Executive Agency for Higher Education, Research, Development and Innovation Funding (UEFISCDI, Romania).

7.2. Teaching - Supervision - Juries

7.2.1. Teaching

Licence : Vincent Prunet, Algorithms and Data Structures, 8 ETD, L2, Lycée International de Valbonne Sophia Antipolis (within the scope of the national Inria action to promote early CS courses in all scientific curricula), France

Master : Nataliia Bielova, Information Flow Security in Web Applications, 15 ETD, University of Pierre et Marie Curie, France

Master : Tamara Rezk, Web Application Security, 28H ETD, University of Nice Sophia Antipolis, France

Master : Tamara Rezk, Proofs of Cryptography, 28H ETD, University of Nice Sophia Antipolis, France

Master : Tamara Rezk, Information Flow Security in Web Applications, 15 ETD, University of Pierre et Marie Curie, France

7.2.2. Supervision

PhD in progress : **Colin Vidal**, *Programmation Web réactive*, University of Nice, 1/07/2015, **Manuel Serrano** and **Gérard Berry**.

PhD in progress : **Dolière Francis Some**, *Web Tracking Prevention*, University of Nice, 1/11/2015, **Nataliia Bielova** and **Tamara Rezk**.

PFE Master in progress: Leila Kuntar, Analysis of web tracking technologies that use 1x1 pixel image, University of Nice, Nataliia Bielova

7.2.3. Juries

- Nataliia Bielova was an examiner of the PhD thesis of Willem De Groef, KU Leuven, Belgium.
- Ilaria Castellani was a member of the "Comité de sélection " for a position of Maître de conférences at the University of Paris Diderot (Paris 7), IRIF Laboratory.

[0] https://www.dagstuhl.de/en/program/calendar/semhp/?semnr=17162

- Ilaria Castellani was a reviewer of the PhD thesis of Saverio Giallorenzo, University of Bologna. She took part in the jury of this PhD thesis, as well as of ten other PhD theses defended in the same round.
- Ilaria Castellani was an examiner for the PhD thesis of Aurélien Deharbe, Université Pierre et Marie Curie (Paris 6).
- Tamara Rezk was an examiner of the PFE juries for Security and Privacy and Mobile Cloud and IoT at Univesity of Nice Sophia Antipolis.
- Manuel Serrano was an examiner of the PhD thesis of Rabah Laouadi, Université de Montpellier.
- Manuel Serrano was an examiner of the PhD thesis of Julien Pagès, Université de Montpellier.

7.3. Popularization

- Web users are continuously tracked as they browse the Web. One of the techniques for tracking is device fingerprinting that distinguishes users based on their Web browser and operating system properties. Together with Inria Celtique team, we have proposed solutions to detect and prevent device fingerprinting via runtime monitoring of JavaScript programs. We have published an article in a general public ERCIM News magazine [0] about prevention of device fingerprinting via program monitoring [10].
- We have implemented the *WebStats* website [0]. This website collects, on a monthly basis, a number of JavaScript and security statistics about top 10 000 webpages: the usage of popular JavaScript libraries; the usage of different language constructs in these libraries; use of Content Security Policies and secure cookies, etc. The *WebStats* website can be used by programmers (to understand which JavaScript libraries are more popular), researchers in programming languages (when designing a subset of JavaScript, to safely exclude the language constructs that are rarely used according to *WebStats*), and researchers in privacy (to analyse which tracking libraries are the most prevalent).

7.4. Transfer

7.4.1. WebRobotics

The WebRobotics initiative aims at developing collaborations with partner academic and industry teams to jointly prototype and experiment end user applications involving assistive robots and sensor devices (depending on the size and number of the embedded components, applications may be either classified as robotic or IoT ones). Each WebRobotics project is structured around partner medical institutions that provide key requirements to specifications and use the actual prototype throughout their daily activity. WebRobotics Applications all use Hop.js as their core framework, natively supporting web protocols for communication and distribution of tasks, and any web enabled device such as a smartphone or tablet to drive the robots and applications. In 2016, the initiative accounted to two full time engineers until the completion of the project, mid year.

The Top Three Benefits of WebRobotics:

- WebRobotics focuses on key societal issues, developing real applications for demanding users.
- Application developers and users feedback to Hop.js framework developers, helping identify and prioritize key requirements.
- The WebRobotics application portfolio fosters the dissemination and transfer of the Hop.js technology to the Industry.

[0] http://ercim-news.ercim.eu/en106/special/using-javascript-monitoring-to-prevent-device-fingerprinting
[0] http://webstats.inria.fr/

The WebRobotics initiative now encompasses several prototypes in use by medical foundations and hospitals.

- RAPP. The WebRobotics project is part of the RAPP FP7 european project, to be completed in December 2016, where Hop.js technology is used by several academic and SME R&D teams to develop a distributed software platform and applications for assistive robotics. Two prototypes have been developed, the first one is a personal coach robot (a Nao humanoid robot embedding Hop.js distributed applications), and the second one is a smart rollator (a walking aid with additional hardware and software services for rehabilitation, training and activity monitoring. The rollator hardware and robotic components are provided by Inria Hephaistos). Both prototypes are being evaluated by partner medical institutions.
- Hopcare. Indes collaborates with other research teams (Inria STARS, Nice University Cobtek Project) and local institutes and SMEs to foster the development distributed monitoring and supervision applications with the Hop.js technology. An expert engineer is dedicated to this project (grant from UCN@Sophia Labex, until April 2016).
  - ICP (Institut Claude Pompidou Hospital, in Nice) is now using the Alzheimer diagnosis tool developed using Hop.js. User Data generated from Inria/Stars sensors and image analysis software are collected by a Hop.js server and processed before being delivered to the Physician's web tablet, as an editable web report, or paper ready PDF reports.
  - The activity monitoring application enables real-time monitoring of various events generated by hardware/software monitoring tools (such as the video monitoring applications from Inria/Stars) as well as user defined events. Hop.js is the common framework for the whole application (communications with remote information servers, processing of input data, database management, user authentication and authorization, custom views for web clients). The application will soon be deployed at the Nice Valrose EHPAD (a specialized institution for elderly who need medical care), where Inria runs an experimentation lab.
  - A third application has been developed to enable the configuration and use of Inria/Stars video analysis tools through a web interface. The application is used by researchers to tune their data processing algorithms.

7.4.2. Hop.js for IoT

As more and more software developers come to IoT, teams are facing critical challenges due to the inherent complexity of multi-platform distributed development, leading to team building issues, long and costly development cycles to deliver products with the highest quality, usability, and security standards

The Hop.js software suite enables agile software teams to build flexible, robust and secure end-to-end IoT applications with a single language and a consistent set of API and built-in software components.

Building on the Hop.js technology and the successful WebRobotics experiments, a startup project has been launched in 2016 as a spin-off of the Indes team, with the support of Inria DGD-T, funding two engineers from July 2016.

The team has initiated partnerships with IoT hardware vendors, adapted Hop.js to highly constrained execution environments on microcontrollers, and participated to a number of public and business events to promote the solution and meet future customers. The startup company is expected to launch in 2017.

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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).

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Earth, Environmental and Energy Sciences

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Team LEMON

Creation of the Team: 2014 January 01

Keywords:

Computer Science and Digital Science:
6.1.1. - Continuous Modeling (PDE, ODE)
6.1.2. - Stochastic Modeling (SPDE, SDE)
6.1.4. - Multiscale modeling
6.1.5. - Multiphysics modeling
6.2.1. - Numerical analysis of PDE and ODE
6.2.2. - Numerical probability
6.2.3. - Probabilistic methods
6.3.4. - Model reduction

Other Research Topics and Application Domains:
3.3.2. - Water: sea & ocean, lake & river
3.3.3. - Littoral
3.3.4. - Atmosphere
3.4.1. - Natural risks
3.4.3. - Pollution
4.3.2. - Hydro-energy
4.3.3. - Wind energy
8.3. - Urbanism and urban planning
9.9.1. - Environmental risks

The team is located in Montpellier.

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2. Overall Objectives

2.1. Context

Coastal zones are the theatre for numerous interfaces. The main elements that come to mind are the sea/earth interface, saline/brackish/fresh water interfaces and sediment/biological world interfaces. These elements cause most of the phenomena met within coastal zones to be in fragile equilibrium or more often, in constant evolution. This is due to the evolving external pressures, such as anthropic activity or physical forces (tectonic features, tide, precipitations, storms, sea level rise, sediment transport, etc.). In order to illustrate the considerable importance of such a research project, let us underline the following figures:

- **60 % of the world population lives in a 100km wide coastal strip** (80% within 30km in Brittany),
- **current sea level rise** has occurred at a mean rate of 1.8 mm per year for the past century, and more recently at rates estimated near 2.8 ± 0.4 to 3.1 ± 0.7 mm per year (1993-2003). It is likely to rise in the future: IPCC recently anticipated a 1.5m sea level rise within the next century,

It results that **coastal management** requires the development of theoretical and applied models to facilitate the **decision process**. For example, a city that wants to develop a harbour needs to anticipate the time-evolution of urban floods. The construction of defense barriers to protect buildings and houses from natural hazards relies on the knowledge of potential submersion events, in a period where the impact of global climatic and anthropic changes on the coastal zone is expected to generate increased coastal risks (IPCC 2007 and 2013). One also needs to analyze *"what if"* scenarios for proposed changes in land use or land cover in coastal regions (such as French Mont Saint-Michel).
As a matter of fact, the software packages available for engineering applications are usually not satisfactory. More specifically, some modeling hypotheses (such as the hydrostatic approximation) should be weakened, and more appropriate numerical schemes should be implemented. What is proposed with LEMON is to **increase the quality of coastal engineering numerical tools**, thanks to better designed mathematical and numerical models.

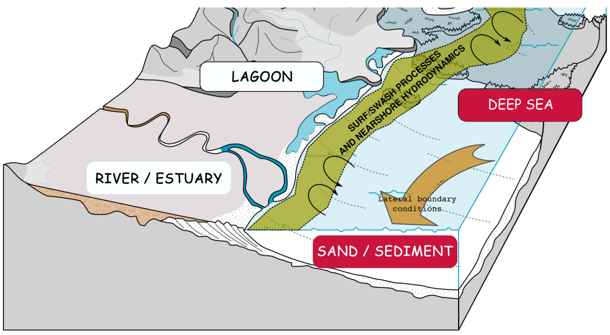

Figure 1. Examples of interacting nearshore processes. Courtesy F. Bouchette.

The mathematical modeling of the phenomena occurring within coastal zones and their interactions is currently a major scientific issue. If we want to model coastal zones, we have to consider the fact that they cover a very wide range of situations and that they are the result of several complex interacting phenomena (see Figure 1). More specifically, many time scales and space scales are involved and many physical and biological phenomena are in action. Moreover, within each zone, specific interactions between those phenomena make it an almost unique situation. Hence, we are far from having a database aggregating every possible situation. Modeling complex phenomena with the objective of building and improving management/decision tools requires the interaction of several models, each of them being dedicated to the simulation of a specific process. Such (mathematical and numerical) models usually exist but scarcely interact: therefore there is a need to understand how these bricks can be modified (forcing terms, boundary conditions) in order to be assembled. It will require a dialog with specialists of the application domain (geophysics, mechanical engineering, biology, hydrology, etc.) to help to develop new mathematical and numerical models for coastal engineering.
Developing more accurate and/or less CPU demanding models and coupling them together, LEMON will have a strong impact in the applications targeted and in coastal management.

3. Research Program

3.1. State of the Art

3.1.1. Shallow Water Models

Shallow Water (SW) wave dynamics and dissipation represent an important research field. This is because shallow water flows are the most common flows in geophysics. In shallow water regions, dispersive effects (non-hydrostatic pressure effects related to strong curvature in the flow streamlines) can become significant and affect wave transformations. The shoaling of the wave (the "steepening" that happens before the breaking) cannot be described with the usual Saint-Venant equations. To model such various evolutions, one has to use more sophisticated models (Boussinesq, Green-Naghdi...). Nowadays, the classical Saint-Venant equations can be solved numerically in an accurate way, allowing the generation of bores and the shoreline motion to be handled, using recent finite-volume or discontinuous-Galerkin schemes. In contrast, very few advanced works regarding the derivation and modern numerical solution of dispersive equations [23], [27], [56] are available in one dimensions, let alone in the multidimensional case. We can refer to [55], [30] for some linear dispersive equations, treated with finite-element methods, or to [27] for the first use of advanced high-order compact finite-volume methods for the Serre equations. Recent work undertaken during the ANR MathOCEAN [23] lead to some new 1D fully nonlinear and weakly dispersive models (Green-Naghdi like models) that allow to accurately handle the nonlinear waves transformations. High order accuracy numerical methods (based on a second-order splitting strategy) have been developed and implemented, raising a new and promising 1D numerical model. However, there is still a lack of new development regarding the multidimensional case.
In shallow water regions, depending on the complex balance between non-linear effects, dispersive effects and energy dissipation due to wave breaking, wave fronts can evolve into a large range of bore types, from purely breaking to purely undular bore. Boussinesq or Green-Naghdi models can handle these phenomena [21] . However, these models neglect the wave overturning and the associated dissipation, and the dispersive terms are not justified in the vicinity of the singularity. Previous numerical studies concerning bore dynamics using depth-averaged models have been devoted to either purely broken bores using NSW models [24], or undular bores using Boussinesq-type models [34]. Let us also mention [32] for tsunami modeling and [31], [43] for the dam-break problem. A model able to reproduce the various bore shapes, as well as the transition from one type of bore to another, is required. A first step has been made with the one-dimensional code [23], [53]. The SWASH project led by Zijlema at Delft [56] addresses the same issues.

3.1.2. Open boundary conditions and coupling algorithms

For every model set in a bounded domain, there is a need to consider boundary conditions. When the boundaries correspond to a modeling choice rather than to a physical reality, the corresponding boundary conditions should not create spurious oscillations or other unphysical behaviour at the artificial boundary. Such conditions are called **open boundary conditions** (OBC). They have been widely studied by applied mathematicians since the pionneering work of [33] on transparent boundary conditions. Deep studies of these operators have been performed in the case of linear equations, [38], [22], [50]. Unfortunately, in the case of geophysical fluid dynamics, this theory leads to nonlocal conditions (even in linear cases) that are not usable in numerical models. Most of current models (including high quality operational ones) modestly use a *no flux* condition (namely an homogeneous Neumann boundary condition) when a free boundary condition is required. But in many cases, Neumann homogeneous conditions are a very poor approximation of the exact transparent conditions. Hence the need to build higher order approximations of these conditions that remain numerically tractable.

Numerous physical processes are involved in coastal modeling, each of them depending on others (surface winds for coastal oceanography, sea currents for sandbars dynamics, etc.). Connecting two (or more) model solutions at their interface is a difficult task, that is often addressed in a simplified way from the mathematical viewpoint: this can be viewed as the one and only iteration of an iterative process. This results with a low quality coupled system, which could be improved either with additional iterations, and/or thanks to the improvement of interface boundary conditions and the use of OBC (see above). Promising results have been obtained in the framework of **ocean-atmosphere coupling** (in a simplified modeling context) in [44], where the use of advanced coupling techniques (based on domain decomposition algorithm) are introduced.

3.1.3. A need for upscaled shallow water models.

The mathematical modeling of **fluid-biology** coupled systems in lagoon ecosystems requires one or several water models. It is of course not necessary (and not numerically feasible) to use accurate non-hydrostatic turbulent models to force the biological processes over very long periods of time. There is a compromise to be reached between accurate (but untractable) fluid models such as the Navier-Stokes equations and simple (but imprecise) models such as [35].

In urbanized coastal zones, upscaling is also a key issue. This stems not only from the multi-scale aspects dealt with in the previous subsection, but also from modeling efficiency considerations.

The typical size of the relevant hydraulic feature in an urban area is between 0.1 m and 1.0 m, while the size of an urban area usually ranges from 10^3 m to 10^4 m. Refined flow computations (e.g. in simulating the impact of a tsunami) over entire coastal conurbations using a 2D horizontal model thus require 10^6 to 10^9 elements. From an engineering perspective, this makes both the CPU and man-supervised mesh design efforts unaffordable in the present state of technology.

Upscaling provides an answer to this problem by allowing macroscopic equations to be derived from the small-scale governing equations. The powerful, multiple scale expansion-based homogeneization technique [20], [19], [49] has been applied successfully to flow and transport upscaling in porous media, but its use is subordinated to the stringent assumptions of (i) the existence of a Representative Elementary Volume (REV), (ii) the scale separation principle, and (iii) the process is not purely hyperbolic at the microscopic scale, otherwise precluding the study of transient solutions [20]. Unfortunately, the REV has been shown recently not to exist in urban areas [37]. Besides, the scale separation principle is violated in the case of sharp transients (such as tsunami waves) impacting urban areas because the typical wavelength is of the same order of magnitude as the microscopic detail (the street/block size). Moreover, 2D shallow water equations are essentially hyperbolic, thus violating the third assumption.

These hurdles are overcome by averaging approaches. Single porosity-based, macroscopic shallow water models have been proposed [29], [36], [39] and applied successfully to urban flood modeling scale experiments [36], [45], [52]. They allow the CPU time to be divided by 10 to 100 compared to classical 2D shallow water models. Recent extensions of these models have been proposed in the form of integral porosity [51] and multiple porosity [37] shallow water models.

3.2. Scientific Objectives

Our main challenge is: build and couple elementary models in coastal areas to improve their capacity to simulate complex dynamics. This challenge consists of three principal scientific objectives. First of all, each of the elementary models has to be consistently developed (regardless of boundary conditions and interactions with other processes). Then open boundary conditions (for the simulation of physical processes in bounded domains) and links between the models (interface conditions) have to be identified and formalized. Finally, models and boundary conditions (*i.e.* coupled systems) should be proposed, analyzed and implemented in a common platform.

3.2.1. Single process models and boundary conditions

The time-evolution of a water flow in a three-dimensional computational domain is classically modeled by Navier-Stokes equations for incompressible fluids. Depending on the physical description of the considered domain, these equations can be simplified or enriched. Consequently, there are **numerous water dynamics models** that are derived from the original Navier-Stokes equations, such as primitive equations, shallow water equations (see [28]), Boussinesq-type dispersive models [21]), etc. The aforementioned models have **very different mathematical natures**: hyperbolic *vs* parabolic, hydrostatic *vs* non-hydrostatic, inviscid *vs* viscous, etc. They all carry nonlinearities that make their mathematical study (existence, uniqueness and regularity of weak and/or strong solutions) highly challenging (not to speak about the $1M Clay competition for the 3D Navier Stokes equations, which may remain open for some time).

The objective is to focus on the mathematical and numerical modeling of models adapted to **nearshore dynamics**, accounting for complicated wave processes. There exists a large range of models, from the shallow water equations (eventually weakly dispersive) to some fully dispersive deeper models. All these models can be obtained from a suitable asymptotic analysis of the water wave equations (Zakharov formulation) and if the theoretical study of these equations has been recently investigated [42], there is still some serious numerical challenges. So we plan to focus on the derivation and implementation of robust and high order discretization methods for suitable two dimensional models, including enhanced fully nonlinear dispersive models and fully dispersive models, like the Matsuno-generalized approach proposed in [41]. Another objective is to study the shallow water dispersive models without any irrotational flow assumption. Such a study would be of great interest for the study of nearshore circulation (wave induced rip currents).

For obvious physical and/or computational reasons, our models are set in bounded domains. Two types of boundaries are considered: physical and mathematical. Physical boundaries are materialized by an existing interface (atmosphere/ocean, ocean/sand, shoreline, etc.) whereas mathematical boundaries appear with the truncation of the domain of interest. In the latter case, **open boundary conditions** are mandatory in order not to create spurious reflexions at the boundaries. Such boundary conditions being nonlocal and impossible to use in practice, we shall look for approximations. We shall obtain them thanks to the asymptotic analysis of the (pseudo-differential) boundary operators with respect to small parameters (viscosity, domain aspect ratio, Rossby number, etc.). Naturally, we **will seek the boundary conditions leading to the best compromise** between mathematical well-posedness and physical consistency. This will make extensive use of the mathematical theory of **absorbing operators** and their approximations [33].

3.2.2. Coupled systems

The Green-Naghdi equations provide a correct description of the waves up to the breaking point while the Saint-Venant equations are more suitable for the description of the surf zone (i.e. after the breaking). Therefore, the challenge here is first to **design a coupling strategy** between these two systems of equations, first in a simplified one-dimensional case, then to the two-dimensional case both on cartesian and unstructured grids. High order accuracy should be achieved through the use of flexible Discontinuous-Galerkin methods.

Additionally, we will couple our weakly dispersive shallow water models to other fully dispersive deeper water models. We plan to mathematically analyze the coupling between these models. In a first step, we have to understand well the mixed problem (initial and boundary conditions) for these systems. In a second step, these new mathematical development have to be embedded within a numerically efficient strong coupling approach. The deep water model should be fully dispersive (solved using spectral methods, for instance) and the shallow-water model will be, in a first approach, the Saint-Venant equations. Then, when the 2D extension of the currently developped Green-Naghdi numerical code will be available, the improved coupling with a weakly dispersive shallow water model should be considered.

In the context of Schwarz relaxation methods, usual techniques can be seen as the first iteration (not converged) of an iterative algorithm. Thanks to the work performed on efficient boundary conditions, we shall **improve the quality of current coupling algorithms**, allowing for qualitatively satisfying solutions **with a reduced computational cost** (small number of iterations).
We are also willing to explore the role of geophysical processes on some biological ones. For example, the design of optimal shellfish farms relies on confinement maps and plankton dynamics, which strongly depend on long-time averaged currents. Equations that model the time evolution of species in a coastal ecosystem are relatively simple from a modeling viewpoint: they mainly consist of ODEs, and possibly advection-diffusion equations. The issue we want to tackle is the choice of the fluid model that should be coupled to them, accounting for the important time scales discrepancy between biological (evolution) processes and coastal fluid dynamics. Discrimination criteria between refined models (such as turbulent Navier-Stokes) and cheap ones (see [35]) will be proposed.

Coastal processes evolve at very different time scales: atmosphere (seconds/minutes), ocean (hours), sediment (months/years) and species evolution (years/decades). Their coupling can be seen as a *slow-fast* dynamical system, and a naïve way to couple them would be to pick the smallest time-step and run the two models together: but the computational cost would then be way too large. Consequently **homogenization techniques or other upscaling methods** should be used in order to account for these various time scales at an affordable computational cost. The research objectives are the following:

- So far, the proposed upscaled models have been validated against theoretical results obtained from refined 2D shallow water models and/or very limited data sets from scale model experiments. The various approaches proposed in the literature [25], [26], [29], [36], [37], [39], [45], [51], [52] have not been compared over the same data sets. Part of the research effort will focus on the extensive validation of the models on the basis of scale model experiments. Active cooperation will be sought with a number of national and international Academic partners involved in urban hydraulics (UCL Louvain-la-Neuve, IMFS Strasbourg, Irvine University California) with operational experimental facilities.
- Upscaling of source terms. Two types of source terms play a key role in shallow water models: geometry-induced source terms (arising from the irregular bathymetry) and friction/turbulence-induced energy loss terms. In all the upscaled shallow water models presented so far, only the large scale effects of topographical variations have been upscaled. In the case of wetting/drying phenomena and small depths (e.g. the *Camargue* tidal flats), however, it is forseen that subgrid-scale topographic variations may play a predominant role. Research on the integration of subgrid-scale topography into macrosocopic shallow water models is thus needed. Upscaling of friction/turbulence-induced head loss terms is also a subject for research, with a number of competing approaches available from the literature [36], [37], [51], [54].
- Upscaling of transport processes. The upscaling of surface pollutant transport processes in the urban environment has not been addressed so far in the literature. Free surface flows in urban areas are characterized by strongly variable (in both time and space) flow fields. Dead/swirling zones have been shown to play a predominant role in the upscaling of the flow equations [37], [51]. Their role is expected to be even stronger in the upscaling of contaminant transport. While numerical experiments indicate that the microscopic hydrodynamic time scales are small compared to the macroscopic time scales, theoretical considerations indicate that this may not be the case with scalar

transport. Trapping phenomena at the microscopic scale are well-known to be upscaled in the form of fractional dynamics models in the long time limit [40], [47]. The difficulty in the present research is that upscaling is not sought only for the long time limit but also for all time scales. Fractional dynamics will thus probably not suffice to a proper upscaling of the transport equations at all time scales.

3.2.3. Numerical platform

As a long term objective, the team shall create a common architecture for existing codes, and also the future codes developed by the project members, to offer a simplified management of various evolutions and a single and well documented tool for our partners. It will aim to be self-contained including pre and post-processing tools (efficient meshing approaches, GMT and VTK libraries), but must of course also be opened to user's suggestions, and account for existing tools inside and outside Inria. This numerical platform will be dedicated to the simulation of all the phenomena of interest, including flow propagation, sediment evolution, model coupling on large scales, from deep water to the shoreline, including swell propagation, shoaling, breaking and run-up. This numerical platform clearly aims at becoming a reference software in the community. It should be used to **develop a specific test case** around Montpellier which embeds many processes and their mutual interactions: from the *Camargue* (where the Rhône river flows into the Mediterranean sea) to the *Étang de Thau* (a wide lagoon where shellfishes are plentiful), **all the processes studied in the project occur in a 100km wide region**, including of course the various hydrodynamics regimes (from the deep sea to the shoaling, surf and swash zones) and crucial morphodynamic issues (*e.g.* in the town of Sete).

4. Application Domains

4.1. Coastal Oceanography

Participants: Fabien Marche, Antoine Rousseau.

Saint-Venant and Boussinesq equations have been widely applied until recently to model and simulate the propagation and transformations of waves in the nearshore area, over rapidly varying topography. However, the first equations do not include dispersive effects, and consequently have a domain of validity limited to the surf zone. The second set of equations overcome the limitations of the SV equations but relies on a "small amplitude assumption" and is therefore unable to model the whole range of waves transformations. This is the reason why they are usually called "weakly nonlinear Boussinesq equations". A better suited set of equations is known as the Green-Naghdi equations, but until recently, they have received far less attention, both from the theoretical and numerical point of view. In particular, there is no available numerical method of arbitrary ordre for 2d simulations on unstructured meshes. Additionally, the construction of rigorous positive preserving schemes is a paramount for the study of waves run-up.

4.2. Urban Floods

Participants: Carole Delenne, Vincent Guinot, Antoine Rousseau.

Floods have been identified by the National Accounting Authority (Cour des Comptes) to represent up to 1% of the GNP in terms of damage cost. For crisis management purposes, modeling urban floods at the scale of the conurbation is highly desirable. This however cannot be achieved in the current state of technology because of the meshing and computational cost (up to one billion cells being needed to mesh an entire urban area). This can be overcome by upscaling the shallow water equations so as to obtain large scale models that can operate three orders of magnitude faster than refined 2D models. Various upscaled versions of the upscaled 2D Shallow Water Equations have been proposed in the literature, some of which by members of the Lemon team. Further developments are being carried out, including the subgrid-scale description of topography variations and a better representation of energy dissipation terms. Laboratory experiments are also needed to discriminate between the various existing models.

4.3. River Hydraulics

Participants: Vincent Guinot, Antoine Rousseau.

Shallow Water (SW) models are widely used for the numerical modeling of river flows. Depending on the geometry of the domain, of the flow regime, and of required accuracy, either 1D or 2D SW models are implemented. It is thus necessary to couple 1D models with 2D models when both models are used to represent different portions of the same river. Moreover, when a river flows into the sea/ocean (e.g. the Rhône river in the Mediterranean), one may need to couple a 2D SW with a full 3D model (such as the Navier-Stokes equations) of the estuary. These issues have been widely addressed by the river-engineering community, but often with somehow crude approaches in terms of coupling algorithms. This may be improved thanks to more advanced boundary conditions, and with the use of Schwarz iterative methods for example.

5. Highlights of the Year

5.1. Highlights of the Year

- Antoine ROUSSEAU spent 9 months in the office of Inria Chile (Santiago, Chile) from February to October 2016 to collaborate on the new project on *Marine Energies Research International Center* (MERIC) in Chile. Antoine is the scientific coordinator of the research line “Advanced modeling for marine energy”, and several members of LEMON, CARDAMOM and TOSCA research teams will be involved in this 8 years project in partnership with DCNS and Enel.

6. New Software and Platforms

6.1. TsunamiLab

Participant: Antoine Rousseau.

Tsunami-Lab is an educational platform enabling simulation and visualization of tsunami effects in real time, with several historical scenarios and the possibility to build your own one. The target of this project is to provide students as well as general audience with an educational tool, intended to reduce tsunamis impact in Chile and help sparing human lives.
Tsunami-Lab was initated by José Galaz, engineer in mathematics and civil ingeneering, when he was working at the National Research Center for Integrated Gestion of Natural Hazards (CIGIDEN). The app is born with the match of a need - teach general audience more efficient methods to decrease tsunamis impact and spare human lives - and the use of new technologies. Later, a collaboration came up between CIGIDEN, Inria Chile and Inria (team LEMON) in order to optimize this project development.

- Participant: Antoine Rousseau
- Contact: José Galaz, jdgalazm@gmail.com
- URL: https://tsunamilab.inria.fr/

6.2. SW2D

Participants: Carole Delenne, Vincent Guinot.

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.

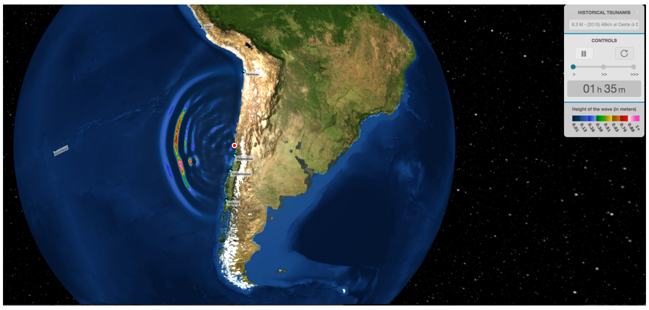

Figure 2. Propagation of a tsunami wave created by the a 8.3M earthquake in Chile (2015) using the TsunamiLab platform.

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
- three different closure relationships between the averaged flow variables and porosity-based fluxes
- 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.
- Contact: Vincent Guinot
- URL: http://vincentguinot.free.fr

6.3. WindPoS

Participant: Antoine Rousseau.

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).

In 2013, WindPoS became the kernel of the wind farm modeling of the Fundacion Inria Chile. In France, its development is going on through the collaborative Modéol project on the evaluation of wind potential.

This is a joint work with Mireille Bossy from the team TOSCA.

- Contact: Mireille Bossy, mireille.bossy@inria.fr
- URL: http://windpos.inria.fr

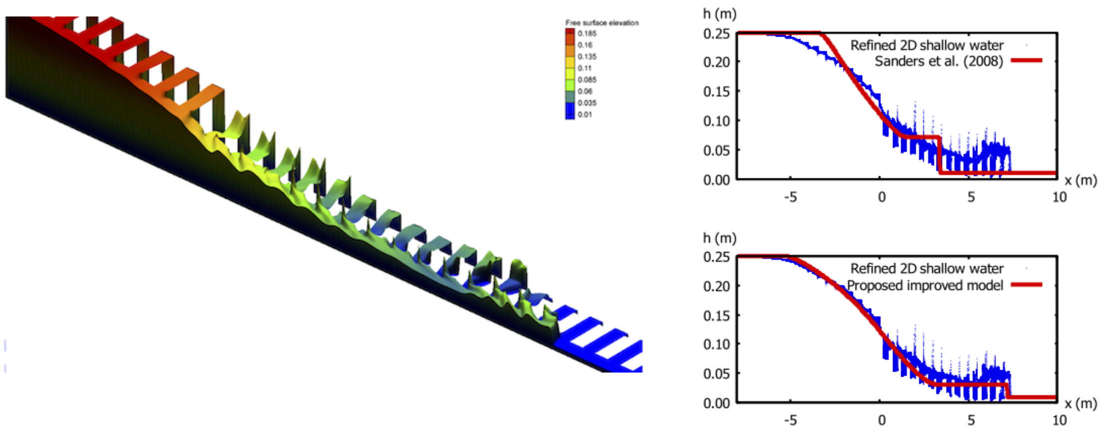

Figure 3. Propagation of a flood wave into a channel with lateral storage. Refined 2D simulation using the SW2D computational code

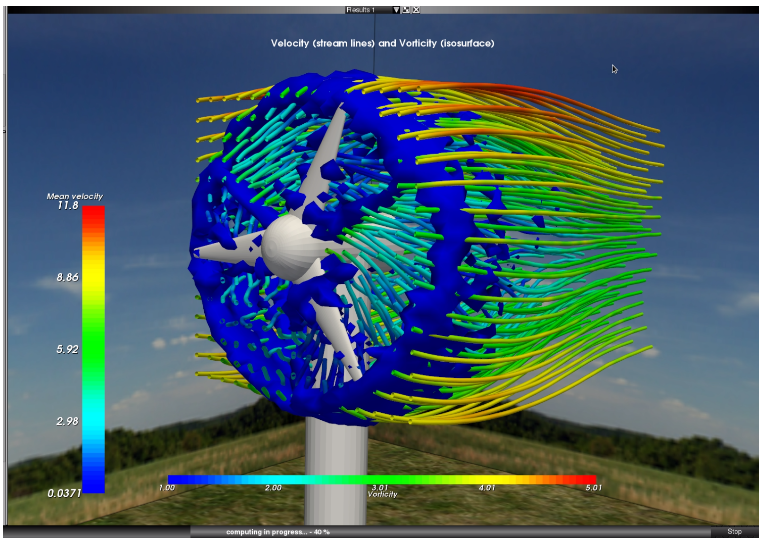

Figure 4. Velocity streamlines and vorticity around a wind mill (artistic view). WINDPOS Project.

7. New Results

7.1. Ocean modeling

Participants: Fabien Marche, Antoine Rousseau.

7.1.1. A first discrete formulation for Green-Naghdi equations on unstructured general meshes

We introduce in [17] the first numerical method available in the literature to approximate the solutions of the Green-Naghdi equations on fairly general unstructured meshes. The method relies on coupled elliptic and hyperbolic problems, the first one accounting for a dispersive correction of the free surface flow description provided by the second one, and on discontinuous polynomial approximations of arbitrary order and the construction of discrete differential operators suitable for such non-conforming approximations. It allows to handle general meshes and nonconforming interfaces. A nonlinear stability result is proved, together with the preservation at the discrete level of motionless steady states. Several test cases highlight the accuracy of this discrete formulation.

7.1.2. Quasi-hydrostatic ocean models

In [9], we work on nontraditional models where the so-called traditional approximation on the Coriolis force is removed. In the derivation of the quasi-geostrophic equations, we obtain new terms in δ/ε, where the domain aspect ratio and the Rossby number are both small numbers. We provide here some rigorous crossed-asymptotics with regards to these parameters , prove some mathematical and physical results on the nontraditional models, and situate them among traditional ones. This was also published as lecture notes given by Antoine ROUSSEAU in 2014: see [8].

7.1.3. Interface conditions for ocean models

In [4] we are interested in the search of interface conditions to couple hydrostatic and nonhydrostatic ocean models. To this aim, we consider simplified systems and use a time discretization to handle linear equations. We recall the links between the two models (with the particular role of the aspect ratio $\delta = H/L$) and introduce an iterative method based on the Schwarz algorithm (widely used in domain decomposition methods). The convergence of this method depends strongly on the choice of interface conditions: this is why we look for exact absorbing conditions and their approximations in order to provide tractable and efficient coupling algorithms.
In [3] we present a study of optimized Schwarz domain decomposition methods for Navier-Stokes equations. Once discretized in time, optimal transparent boundary conditions are derived for the resulting Stokes equations, and a series of local approximations for these nonlocal conditions are proposed. Their convergence properties are studied, and numerical simulations are conducted on the test case of the driven cavity. It is shown that conditions involving one or two degrees of freedom can improve the convergence properties of the original algorithm.

7.2. Renewable energies

Participant: Antoine Rousseau.

7.2.1. Wind circulation around mills

In [5] we present a new methodology, together with numerical studies, related to a Lagrangian stochastic approach applied to the computation of the wind circulation around mills. We present our numerical method and numerical experiments in the case of non rotating and rotating actuator disc models. First, for validation purpose we compare some numerical experiments against wind tunnel measurements. Second we perform some numerical experiments at the atmospheric scale and present some features of our numerical method, in particular the computation of the probability distribution of the wind in the wake zone, as a byproduct of the fluid particle model and the associated PDF method.

7.3. Multiscale modeling for environmental issues

Participants: Mathieu Dartevelle, Carole Delenne, Vincent Guinot, Antoine Rousseau.

7.3.1. Upscaled modeling of a coastal lagoon in Camargue

In 2015, Sélim Cornet developed a numerical model for the hydrodynamics of Vaccares system in Camargue. The data and reference simulations (made with TELEMAC-2D) were provided by Tour du Valat (contact O. Boutron). Sélim's work consisted in the implementation and validation of the porosity shallow water model developped by Vincent GUINOT , in order to obtain accurate but inexpensive simulations of the Vaccares hydrosystem. In 2016, we identified inconsistencies in the porosity closure model. These modeling issues have been analysed and a new theoretical approach, including new energy principles in the derivation of the porosity model, are under investigation.

7.3.2. Feedback strategies for decontamination of water resources

In [2] we show how to couple systems of ODEs and PDEs to provide efficient feedback strategies for the biological decontamination of water resources. For natural resources, we impose not to introduce any bacteria in the resource and to treat it aside preserving a constant volume of the resource at any time. The feedback strategies are derived from the minimal time synthesis of the system of ODEs.

7.3.3. Dispersion in porous media

Solute dispersion in porous media is usually modelled using Fick's law or fractional variations of the solute dispersion equation. The Fickian model, however, is known to exhibit a number of drawbacks, such as poor scaling properties. This is also true for its fractional counterparts, that perform with limited success when compared to experimental data sets. In [46], a high-quality experimental device is built in the form of periodic heterogeneities (Model Heterogeneous Porous Medium) of length 15 cm. Placing up to 10 MHPM in series allows the scaling properties of the dispersion model to be analyzed. Besides providing a high quality experimental database, the results in [46] indicate that (i) previously identified scaling trends for the dispersion coefficient may easily be explained by experiment variability, (ii) there exists a linear transport model that allows the experimental behaviour to be reproduced at all scales, (iii) this model is not the advection-dispersion model (even fractional). More experiments have been performed this year with a different connexion between each MHPM. More experiments have been performed this year with a different connexion between each MHPM. The benchmarking of various numerical models is currently under process; it includes classical models such as Advection-Diffusion, Mobile-Immobile, Multi Rate . . . as well as a proposed Purely Advective Multi Region model.

7.3.4. Modeling and identification for environmental applications

In collaboration with Mohsen Chebbi (ENIT, Tunis) and Salwa Toumi (ENIT, Tunis), we propose stochastic models of anaerobic membrane bioreactors [10]. These biotechnology processes are usually described as differential equations valid at large population scale. We propose model at different scales. At the microscopic scale, we consider a pure jump stochastic model that can be exactly simulated. However, when the size of the population is large that type of exact simulation is not feasible, hence we propose approximated simulation methods in discrete time, of the Poisson type or of the diffusive type. We establish the law of large numbers and the central limit theorem of the functional type.

We also consider different problems of simultaneous filtering and parameter estimation for hidden Markov models: in collaboration with Samuel Nyobe Som (University of Yaoundé 1) we study natural ressources examples; in collaboration with Oussama Hadj-Abdelkader (University of Tlemcen) we study applications in biotechnology. In both cases the fact that the frequency of data acquisition is slow enough to improve classical techniques.

7.4. Other results

Participants: Fabien Campillo, Carole Delenne, Antoine Rousseau.

7.4.1. Topography assessment from ordinal and continuous information

Hydrodynamic models in two dimensions require a precise knowledge of the domain topography, but data acquisition (field surveys, RADAR, etc.) remains difficult to set up at a large scale. Progress in remote sensing data now allows the automatic monitoring of water surfaces delineation from areal or satellite images (e.g. [48]); and flood dynamics from remote sensing data are known to be informative on floodplain topography for long. The idea is thus to combine sparse punctual information (obtained from ground survey) with continuous contour lines (obtained from image treatment) to better assess the domain topography. Two different approaches have been tested during Mathieu Dartevelle's internship (3 months): the first one is based on geostatistical considerations (kriging and conditional simulations) and the second one, deterministic, uses spline functions obtained from a minimisation process. The main challenge stands in the fact that, if the contour line is known to be an isovalue curve, its elevation is not known. First results have been presented in [12] but work is still needed especially to retrieve a precise estimation of curve elevation from very few data points. This work is done in collaboration with Jean-Stéphane Bailly (Lisah, AgroParisTech Montpellier).

7.4.2. Growth-fragmentation-death models

In collaboration with Coralie Fritsch (Inria Nancy) and Otso Ovaskainen (University of Helsinki), we propose a numerical approach that can be used to study the invasion fitness of a mutant in evolutionary models and to determine evolutionary singular strategies when the competitive exclusion principle holds [18]. Though the method is general, we illustrate this method with a mass-structured individual-based chemostat model. We assume that the mutations are rare and that the resident population is large, in which case the mutant population can be viewed, on a short time scale, as evolving in a constant environment. Both deterministic and stochastic models can be proposed to describe such a problem. We exploit a previously derived mathematical relationship between these models [7] to derive a general method for analyzing the invasion fitness of stochastic models.

In collaboration with Nicolas Champagnat and Coralie Fritsch (Inria Nancy), we studied the variations of the principal eigenvalue associated to a growth-fragmentation-death equation with respect to a parameter [16]. We use the probabilistic individual-based interpretation of the model. We study the variations of the survival probability of the stochastic model, using a generation by generation approach. Then, making use of the link between the survival probability and the principal eigenvalue established in a previous work, we deduce the variations of the eigenvalue with respect to the parameter of the model.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Free surface hydraulics

The finite volume-based, SW2D computational code (see Software section) is used by Cereg Ingénierie and Enveo (Montpellier Lavérune location) on a regular basis to carry out flood risk assessment studies. The code is constantly being developed on a work-for-hire basis depending on the company needs. The developments mostly concern pre- and post-processing functionalities, as well as specific hydraulic modules.

8.1.2. Hydrodynamics of coastal lagoons with porosity models

A two-dimensional shallow water with depth-variable porosity has been developed. The depth-variable porosity allows the subgrid-scale variations of the topography and hydraulic connectivity to be accounted for. The governing equations are written in conservation form and solved using a finite volume scheme. This allows the CPU time of the computational code to be divided by 2 to 3 orders of magnitude. The model is currently being tested against in situ measurements in the Vaccarès system in collaboration with Tour du Valat.

8.2. Bilateral Grants with Industry

Antoine ROUSSEAU collaborates with ARTELIA in the framework of M-P Daou's PhD thesis (CIFRE).

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) counts 3 partners: Cerec Ingénierie, HSM and Predict Services. In this porject, the upscaled shallow water model with porosity SW2D developed at HSM is embedded in a software chain that will allow fast uran flood computations from forecasted precisiptation fields. The project is funded under the Feder scheme. It has earned a distinction from the local Scientific Advisory Committee ("Coup de coeur du COSTI").

9.2. National Initiatives

9.2.1. ANR

Fabien MARCHE is member of the ANR project BonD (PI Sylvie Benzoni), 2013-2017

Fabien MARCHE is member of the ANR project ACHYLLES (PI Rodolphe Turpault), 2014-2017

Fabien CAMPILLO is member of the ANR project Slofadybio, 2015-2016

Antoine ROUSSEAU is member of the ANR project ANSWER (PI Céline Casenave), 2016-2019

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

Vincent GUINOT was the main investigator of an International Training Network (ITN) proposal in 2016. The proposal was not accepted and will be submitted again in 2017, accounting for the remarks made by the reviewers.

9.4. International Initiatives

9.4.1. Inria International Labs

9.4.1.1. Inria Chile

Antoine ROUSSEAU spent 9 months at Inria Chile from January to October 2016.

9.4.2. Inria International Partners

9.4.2.1. Declared Inria International Partners

In 2015, the *Marine Energies Research International Center* (MERIC) was launched in Chile by CORFO. Antoine ROUSSEAU will be 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 and Fabien MARCHE are involved in the research line *advanced modeling for marine energy*.

9.4.2.2. Informal International Partners

Vincent GUINOT collaborates with B.F. Sanders (Irvine University, Californie, USA)

Carole DELENNE and Vincent GUINOT collaborates with S. Soares-Frazao (Unité de Génie Civil, Université catholique de Louvain, Belgium)

Antoine ROUSSEAU continues to collaborate with H. Ramirez (CMM, Santiago) and P. Gajardo (UTFSM, Valparaiso) after the end of the Inria associated team Dymecos (2015).

9.5. International Research Visitors

9.5.1. Research Stays Abroad

Antoine ROUSSEAU spent 9 months at Inria Chile from January to October 2016. He co-advised 2 master students and 1 research engineer in the framework of the MERIC project in Chile. Antoine ROUSSEAU also participated to the Tsunamilab project between Inria Chile and CIGIDEN.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Journal

10.1.1.1. Member of the editorial board

Vincent GUINOT : Journal of Hydroinformatics.

Antoine ROUSSEAU : Discrete and Continuous Dynamical Systems, Series S.

10.1.1.2. Reviewer

Fabien MARCHE : Advances in Applied Mathematics and Mechanics, International Journal for Numerical Methods in Fluids, Journal of Applied and Computational Mathematics, Journal of Computational Physics, Journal of Scientific Computing and SIAM Journal on Scientific Computing.

Vincent GUINOT : Journal of Hydrology and Journal of Hydroinformatics.

Antoine ROUSSEAU : Applied Numerical Mathematics, International Journal for Numerical Methods in Fluids.

10.1.2. Invited talks

Carole DELENNE workshop « Modelling the flood peril » Paris, May 30th and 31st, Université Pierre et Marie Curie

Antoine ROUSSEAU : Café Scientifique (Institut Français de Santiago, Ambassade de France), August 6th, 2016

Antoine ROUSSEAU : 4th French-Chilean workshop on Bioprocess Modeling, Santiago, Sept. 2016

10.1.3. Research administration

Antoine ROUSSEAU belongs to the workgroup dedicated to the development of SELECT, an Inria internal software to manage scientific recruitment. Carole DELENNE responsable d'année EGC3, direction des études EGC et tutorat de 5 apprentis (je sais pas où ca se met…)

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

F. Campillo, Stochastic modelling of ecosystems, 20 h, M2R Biostatistics, Univ. Montpellier

F. Campillo, Object oriented programming: probabilistic modeling and statistical numerics for biology, 20 h, Doctoral lectures, Univ. Montpellier

C. Delenne, Méthodes mathématiques pour l'ingénieur, 10.5H CM, 22.5hTD, L3, Polytech Montpellier

C. Delenne, Hydraulique, 60hTP, M1, Polytech Montpellier

C. Delenne, Hydraulic transients, 27hTD, M1, Polytech Montpellier

C. Delenne, Modélisation hydraulique à surface libre 2D, 6h TD, M2, Polytech Montpellier

C. Delenne, Tutorat de stages et projets, 77hETD, L3-M2, Polytech Montpellier

C. Delenne, Mathématiques, 15h CM, 15hTD, L3 (apprentissage), Polytech Montpellier

C. Delenne, Hydraulique, 28hTD, L1, IUT Génie Civil, Nîmes

V. Guinot, Mécanique des fluides, 72h ETD, L3, Polytech'Montpellier

V. Guinot, Hydraulique à surface libre, 60h ETD, L3, Polytech'Montpellier

V. Guinot, Méthodes Mathématiques pour l'Ingénieur, 18h ETD, M1, Polytech'Montpellier

V. Guinot, Hydraulique des Réseaux, 30h ETD, M1, Polytech'Montpellier

V. Guinot, Mécanique des Fluides, Master SPAE, 36h ETD, M1, UMontpellier

V. Guinot, Transitoires hydrauliques, 54 h ETD, M1, Polytech'Montpellier

V. Guinot, tutorat de stages ingénieur, 15h ETD, M1, Polytech'Montpellier

V. Guinot, Modélisation hydraulique à surface libre 2D, 6h ETD, M2, Polytech'Montpellier

V. Guinot, Projet Industriel de Fin d'Etudes (PIFE), 30h ETD, M2, Polytech'Montpellier

V. Guinot, Tutorat de Stage de fin d'études ingénieur, 18h ETD, M2, Polytech'Montpellier

F. Marche, Biomaths, 72h TD., L1, Université Montpellier

F. Marche, Analyse numérique des EDP, 24H CM, 12H TD, 15H TP., M1, Université Montpellier

F. Marche, Calcul scientifique avancé, 26H CM, M2R, Université Montpellier

A. Rousseau, Towards Coupling Coastal and Large Ocean Models, 6h, Master, PUC, Santiago, Chile

A. Rousseau, Introduction to numerical methods in CFD, 6h, Master, Inria Chile, Santiago, Chile

A. Rousseau, Introduction to ROMS, 12h, Master, Inria Chile and CIGIDEN, Santiago, Chile

10.2.2. Supervision

PhD: Mehdi Pierre Daou, *Développement d'une méthodologie de couplage multi-modèles avec changements de dimension. Validation sur un cas-test réaliste en dynamique littorale*, Univ. Grenoble, Sept. 2016, Eric Blayo (EPI MOISE) and Antoine Rousseau

PhD in progress: Mohsen Chebbi, Modélisation stochastique de procédés membranaires de traitement des eaux usées. September 2014, S. Toumi (ENIT, Tunis) and F. Campillo

PhD in progress: Oussama Hadj-Abdelkader, Filtrage particulaire pour le chemostat. September 2014, A. Hadj-Abdelkader (Univ. Tlemcen) and F. Campillo

10.2.3. Juries

Carole DELENNE : Jury member: Andriarimina Daniel Rakotonirina, *Fluid-solid interactions in a non-convex granular media: application to rotating drums and packed bed reactors*, december 2016, ENS Lyon

Antoine ROUSSEAU : Referee and jury member: Mrs Souad Khiari, *Problèmes Inverses de Points Sources dans les Modèles de Transport Dispersif de Contaminants Identifiabilité et Observabilité*, October 2016, Université de Technologie de Compiègne & Université de Tunis El-Manar / ENIT

Antoine ROUSSEAU : Jury member: M. Mehdi Pierre Daou, *Développement d'une méthodologie de couplage multi-modèles avec changements de dimension. Validation sur un cas-test réaliste en dynamique littorale*, September 2016, Univ. Grenoble

Antoine ROUSSEAU : Jury member: M. Victor Riquelme, *Problemas de control óptimo para la bioremediación de recursos acuíferos*, September 2016, Univ. de Chile, Santiago & Univ. Montpellier

Fabien MARCHE : Jury member: Mrs Nora Aissiouene, *Analyse numérique et approximation discrète d'un modèle dispersif en eau peu profonde*, December 2016, Univ. Pierre et Marie Curie, Paris

Antoine ROUSSEAU : Jury member: Mrs Carine Lucas, *Modélisation de problèmes de me´canique des fluides : approches théoriques et numériques*, December 2016, Université d'Orléans

Teaching manager of the department "Water and Civil Engineering", Polytech Montpellier, in charge of the first year of the training. Academic supervisor of 5 apprentices.

10.3. Popularization

Antoine ROUSSEAU gave several conferences for highschool students and their teachers in France and Chile, on the topics of mathematical modeling for environmental sciences:

Fête de la Science, Oct. 2016, Genopolys Montpellier

Café Científicó, Aug. 2016, Instituto Francés, Santiago, Chile

Antoine ROUSSEAU is member of the national Inria network for scientific outreach *Médiation scientifique*

Antoine ROUSSEAU is member of the editorial board of Interstices

Antoine ROUSSEAU co-authored the Calendrier Mathématique 2017

11. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] M. P. DAOU.*Methodological development for model coupling with dimension heterogeneity. Validation on a realistic test-case*, Université Grenoble Alpes, September 2016, https://tel.archives-ouvertes.fr/tel-01380084.

Articles in International Peer-Reviewed Journal

[2] S. BARBIER, A. RAPAPORT, A. ROUSSEAU.*Modelling of biological decontamination of a water resource in natural environment and related feedback strategies*, in "Journal of Scientific Computing", 2016, vol. 68, n° 3, 14 [*DOI :* 10.1007/s10915-016-0178-9], https://hal.inria.fr/hal-01138335.

[3] E. BLAYO, D. CHEREL, A. ROUSSEAU.*Towards optimized Schwarz methods for the Navier-Stokes equations*, in "Journal of Scientific Computing", 2016, vol. 66, p. 275–295, https://hal.inria.fr/hal-00982087.

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[5] M. BOSSY, J. ESPINA, J. MORICE, C. PARIS, A. ROUSSEAU.*Modeling the wind circulation around mills with a Lagrangian stochastic approach*, in "SMAI Journal of Computational Mathematics", September 2016, vol. 2, p. 177-214 [*DOI :* 10.5802/SMAI-JCM.13], https://hal.inria.fr/hal-01401140.

[6] F. CHAVE, D. A. DI PIETRO, F. MARCHE, F. PIGEONNEAU.*A Hybrid High-Order method for the Cahn-Hilliard problem in mixed form*, in "SIAM Journal on Numerical Analysis", 2016, vol. 54, n° 3, p. 1873-1898, https://hal.archives-ouvertes.fr/hal-01203733.

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International Conferences with Proceedings

[10] F. CAMPILLO, M. CHEBBI, S. TOUMI.*Stochastic modeling of the anaeorobic model AM2b: Models at different scales*, in "13th Africain Conference on Research in Computer Science and Applied Mathematics (CARI 2016)", Tunis, Tunisia, October 2016, https://hal.inria.fr/hal-01406450.

[11] N. CHAHINIAN, A.-L. PIAT-MARCHAND, S. BRINGAY, M. TEISSEIRE, E. BOULOGNE, L. DERUELLE, M. DERRAS, C. DELENNE.*How can big data be used to reduce uncertainty in stormwater modelling?*, in "Spatial Accuracy", Montpellier, France, Proceedings of Spatial Accuracy 2016, July 2016, n° ISBN: 978-2-9105-4510-5, p. 322-329, https://hal.archives-ouvertes.fr/hal-01417491.

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Other Publications

[13] C. ACARY-ROBERT, L. DAGNAS, A. ROUSSEAU.*Modelling and simulation of coastal lagoons. : Application to the Tunquén lagoon, Chilean pacific coast*, June 2016, working paper or preprint, https://hal.inria.fr/hal-01327333.

[14] N. AISSIOUENE, T. AMTOUT, M. BRACHET, E. FRÉNOD, R. HILD, C. PRUD 'HOMME, A. ROUSSEAU, S. SALMON.*Hydromorpho: A coupled model for unsteady Stokes/Exner equations and numerical results with Feel++ library*, February 2016, working paper or preprint, https://hal.inria.fr/hal-01266223.

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Project-Team MAESTRO

Models for the performance analysis and the control of networks

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Networks and Telecommunications

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Project-Team MAESTRO

Creation of the Project-Team: 2003 October 01, end of the Project-Team: 2016 December 31

Keywords:

Computer Science and Digital Science:

1.2. - Networks
1.2.4. - QoS, performance evaluation
1.2.9. - Social Networks
1.5. - Complex systems
1.5.2. - Communicating systems
3.3.3. - Big data analysis
3.5. - Social networks
3.5.1. - Analysis of large graphs
3.5.2. - Recommendation systems
6. - Modeling, simulation and control
6.1. - Mathematical Modeling
6.1.1. - Continuous Modeling (PDE, ODE)
6.1.2. - Stochastic Modeling (SPDE, SDE)
6.2.2. - Numerical probability
6.2.3. - Probabilistic methods
6.2.6. - Optimization
6.4.1. - Deterministic control
6.4.2. - Stochastic control
7.1. - Parallel and distributed algorithms
7.2. - Discrete mathematics, combinatorics
7.3. - Optimization
7.10. - Network science
7.11. - Performance evaluation
7.14. - Game Theory

Other Research Topics and Application Domains:

3.1. - Sustainable development
3.1.1. - Resource management
4. - Energy
4.3.4. - Solar Energy
4.4. - Energy delivery
4.4.1. - Smart grids
4.5.1. - Green computing
6.2.1. - Wired technologies
6.2.2. - Radio technology
6.3.2. - Network protocols
6.3.3. - Network Management
6.3.4. - Social Networks

8.1. - Smart building/home
9.2.1. - Music, sound
9.4.1. - Computer science
9.4.2. - Mathematics
9.5.3. - Economy, Finance
9.5.4. - Management science
9.5.5. - Sociology

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Other

Dimitra Tsigkari [Inria, pre-PhD Student, until Nov 2016]

2. Overall Objectives

2.1. Presentation of MAESTRO

MAESTRO is an Inria project-team whose members are located in Sophia Antipolis (S. Alouf, K. Avrachenkov, G. Neglia), at LIA (Lab. of Informatics of Avignon) in Avignon (E. Altman) and at LIRMM (Lab. Informatics, Robotics and Microelectronics of Montpellier) in Montpellier (A. Jean-Marie). MAESTRO is concerned with the modeling, performance evaluation, optimization and control of stochastic Discrete-Event Dynamical Systems (DEDS), with a particular emphasis on networks and their applications. The scientific contributions are both theoretical, with the development of new modeling formalisms, and applied, with: a) the solution of specific problems arising in one of our application domains, b) the development of software tools for the performance evaluation of DEDS, and c) the patenting of new methods jointly with industrial partners.

3. Research Program

3.1. Research Directions

MAESTRO's research directions belong to five main themes motivated by direct applications: network science, wireless networks, network engineering games, green networking and smart grids, content-oriented systems. These directions are very connected: network engineering games find applications in many networking fields, from wireless protocols to applications such as social networks. Green IT studies are often concerned with wireless networks, etc. The study of these applications often raises questions of methodological nature, less close to direct applications; these advances are reported in a separate section.

3.1.1. Network Science

MAESTRO contributes to this new fast growing research subject. "Network Science" or "Complex Network Analysis" aims at understanding the structural properties and the dynamics of a variety of large-scale networks in telecommunications (e.g. the graph of autonomous systems, the Web graph), social science (e.g. community of interest, advertisement, reputation, recommendation systems), bibliometrics (e.g. citations, co-authors), biology (e.g. spread of an epidemic, protein-protein interactions), and physics. It has been observed that the complex networks encountered in these areas share common properties such as power law degree distribution, small average distances, community structure, etc. It also appears that many general questions/applications (e.g. community detection, epidemic spreading, search, anomaly detection) are common in various disciplines which study networks. In particular, we aim at understanding the evolution of complex networks with the help of game theoretical tools in connection with Network Engineering Games, as described below. We design efficient tools for measuring specific properties of large scale complex networks and their dynamics. More specifically, we work on the problem of distributed optimization in large networks where nodes cooperatively solve an optimization problem relying only on local information exchange.

3.1.2. Wireless Networks

The amazing technological advances in wireless devices has led networks to become heterogeneous and very complex. Many research groups worldwide investigate performance evaluation of wireless technologies. MAESTRO's specificity relies on the use of a large variety of analytic tools from applied probability, control theory and distributed optimization to study and improve wireless networks functionalities. We investigate in particular problems of self-organization, channel selection and power control, the association problem and others.

3.1.3. Network Engineering Games

The foundations of *Network Engineering Games* are currently being laid. These are games arising in telecommunications engineering at all the networking layers. This includes considerations from information and communications theory for dealing with the physical and link layers, along with cross layer approaches. MAESTRO's focus is on three areas: *routing games*, *evolutionary games* and *epidemic games*. In routing games we progress on the theory for costs that are not additive over links (such as packet losses or call blocking probabilities). We pursue their research in the stochastic extension of evolutionary game theory, namely the "anonymous sequential games" in which we study the total expected costs and the average cost. Within epidemic games they study epidemics that compete against each other. We apply this to social networks, considering in particular the coupling between various social networks (e.g. propagation strategies that combine Twitter, FaceBook and other social networks).

3.1.4. Green Networking and Smart Grids

The ICT (Information and Communications Technology) sector is becoming one of the main energy consumers worldwide. There is awareness that networks should have a reduced environmental footprint. Our objective is to have a systematically "green" approach when solving optimization problems. The energy cost and the environmental impact should be considered in optimization functions along with traditional performance metrics such as throughput, fairness or delay. We aim at contributing to the design and the analysis of future green networks, in particular those using renewable energy.

Researchers envision that future electricity distribution network will be “smart”, with a large number of small generators (due to an extensive use of renewable energies) and of consumer devices able to adapt their energy needs to a time-varying offer. Generators and devices will be able to locally communicate through the electrical grid itself (or more traditional communication networks), in order to optimize production, transport and use of the energy. This is definitely a new application scenario for MAESTRO, to which we hope to be able to contribute with our expertise on analytic models and performance evaluation.

3.1.5. Content-Oriented Systems

We generally study problems related with the placement and the retrieval of data in communication networks.

We are particularly interested in In-network caching, a widely adopted technique to provide an efficient access to data or resources on a world-wide deployed system while ensuring scalability and availability. For instance, caches are integral components of the Domain Name System, the World Wide Web, Content Distribution Networks, or the recently proposed Information-Centric Network (ICN) architectures. We analyze network of caches, study their optimal placement in the network and optimize data placement in caches/servers.

We also study other aspects related to replication and placement of data: how much to replicate it and on which servers to place it? Finally, we study optimal ways of retrieving the data through prefetching.

3.1.6. Advances in Methodological Tools

MAESTRO has a methodological activity that aims at advancing the state of the art in the tools used for the general performance evaluation and control of systems. We contribute to such fields as perturbation analysis, Markov processes, queueing theory, control theory and game theory. Another objective is to enhance our activity on general-purpose modeling algorithms and software for controlled and uncontrolled stochastic systems.

3.2. Scientific Foundations

The main mathematical tools and formalisms used in MAESTRO include:

- theory of stochastic processes: Markov process, renewal process, branching process, point process, Palm measure, large deviations, mean-field approximation, fluid approximation;
- theory of dynamical discrete-event systems: queues, pathwise and stochastic comparisons, random matrix theory;
- theory of control and scheduling: dynamic programming, Markov decision process, game theory, deterministic and stochastic scheduling; stochastic approximation algorithms;
- theory of singular perturbations.

4. Application Domains

4.1. Main Application Domains

MAESTRO’s main application area is networking, to which we apply modeling, performance evaluation, optimization and control. Our primary focus is on protocols and network architectures, and recent evolutions include the study of the Web and social networks, as well as models for Green IT.

- Wireless (cellular, ad hoc, sensor) networks: WLAN, WiMAX, UMTS, LTE, HSPA, delay tolerant networks (DTN), power control, medium access control, transmission rate control, redundancy in source coding, mobility models, coverage, routing, green base stations,
- Internet applications: social networks, content distribution systems, peer-to-peer systems, overlay networks, multimedia traffic, video-on-demand, multicast;
- Information-Centric Networking (ICN) architectures: Content-Centric Network (CCN, also called Content-Oriented Networks);
- Internet infrastructure: TCP, high speed congestion control, voice over IP, service differentiation, quality of service, web caches, proxy caches.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

The paper "Access-time Aware cache Algorithms" by Giovanni Neglia; Damiano Carra; Mingdong Feng; Vaishnav Janardhan; Pietro Michiardi and Dimitra Tsigkari got the Best Paper Award at ITC 28 in Würzburg.

The article "Sonorous Cartography for Sighted and Blind People" by Didier Josselin, Andelbery Saidi, Dorian Roussel, Said Boularouk, Olivier Bonin, Eitan Altman, Driss Matrouf got the Best Short Paper Award at the conference 19th AGILE International on Geographic Information Science, Helsinki, Finland, June 14-17, 2016.

S. Alouf has received a "Recognition of Service Award" from the ACM in September 2016.
BEST PAPERS AWARDS :
[46] **International Teletraffic Congress ITC-28**. G. NEGLIA, D. CARRA, M. FENG, V. JANARDHAN, P. MICHIARDI, D. TSIGKARI.
[40] **AGILE'2016 - 19th AGILE International Conference on Geographic Information Science**. D. JOSSELIN, D. ROUSSEL, S. BOULAROUK, A. SAIDI, D. MATROUF, O. BONIN, E. ALTMAN.

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, Issam Rabhi
- Partner: UVSQ (Univ. Versailles Saint-Quentin)
- Contact: Alain Jean-Marie
- URL: http://marmotecore.gforge.inria.fr/

6.2. ns-3

KEYWORDS: Simulation - Communication networks
FUNCTIONAL DESCRIPTION

ns-3 is a discrete-event network simulator for Internet systems, targeted primarily for research and educational use.

In the framework of the research project with ALSTOM Transport (see §8.1.3), we have extensively validated several modules of ns-3, related to the PHY and the MAC layers. We have implemented a directional antenna using 3-dimensional data for the radiation diagram. Modules related to the Automatic Train Protection function used in train systems have been implemented and validated. We have also developed a generator of video traffic and objects that allow to generate easily simulation scenarios.

We have made available the code related to the communication based train control and the one generating video traffic. Some of our contribution to the ns-3 simulator and selected results illustrating some of the issues that can be addressed using our contribution are presented and discussed in [35].

- Participants: Sara Alouf, Giovanni Neglia and Alina Tuholukova
- Contact: Alina Tuholukova
- ns-3 codereview issue of the cbtc module: https://codereview.appspot.com/289110043
- ns-3 codereview issue of the video generator: https://codereview.appspot.com/286160043

7. New Results

7.1. Network Science

Participants: Eitan Altman, Konstantin Avrachenkov, Arun Kadavankandy, Jithin Kazhuthuveettil Sreedharan, Hlib Mykhailenko, Giovanni Neglia, Alina Tuholukova.

7.1.1. Computation on Large Graphs

The MAESTRO team has been working on how to partition large graphs in distributed computation frameworks in order to speed up the execution time.

In [43], H. Mykhailenko and G. Neglia in collaboration with F. Huet (Univ. Côte d'Azur, CNRS, I3S), provide an overview of existing edge partitioning algorithms. However, based only on published work, it is not possible to draw a clear conclusion about the relative performances of these partitioners. For this reason, the authors compare all the edge partitioners currently available for the widely-used framework for graph processing Apache GraphX. Preliminary results suggest that the Hybrid-Cut partitioner provides the best performance.

In [44], H. Mykhailenko and G. Neglia in collaboration with F. Huet (Univ. Côte d'Azur, CNRS, I3S), focus on vertex-cut graph partitioning and they investigate how it is possible to evaluate the quality of a partition before running the computation. To this purpose the authors scrutinize a set of metrics proposed in literature. They carry experiments with Apache GraphX and they perform an accurate statistical analysis. Preliminary experimental results show that communication metrics like vertex-cut and communication cost are effective predictors on most of the cases.

7.1.2. Network centrality measures

In [19], K. Avrachenkov in collaboration with V. Mazalov (Karelian Institute of Applied Mathematical Research, Russia), L. Trukhina (Baikal State Univ. of Economics and Law, Russia) and B. Tsynguev (Transbaikal State Univ., Russia) worked on network centrality measures based on game-theoretic concepts. The betweenness centrality is one of the basic concepts in the analysis of the social networks. Initial definition for the betweenness of a node in the graph is based on the fraction of the number of geodesics (shortest paths) between any two nodes that given node lies on, to the total number of the shortest paths connecting these nodes. This method has polynomial complexity. We propose a new concept of the betweenness centrality for weighted graphs using the methods of cooperative game theory. The characteristic function is determined by special way for different coalitions (subsets of the graph). Two approaches are used to determine the characteristic function. In the first approach the characteristic function is determined via the number of direct and indirect weighted connecting paths in the coalition. In the second approach the coalition is considered as an electric network and the characteristic function is determined as a total current in this network. We use Kirchhoff's law. After that the betweenness centrality is determined as the Myerson value. The results of computer simulations for some examples of networks, in particular, for the popular social network "VKontakte", as well as the comparing with the PageRank method are presented.

7.1.3. Sampling and Inference of Complex Networks

In [32] K. Avrachenkov, G. Neglia and A. Tuholukova study chain-referral methods for sampling in social networks. These methods rely on subjects of the study recruiting other participants among their set of connections. This approach gives us the possibility to perform sampling when the other methods, that imply the knowledge of the whole network or its global characteristics, fail. Chain- referral methods can be implemented with random walks or crawling in the case of online social networks. However, the estimations made on the collected samples can have high variance, especially with small sample size. The other drawback is the potential bias due to the way the samples are collected. We suggest and analyze a subsampling technique, where some users are requested only to recruit other users but do not participate to the study. Assuming that the referral has lower cost than actual participation, this technique takes advantage of exploring a larger variety of population, thus decreasing significantly the variance of the estimator. We test the method on real social networks and on synthetic ones. As by-product, we propose a Gibbs-like method for generating synthetic networks with desired properties.

Function estimation on Online Social Networks (OSN) is an important field of study in complex network analysis. An efficient way to do function estimation on large networks is to use random walks. We can then defer to the extensive theory of Markov chains to do error analysis of these estimators. In [29], K. Avrachenkov, A. Kadavankandy and J.K. Sreedharan in collaboration with V. Borkar (IIT Bombay, India) compare two existing techniques, Metropolis-Hastings MCMC and Respondent-Driven Sampling, that use random walks to do function estimation and compare them with a new reinforcement learning based technique. We provide both theoretical and empirical analyses for the estimators we consider.

In [33] K. Avrachenkov and J.K. Sreedharan in collaboration with B. Ribeiro (Purdue Univ., USA) develop random walk based methods for inference in Online Social Networks (OSNs) to answer questions like are OSN users more likely to form friendships with those with similar attributes? Do users at an OSN A score content more favorably than OSN B users? Such questions frequently arise in the context of Social Network Analysis (SNA) but often crawling an OSN network via its Application Programming Interface (API) is the only way to gather data from a third party. To date, these partial API crawls are the majority of public datasets and the synonym of lack of statistical guarantees in incomplete-data comparisons, severely limiting SNA research progress. Using regenerative properties of the random walks, we propose estimation techniques based on short crawls that have proven statistical guarantees. Moreover, our short crawls can be implemented in massively distributed algorithms. We also provide an adaptive crawler that makes our method parameter-free, significantly improving our statistical guarantees. We then derive the Bayesian approximation of the posterior of the estimates, and in addition, obtain an estimator for the expected value of node and edge statistics in an equivalent configuration model or Chung-Lu random graph model of the given network (where nodes are connected randomly) and use it as a basis for testing null hypotheses. The theoretical results are supported with simulations on a variety of real-world networks.

In [30] K. Avrachenkov in collaboration with L. Iskhakov and M. Mironov (Moscow Institute of Physics and Technology, Russia) consider pairwise Markov random fields which have a number of important applications in statistical physics, image processing and machine learning such as Ising model and labeling problem to name a couple. Our own motivation comes from the need to produce synthetic models for social networks with attributes. First, we give conditions for rapid mixing of the associated Glauber dynamics and consider interesting particular cases. Then, for pairwise Markov random fields with submodular energy functions we construct monotone perfect simulation.

7.1.4. Distributed algorithms for complex network analysis

In [31] K. Avrachenkov and J.K. Sreedharan in collaboration with P. Jacquet (Nokia Bell Labs, France) address the problem of finding top-k eigenvalues and corresponding eigenvectors of symmetric graph matrices in networks in a distributed way. We propose a novel idea called complex power iterations in order to decompose the eigenvalues and eigenvectors at node level, analogous to time-frequency analysis in signal processing. At each node, eigenvalues correspond to the frequencies of spectral peaks and respective eigenvector components are the amplitudes at those points. Based on complex power iterations and motivated from fluid diffusion processes in networks, we devise distributed algorithms with different orders of approximation. We also introduce a Monte Carlo technique with gossiping which substantially reduces the computational overhead. An equivalent parallel random walk algorithm is also presented. We validate the algorithms with simulations on real-world networks. Our formulation of the spectral decomposition can be easily adapted to a simple algorithm based on quantum random walks. With the advent of quantum computing, the proposed quantum algorithm will be extremely useful.

In [56] K. Avrachenkov in collaboration with V. Borkar and K. Saboo (IIT Bombay, India) propose two asynchronously distributed approaches for graph-based semi-supervised learning. The first approach is based on stochastic approximation, whereas the second approach is based on randomized Kaczmarz algorithm. In addition to the possibility of distributed implementation, both approaches can be naturally applied online to streaming data. We analyse both approaches theoretically and by experiments. It appears that there is no clear winner and we provide indications about cases of superiority for each approach.

7.1.5. Random Matrix Theory for Complex Networks

In [41] A. Kadavankandy and K. Avrachenkov in collaboration with L. Cottatellucci (Eurecom, France) describe a test statistic based on the L1-norm of the eigenvectors of a modularity matrix to detect the presence of an embedded Erdos-Renyi (ER) subgraph inside a larger ER random graph. An embedded subgraph may model a hidden community in a large network such as a social network or a computer network. We make use of the properties of the asymptotic distribution of eigenvectors of random graphs to derive the distribution of the test statistic under certain conditions on the subgraph size and edge probabilities. We show that the distributions differ sufficiently for well defined ranges of subgraph sizes and edge probabilities of the background graph and the subgraph. This method can have applications where it is sufficient to know whether there is an anomaly in a given graph without the need to infer its location. The results we derive on the distribution of the components of the eigenvector may also be useful to detect the subgraph nodes.

7.1.6. Network Growth Models

Network growth and evolution is a fundamental theme that has puzzled scientists for the past decades. A number of models have been proposed to capture important properties of real networks. In an attempt to better describe reality, more recent growth models embody local rules of attachment, however they still require a primitive to randomly select an existing network node and then some kind of global knowledge about the network (at least the set of nodes and how to reach them). In [28] G. Neglia, in collaboration with B. Amorim, D. Figueiredo and G. Iacobelli (Federal Univ. of Rio de Janeiro, Brazil), proposes a purely local network growth model that makes no use of global sampling across the nodes. The model is based on a continuously moving random walk that after s steps connects a new node to its current location, but never restarts. Through extensive simulations and theoretical arguments, they analyze the behavior of the model finding a fundamental dependency on the parity of s, where networks with either exponential or a conditional power law degree distribution can emerge. As s increases parity dependency diminishes and the model recovers the degree distribution of Barabási-Albert preferential attachment model. The proposed purely local model indicates that networks can grow to exhibit interesting properties even in the absence of any global rule, such as global node sampling.

7.1.7. Competition over popularity in online social networks

In [24] E. Altman in collaboration with A. Jain and Y. Hayel (UAPV) consider a stochastic game that describes competition through advertisement over the popularity of their content. They show that the equilibrium may or may not be unique, depending on the system's parameters. They identify structural properties of the equilibria. In particular, they show that a finite improvement property holds on the best response pure policies which implies the existence of pure equilibria. They further show that all pure equilibria are fully ordered in the performance they provide to the players and propose a procedure to obtain the best equilibrium.

7.1.8. Trend detection in social networks using Hawkes processes

In [18], J. C. Louzada Pinto and T. Chahed from Telecom SudParis in collaboration with E. Altman propose a general Hawkes-based framework to model information diffusion in social networks. The proposed framework takes into consideration the hidden interactions between users as well as the interactions between contents and social networks, and can also accommodate dynamic social networks and various temporal effects of the diffusion, which provides a complete analysis of the hidden influences in social networks. This framework can be combined with topic modeling, for which modified collapsed Gibbs sampling and variational Bayes techniques are derived. We provide an estimation algorithm based on nonnegative tensor factorization techniques, which together with a dimensionality reduction argument are able to discover the latent community structure of the social network. We provide numerical examples from real-life networks: a Game of Thrones and a MemeTracker datasets.

7.1.9. Potential Game approach to defense against virus attacks in networks

The Susceptible-Infected-Susceptible (SIS) model is a classical epidemic model where agents alternate between a sane (susceptible) and an infected state. SIS epidemic non-zero sum games have been recently used to analyse virus protection in networks. A potential game approach was proposed for solving the game for the case of a fully connected network. In [42], F.-X. Legenvre and Y. Hayel (UAPV) in collaboration with E. Altman extend this result to an arbitrary topology by showing that the general topology game is a generalized ordinal potential game. We apply this result to study numerically some examples.

7.2. Wireless Networks

Participants: Sara Alouf, Eitan Altman, Giovanni Neglia, Alina Tuholukova.

7.2.1. Control of Delay–Tolerant Networks

In [5] E. Altman and G. Neglia, in collaboration with F. De Pellegrini (Create-Net, Italy) and D. Miorandi (U-Hopper, Italy), study optimal stochastic control of delay tolerant networks. First, the structure of optimal two-hop forwarding policies is derived. In order to be implemented, such policies require knowledge of certain global system parameters such as the number of mobiles or the rate of contacts between mobiles. But, such parameters could be unknown at system design time or may even change over time. In order to address this problem, adaptive policies are designed that combine estimation and control: based on stochastic approximation techniques, such policies are proved to achieve optimal performance in spite of lack of global information. Furthermore, the paper studies interactions that may occur in the presence of several DTNs which compete for the access to a gateway node. The latter problem is formulated as a cost-coupled stochastic game and a unique Nash equilibrium is found. Such equilibrium corresponds to the system configuration in which each DTN adopts the optimal forwarding policy determined for the single network problem.

7.2.2. Performance Evaluation of Train Moving-Block Control

In moving block systems for railway transportation a central controller periodically communicates to the train how far it can safely advance. On-board automatic protection mechanisms stop the train if no message is received during a given time window. In [45], [63] G. Neglia, S. Alouf, and A. Tuholukova in collaboration with A. Dandoush (SME Sudria, France, formerly engineer with MAESTRO) and S. Simoens, P. Dersin, J. Billion and P. Derouet (all from ALSTOM Transport) consider as reference a typical implementation of moving-block control for metro and quantify the rate of spurious Emergency Brakes (EBs), i.e. of train stops due to communication losses and not to an actual risk of collision. Such unexpected EBs can happen at any point on the track and are a major service disturbance.

The general formula for the EB rate found in [45] requires a probabilistic characterization of losses and delays. Calculations are surprisingly simple in the case of homogeneous and independent packet losses. More complex loss scenarios are studied in [59]. The approach is computationally efficient even when emergency brakes are very rare (as they should be) and can no longer be estimated via discrete-event simulations.

The analytical models have also been validated using ns-3 simulations [35].

7.2.3. Speed estimation

After several years of cooperation with Nokia (formerly Alcatel-Lucent) Bell Labs in developing tools for speed estimation from measurement of the radio channel, we have now started to publish our joint patented work. This includes the work on mobility state estimation in LTE by D.-G. Herculea, V. Capdevielle, C. S. Chen, N. Ben Rached and F. Ratovelomanana from Nokia-Bell Labs in collaboration with E. Altman and M. Haddad (UAPV), see [38].

7.2.4. Sonorous cartography for sighted and blind people

E. Altman has been invited by D. Josselin from UMR Espace in UAPV to co-advise a Master project and later a thesis financed by the CNRS on Sonorous cartography. Other persons with whom we collaborate are D. Roussel, S. Boularouk, A. Saidi, M. Driss (from UAPV) and O. Bonin (Laboratoire Ville, Mobilité, Transport) all coauthors of [40] which won the best short paper award in the AGILE conference. In this article, we test the usability of a cartographic tool mixing maps and sounds. This tool is developed within QuantumGIS as a plugin prototype. We first present some theoretical reflections about synesthesia. Secondly, we explain the way we “sonificate” the images, by associating colors and recorded chords and sounds. Then we present the results of several usability tests in France with different users, including blind people.

To help blind people compensate visual perception and to better understand their outdoor environment, S. Boularouk and D. Josselin from UAPV in collaboration with E. Altman, proposed in [49] a method using human-computer interaction via Text-to-Speach. It helps visually impaired people to know surrounding places from OpenStreetMap data by hearing. The principal idea is to convey spatial information by voice synthesis and receive requests from blind people by voice recognition.

7.2.5. Scheduling for mobile users with non-stationary mobility

H. Zaaraoui and Z. Altman from Orange Labs in collaboration with T. Jiménez (UAPV) and E. Altman have studied scheduling in an environment with non-stationary mobility (cars are moving on a road and may have to stop at red lights). They propose scheduling schemes for such mobility patterns and study their performance in in [55] and in [48].

7.2.6. User Association in Multi-user MIMO Small Cell Networks

Dense Networks and large MIMO are two key enablers to achieve high data rates towards next generation 5G networks. In this context, S. Ramanath (Lekha Wireless Solutions and IIT Mumbai) and M. Debbah (Huawei) in collaboration with E. Altman study in [47] user association in an interference limited Multiuser MIMO Small Cell Network. Extending on previous findings, they derive explicit expressions for the optimal ratio of the number of antennas at the base station to the number of users that can associate to a base station in such a Network. The expressions are used to compute the actual number of users that can associate for a given interference level and other system parameters. Simulation results and numerical examples are provided to support our theoretical findings.

7.3. Network Engineering Games

Participants: Eitan Altman, Konstantin Avrachenkov, Giovanni Neglia, Nessrine Trabelsi.

7.3.1. Network formation games

Network formation games have been proposed as a tool to explain the topological characteristics of existing networks. They assume that each node is an autonomous decision-maker, ignoring that in many cases different nodes are under the control of the same authority (e.g. an Autonomous System) and then they operate as a team. In [11] K. Avrachenkov and G. Neglia in collaboration with V.V. Singh (LRI, Univ. Paris-Sud, France) introduce the concept of network formation games for teams of nodes and show how very different network structures can arise also for some simple games studied in the literature. Beside extending the usual definition of pairwise stable networks to this new setting, we define a more general concept of stability toward deviations from a specific set C of teams' coalitions (C-stability). We study then a trembling-hand dynamics, where at each time a coalition of teams can create or sever links in order to reduce its cost, but it can also take wrong decisions with some small probability. We show that this stochastic dynamics selects C-stable networks or networks from closed cycles in the long run as the error probability vanishes.

7.3.2. Routing Games

A central question in routing games has been to establish conditions for uniqueness of the equilibrium, in terms of network topology or of costs. This question is well understood in two classes of routing games. In [27], E. Altman and C. Touati (Inria Grenoble - Rhône-Alpes) study two other frameworks of routing games in which each of several players has an integer number of connections (which are population of packets) to route and where there is a constraint that a connection cannot be split. Through a particular game with a simple three link topology, we identify various novel and surprising properties of games within these frameworks. We show in particular that equilibria are non unique even in the potential game setting of Rosenthal with strictly convex link costs.

7.3.3. Game theory applied to the Internet and social networks

In [25] E. Altman, A. Jain (UAPV) and C. Touati (Inria Grenoble - Rhône-Alpes) in collaboration with N. Shimkin (Technion), present an overview of the use of dynamic games for analyzing competition in the Internet and in on-line social networks. A special emphasis is put on identifying phenomena and tools that are novel with respet to game theory applied to other types of networks.

7.3.4. Resilience of Routing in Parallel Link Networks

E. Altman, C. Touati and A. Singhal (Inria Grenoble - Rhône-Alpes), in collaboration with J. Li (Tsukuba Univ. Japan), use a game approach in [26] to study the resilience problem of routing traffic in a parallel link network with a malicious player. They consider two players: the first wishes to split its traffic so as to minimize its average delay, which the second player, i.e., the malicious player, tries to maximize. The first player has a demand constraint on the total traffic it routes. The second player controls the link capacities: it can decrease by some amount the capacity of each link under a constraint on the sum of capacity degradation. We first show that the average delay function is convex both in traffic and in capacity degradation over the parallel links and thus does not have a saddle point. We identify best responses strategies of each player and compute both the max-min and the min-max values of the game. We provide stable algorithms for computing both max-min and min-max strategies as well as for best responses.

7.3.5. A game theoretic solution for Resource Allocation in LTE Cellular Networks

Due to Orthogonal Frequency Division Multiple Access (OFDMA) mechanism adopted in LTE cellular networks, intra-cell interference is nearly absent. Yet, as these networks are designed for a frequency reuse factor of 1 to maximize the utilization of the licensed bandwidth, inter-cell interference coordination remains an important challenge. In both homogeneous and heterogeneous cellular networks, there is a need for scheduling coordination techniques to efficiently distribute the resources and mitigate inter-cell interference. In [54], N. Trabelsi and E. Altman in collaboration with C. S. Chen, L. Roullet from Nokia Bell Labs and with R. El-Azouzi from UAPV propose a dynamic solution of inter-cell interference coordination performing an optimization of frequency sub-band reuse and transmission power in order to maximize the overall network utility. The proposed framework, based on game theory, permits to dynamically define frequency and transmission power patterns for each cell in the coordinated cluster.

7.4. Green Networking and Smart Grids

Participants: Sara Alouf, Eitan Altman, Alain Jean-Marie, Giovanni Neglia, Dimitra Politaki.

7.4.1. Power Demand Control

Demand-Response (DR) programs, whereby users of an electricity network are encouraged by economic incentives to rearrange their consumption in order to reduce production costs, are envisioned to be a key feature of the smart grid paradigm. Several recent works proposed DR mechanisms and used analytical models to derive optimal incentives. Most of these works, however, rely on a macroscopic description of the population that does not model individual choices of users. In [34], [57] G. Neglia and A. Benegiamo (PhD student in MAESTRO at the submission time), in collaboration with P. Loiseau, conduct a detailed analysis of those models and argue that the macroscopic descriptions 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, they start from a microscopic description that explicitly models each user's decision. They introduce four DR mechanisms with various assumptions on the provider's capabilities. Contrarily to previous studies, they find that the optimization problems that result from these mechanisms are not convex. Local optimizers can be found numerically through a heuristic. The authors present numerical simulations that compare the different mechanisms and their sensitivity to forecast errors. At a high level, their results show that the performance of DR mechanisms under reasonable assumptions on the provider's capabilities are significantly lower than those suggested by previous studies, but that the gap reduces when the population's flexibility increases.

In [22] A. Jean-Marie and G. Neglia in collaboration with I. Tinnirello, L. Giarré, M. Ippolito (Univ. of Palermo, Italy) and G. Di Bella (Telecom Italia, Italy) investigate a realistic and low-cost deployment of large scale direct control of inelastic home appliances whose energy demand cannot be shaped, but simply deferred. The idea is to exploit 1) some simple actuators to be placed on the electric plugs for connecting or disconnecting appliances with heterogeneous control interfaces, including non-smart appliances, and 2) the Internet connections of customers for transporting the activation requests from the actuators to a centralized controller. The solution requires no interaction with home users: in particular, it does not require them to express their energy demand in advance. A queuing theory model is derived to quantify how many users should adopt this solution in order to control a significant aggregated power load without significantly impairing their quality of service.

7.4.2. Geographical Load Balancing across Green Datacenters

"Geographic Load Balancing" is a strategy for reducing the energy cost of data centers spreading across different terrestrial locations. In [20] G. Neglia, in collaboration with M. Sereno (Univ. of Torino, Italy) and G. Bianchi (Univ. of Roma "Tor Vergata", Italy), focuses on load balancing among micro-datacenters powered by renewable energy sources. They model via a Markov Chain the problem of scheduling jobs by prioritizing datacenters where renewable energy is currently available. Not finding a convenient closed form solution for the resulting chain, they use mean field techniques to derive an asymptotic approximate model which instead is shown to have an extremely simple and intuitive steady state solution. After proving, using both theoretical and discrete event simulation results, that the system performance converges to the asymptotic model for an increasing number of datacenters, they exploit the simple closed form model's solution to investigate relationships and trade-offs among the various system parameters.

7.4.3. Stochastic models for solar energy

The recent popularization of renewable energy sources makes it urgent to have realistic and practical models for the renewable energy harvested by photovoltaic panels for instance. Solar radiation is intrinsically stochastic and exhibits fluctuations at several time scales. Due to the sun's position during the day with respect to a given point on Earth, there is a periodic day-night pattern that is observed on top of which short-time burstiness occurs due to fluctuating weather conditions. In [64], D. Politaki and S. Alouf propose a stochastic model for the global solar radiation. They introduce a multiplicative factor that is the ratio between the actual global solar radiation and the idealized clear sky global radiation. The latter is obtained using known astronomical models and captures the day-night pattern of the solar radiation at any given point on Earth. On the other hand, the multiplicative factor captures the short-time burstiness caused by cloudiness. A semi-Markov model is proposed for the latter such that most of the time correlation found in measured data can be reproduced in synthetic traces.

7.5. Content-Oriented Systems

Participants: Sara Alouf, Eitan Altman, Konstantin Avrachenkov, Philippe Nain, Giovanni Neglia, Dimitra Tsigkari.

7.5.1. Modeling modern DNS caches

In-network caching is a widely adopted technique to provide an efficient access to data or resources on a world-wide deployed system while ensuring scalability and availability. In previous years, S. Alouf and N. Choungmo Fofack (former PhD student at MAESTRO, currently at Ingima) have focused on hierarchical systems that rely on expiration-based policies to manage their caches. Each cache in the system maintains for each item a timer that indicates its duration of validity. The Domain Name System (DNS) is a valid application case. The objective was to assess the performance of a polytree of caches. This work has now been published in [4].

7.5.2. Caching policies

In [46], [60], G. Neglia and D. Tsigkari, in collaboration with D. Carra (Univ. of Verona), M. Feng (Akamai Technologies), V. Janardhan (Akamai Technologies) and P. Michiardi (Eurecom), present a new cache replacement policy that takes advantage of a hierarchical caching architecture, and, in particular, of access-time difference between memory and hard disk. They prove that the proposed policy is optimal when requests follow the independent reference model, and significantly reduces the hard-disk load, as they show through their realistic trace-driven evaluation.

7.5.3. Analyzing Caching and Shaping Timeline Networks

Cache networks are one of the building blocks of information centric networks (ICNs). Most of the recent work on cache networks has focused on networks of request driven caches, which are populated based on users requests for content generated by publishers. However, user generated content still poses the most pressing challenges. For such content timelines are the de facto sharing solution. In [53], A. Reiffers-Masson (PhD student in MAESTRO at the time of submission) and E. Altman in collaboration with E. Hargreaves, W. Caarls and D. Sadoc Menasché from UFRJ (Brazil) establish a connection between timelines and publisher-driven caches. We propose simple models and metrics to analyze publisher-driven caches, allowing for variable-sized objects. Then, we design two efficient algorithms for timeline workload shaping, leveraging admission and price control in order, for instance, to aid service providers to attain prescribed service level agreements.

7.5.4. Cooperative view on Caching

The non-cooperative nature of relations between economic actors in todays networks may lead to inefficiencies and may not provide incentives for investing in deploying new technologies. In [36] E. Altman in cooperation with V. Douros and S. Elayoubi (Orange Labs) in collaboration with Y. Hayel (UAPV) have studied the question of how to split costs for deploying caches between Content Providers and Internet Service Providers. They have designed the cost sharing by casting the problem into a coalition game which they solved using the Shapely value concept.

7.5.5. Streaming optimization

The Quality of Experience (QoE) of streaming service is often degraded by frequent play-back interruptions. To mitigate the interruptions, the media player prefetches streaming contents before starting playback, at a cost of initial delay. In [23], Y. Yu and Y. Yu from Fudan Univ. in collaboration with S. Elayoubi (Orange Labs) R. El-Azouzi (UAPV) and E. Altman, study the QoE of streaming from the perspective of flow dynamics. Firstly, a framework is developed for QoE when streaming users join the network randomly and leave after downloading completion. We model the distribution of prefetching delay using partial differential equations (PDEs), and the probability generating function of playout buffer starvations using ordinary differential equations (ODEs) for constant bit-rate (CBR) streaming. Explicit form starvation probabilities and mean start-up delay are obtained. Secondly, we extend our framework to characterize the throughput variation caused by opportunistic scheduling at the base station, and the playback variation of variable bit-rate (VBR) streaming. Our study reveals that the flow dynamics is the fundamental reason of playback starvation. The QoE of streaming service is dominated by the first moments such as the average throughput of opportunistic scheduling and the mean playback rate. While the variances of throughput and playback rate have very limited impact on starvation behavior in practice.

7.6. Advances in Methodological Tools

Participants: Eitan Altman, Konstantin Avrachenkov, Alain Jean-Marie.

7.6.1. Control theory

Linear programming formulations for the discounted and long-run average Markov Decision Processes have evolved along separate trajectories. In 2006, E. Altman conjectured that the linear programming formulations of these two models are, most likely, a manifestation of general properties of singularly perturbed linear programs. In [8] K. Avrachenkov in collaboration with J. Filar and A. Stillman (Flinders Univ., Australia) and V. Gaitsgory (Macquarie Univ., Australia) demonstrate that this is, indeed, the case.

A. Jean-Marie, together with E. Hyon (Univ. Paris-Ouest Nanterre La Défense), completed the analysis of optimal admission control in a single-server queue with impatience. In the presence of a server startup cost, linear holding costs for the queue and individual costs for departures due to impatience, the optimal policy is to either serve customers whenever some are present, or never serve any customer. The situation is decided by a simple criterion comparing the cost of starting the server to a combination of the other parameters. Proving the optimality of such a simple policy is more difficult than expected, and involves the propagation of properties through the dynamic programming operator of a suitably approximated sequence of problems, following methods and results of Blok, Bhulai and Spieksma.

7.6.2. Game theory

7.6.2.1. Uniqueness of equilibrium

E. Altman in cooperation with M. Kumar (IIT Mumbai) and R. Sundaresan (IICs) have derived in [6] a new sufficient condition for uniqueness of equilibrium which extends the Diagonal Strict Concavity condition of Rosen. They further apply the condition to various networking examples.

7.6.2.2. Hybrid games

In collaboration with V. Gaitsgory, I. Brunetti (former member of MAESTRO) and E. Altman have studied in [15] a non-zero sum game in which there are two components of the state space: one is a finite (controlled) Markov chain and the other is a vector of real numbers. Only the Markov chain is controlled; the other part of the state space evolves according to some differential equations whose parameters are the state and actions of the Markov chain. The authors have shown the existence of an asymptotic stationary equilibrium. They show how to derive epsilon equilibria policies for the original problem based on policies that are asymptotically equilibria.

7.6.2.3. Finite games

In [13] K. Avrachenkov in collaboration with V.V. Singh (LRI, Univ. Paris-Sud 11, France) consider coalition formation among players in an n-player finite strategic game over infinite horizon. At each time a randomly formed coalition makes a joint deviation from a current action profile such that at new action profile all the players from the coalition are strictly benefited. Such deviations define a coalitional better-response (CBR) dynamics that is in general stochastic. The CBR dynamics either converges to a K-stable equilibrium or becomes stuck in a closed cycle. We also assume that at each time a selected coalition makes mistake in deviation with small probability that add mutations (perturbations) into CBR dynamics. We prove that all K-stable equilibria and all action profiles from closed cycles, that have minimum stochastic potential, are stochastically stable. Similar statement holds for strict K-stable equilibria. We apply the CBR dynamics to study the dynamic formation of the networks in the presence of mutations. Under the CBR dynamics all strongly stable networks and closed cycles of networks are stochastically stable.

7.6.2.4. Dynamic Games

In a collaboration with M. Tidball (INRA, France), A. Jean-Marie considered the extension of an infinite-horizon dynamic game of groundwater extension [51], due to Provencher and Burt. As usual in this kind of models, the marginal extraction cost depends on the level of the groundwater. The goal of this paper is to point out the importance of the moment where this cost is announced to the players. We consider the case where the cost is announced before the extraction is made and the case where is announced after extractions. For both cases, we also analyse the possibility of taking into account the rainfall or not. The current literature considers only the case where the cost is announced before rain and harvesting. We characterize the equilibrium in the linear-quadratic case. We compare solutions as functions of the discount factor, with the particular cases of zero discount (myopic model) and no discount (maximization of the steady state) from the economic and the environmental points of view. We show that when the level of the groundwater is small, announcing costs after harvesting and rainfall is better from the economic and environmental point of view than the case of announcing it before harvesting and rainfall.

7.6.3. Queueing Theory

7.6.3.1. Retrial queues

In [10] K. Avrachenkov in collaboration with E. Morozov (Karelian Institute of Applied Mathematical Research, Russia) and B. Steyaert (Gent Univ., Belgium) study multi-class retrial queueing systems with Poisson inputs, general service times, and an arbitrary numbers of servers and waiting places. A class-i blocked customer joins orbit i and waits in the orbit for retrial. Orbit i works like a single-server $\cdot/M/1$ queueing system with exponential retrial time regardless of the orbit size. Such retrial systems are referred to as retrial systems with constant retrial rate. Our model is motivated by several telecommunication applications, such as wireless multi-access systems, optical networks and transmission control protocols, but represents independent theoretical interest as well. Using a regenerative approach, we provide sufficient stability conditions which have a clear probabilistic interpretation. We show that the provided sufficient conditions are in fact also necessary, in the case of a single-server system without waiting space and in the case of symmetric classes. We also discuss a very interesting case, when one orbit is unstable, whereas the rest of the system is stable.

In [9] K. Avrachenkov in collaboration with E. Morozov, R. Nekrasova (Karelian Institute of Applied Mathematical Research, Russia), and B. Steyaert (Gent Univ., Belgium) study the stability of a single-server retrial queueing system with constant retrial rate, general input and service processes. First, we present a review of some relevant recent results related to the stability criteria of similar systems. Sufficient stability conditions were obtained by (Avrachenkov and Morozov, 2014), which hold for a rather general retrial system. However, only in case of Poisson input an explicit expression is provided; otherwise one has to rely on simulation. On the other hand, the stability criteria derived by (Lillo, 1996) can be easily computed, but only hold for the case of exponential service times. We present new sufficient stability conditions, which are less tight than the ones obtained by (Avrachenkov and Morozov, 2010), but have an analytical expression under rather general assumptions. A key assumption is that interarrival times belongs to the class of *new better than used* (NBU) distributions. We illustrate the accuracy of the condition based on this assumption (in comparison with known conditions when possible) for a number of non-exponential distributions.

7.6.3.2. Polling Systems

In [12] K. Avrachenkov in collaboration with E. Perel and U. Yechiali (Tel Aviv Univ., Israel) consider a system of two separate finite-buffer $M/M/1$ queues served by a single server, where the switching mechanism between the queues is threshold-based, determined by the queue which is not being served. Applications may be found in data centers, smart traffic-light control and human behavior. We analyse both work-conserving and non-work-conserving policies. We present occasions where the non-work-conserving policy is more economical than the work-conserving policy when high switching costs are involved. An intrinsic feature of the process is an oscillation phenomenon: when the occupancy of one queue decreases, the occupancy of the other queue increases. This fact is illustrated and discussed. By formulating the system as a three-dimensional continuous-time Markov chain we provide a probabilistic analysis of the system and investigate the effects of buffer sizes and arrival rates, as well as service rates, on the system's performance. Numerical examples are presented and extreme cases are investigated.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

MAESTRO members are involved in the

- Inria Nokia Bell Labs joint laboratory: the joint laboratory consists of six ADRs (Action de Recherche/Research Action) in its second phase (starting October 2012). MAESTRO members participate in two ADRs (see §8.1.1 and §8.1.2).
- Inria ALSTOM joint laboratory: the joint laboratory consists of four projects. MAESTRO members participate in project P11 (see §8.1.3).

8.1.1. ADR "Self-Organized Networks in Wireless" (July 2008 – September 2016)

Participant: Eitan Altman.

- Contractor: Nokia Bell Labs (http://www.bell-labs.com)
- Collaborator: Laurent Roullet (coordinator).

Coordinator for Inria: Eric Fleury (team DANTE).

8.1.2. ADR "Network Science" (June 2013 – March 2017)

Participants: Konstantin Avrachenkov [coordinator], Guillaume Huard, Jithin Kazhuthuveettil Sreedharan, Giovanni Neglia.

- Contractor: Nokia Bell Labs (http://www.bell-labs.com)
- Collaborators: Philippe Jacquet (coordinator), Alonso Silva.

"Network Science" aims at understanding the structural properties and the dynamics of various kind of large scale, possibly dynamic, networks in telecommunication (e.g., the Internet, the web graph, peer-to-peer networks), social science (e.g., community of interest, advertisement, recommendation systems), bibliometrics (e.g., citations, co-authors), biology (e.g., spread of an epidemic, protein-protein interactions), and physics. The complex networks encountered in these areas share common properties such as power law degree distribution, small average distances, community structure, etc. Many general questions/applications (e.g., community detection, epidemic spreading, search, anomaly detection) are common in various disciplines and are being analyzed in this ADR "Network Science". In particular, in the framework of this ADR we are interested in efficient network sampling.

8.1.3. Project P11 "Data Communication Network Performance" (December 2013 – May 2016)

Participants: Sara Alouf [coordinator], Konstantin Avrachenkov, Philippe Nain, Giovanni Neglia, Alina Tuholukova.

- Contractor: ALSTOM Transport (http://www.alstom.com/transport/)
- Collaborators: Pierre Cotelle, Pascal Derouet (coordinator from November 2015), Pierre Dersin, Sébastien Simoens (coordinator until October 2015).

The objective of this study is to build a simulation platform (see §6.2) and develop an evaluation methodology for predicting Quality of Service and availability of the various applications supported by the data communication system of train networks.

8.1.4. "Hybrid GPS-free Localization Algorithms" (May 2016 – October 2016)

Participants: Giovanni Neglia [coordinator], Dimitra Politaki.

- Contractor: LUCIE LABS (http://www.lucielabs.com/)
- Collaborators: François Mazard.

G. Neglia and D. Tsigkari, together with F. Mazard (LUCIE LABS) did a literature survey of localization algorithms that could be deployed in Lucie Labs entertainment wristbands. They proposed a localization algorithm that combines information from Bluetooth and WiFi connectivity in a centralized way. This activity was partially funded by AMIES (Agence pour les Mathématiques en Interaction avec l'Entreprise et la Société).

8.2. Bilateral Grants with Industry

8.2.1. 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 et Lorenzo Maggi

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 plan to use methods from both optimization and dynamic programming.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR Marmote

Participants: Alain Jean-Marie, Issam Rabhi.

ANR Program: Modèles Numériques (MN) 2012, number ANR-12-MONU-0019

Project title: MARkovian MOdeling Tools and Environments

Duration: January 2013 - June 2017

Coordinator: Alain Jean Marie (Inria)

Partners: Inria (project-teams DYOGENE, MAESTRO and MESCAL), Univ. Versailles-Saint-Quentin (DAVID lab.), Telecom SudParis (SAMOVAR lab.), Univ. Paris-Est Créteil (LACL), and Univ. Pierre-et-Marie-Curie (LIP6)

Abstract: ANRMARMOTE aims, among other goals, at realizing the prototype of a software environment dedicated to modeling with Markov chains. It brings together seven partner teams, expert in Markovian analysis, who will develop advanced solution algorithms and applications in different scientific domains: reliability, distributed systems, biology, physics and economics.

https://wiki.inria.fr/MARMOTE/Welcome

9.2. European Initiatives

9.2.1. Collaborations in European Programs, Except FP7 & H2020

Participant: Konstantin Avrachenkov.

Program: EU COST

Project acronym: ACROSS

Project title: Autonomous Control for a Reliable Internet of Services

Duration: November 2013 - November 2017

Coordinator: Rob Van Der Mei (CWI) and J.L. Van Den Berg (TNO), The Netherlands

Other partners: see http://www.cost-across.nl/

Abstract: Currently, we are witnessing a paradigm shift from the traditional information-oriented Internet into an Internet of Services (IoS). This transition opens up virtually unbounded possibilities for creating and deploying new services. Eventually, the ICT landscape will migrate into a global system where new services are essentially large-scale service chains, combining and integrating the functionality of (possibly huge) numbers of other services offered by third parties, including cloud services. At the same time, as our modern society is becoming more and more dependent on ICT, these developments raise the need for effective means to ensure quality and reliability of the services running in such a complex environment. Motivated by this, the aim of this Action is to create a European network of experts, from both academia and industry, aiming at the development of autonomous control methods and algorithms for a reliable and quality-aware IoS.

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.

9.3. International Initiatives

9.3.1. Inria Associate Teams Not Involved in an Inria International Labs

9.3.1.1. THANES

Participants: Eitan Altman, Konstantin Avrachenkov, Jithin Kazhuthuveettil Sreedharan, Philippe Nain, Giovanni Neglia.

Title: THeory and Application of NEtwork Science

International Partners (Institution - Laboratory - Researcher):

CMU (Brazil) - Department of Computer Science - Bruno Ribeiro

UFRJ (Brazil) - Department of Computer and Systems Engineering - Edmundo de Souza e Silva, Daniel Ratton Figueiredo, Daniel Sadoc

Duration: 2014 – 2017

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

Our goal is to study how services in Online Social Networks (OSN) can be efficiently designed and managed. This research requires to answer 3 main questions: 1) How can the topology of an OSN be discovered? Many services need or can take advantage of some knowledge of the network structure that is usually not globally available and in any case changes continuously due to structural dynamics. 2) How does services' adoption spread across the OSN? On the one hand the popularity of a service is determined by word-of-mouth through the links of the OSN and, on the other end, the service may contribute to reshape the structure of the OSN (e.g. by creating new connections). 3) How do different services compete for the finite attention and money of OSN users? In particular our purpose is to provide analytical models (corroborated by simulations and experiments on real networks) to understand such complex interactions.

9.3.2. Inria International Partners

9.3.2.1. Informal International Partners

MAESTRO has continued collaborations with researchers from GERAD, Univ. Montreal (Canada), Flinders Univ. (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) and Petrozavodsk State Univ. (Russia); Ghent Univ. (Belgium); see Sections 9.4.1.1 and 9.4.2.1.

9.3.3. Participation in Other International Programs

MAESTRO has continued collaborations with researchers from IIT Mumbai and IISc Bangalore. In 2015, these collaborations where partly supported by IFCAM and Cefipra.

9.3.3.1. International Initiatives

DyGaMe

Title: Dynamic Games Methods: theory, algorithmics and application

International Partners (Institution - Laboratory - Researcher):

Univ. de Chile (Chile) - Department of Industrial Engineering - Fernando Ordóñez

Univ. Nacional de Rosario (Argentina) - Facultad de Ciencias Exactas, Ingeniería y Agrimensura - Eugenio Della Vecchia

CNRS (France) - LIP6 - Emmanuel Hyon

Duration: 2016 - 2017

Start year: 2016

See also: https://project.inria.fr/dygame

Stochastic Dynamic Game Theory is developing in Engineering sciences and is in need of more theoretical results, algorithms and applications. This project brings together researchers from Applied Mathematics, Operations Research and Economics, with the objective of contributing to these aspects. It will more specifically concentrate on agent rationality and the game structure, look for efficient solution algorithms by crossing Applied Mathematics and Operations Research techniques, and apply the results to problems originating from, on the one hand, security/conservation concerns, and on the other hand, sustainable development problems.

CEFIPRA Grant Monte Carlo, no.5100-IT1

Title: Monte Carlo and Learning Schemes for Network Analytics

International Partners (Institution - Laboratory - Researcher):

IIT Bombay (India) - Department of Electrical Engineering - Prof. V.S. Borkar;

IIS Bangalore (India) - Department of Electrical Engineering - Prof. R. Sundaresan.

Duration: 2014 - 2017

Start year: 2014

The project aims to approach various computation problems in network analytics by means of Markov Chain Monte Carlo (MCMC) and related simulation techniques as well as machine learning algorithms such as reinforcement learning, ant colony optimization, etc. This will include network diagnostics such as ranking, centrality measures, computation on networks using local message passing algorithms, resource allocation issues pertaining to networks and network-based systems such as the internet, peer-to-peer networks, social networks. The work will involve both development of analytical tools and extensive validation thereof using simulation studies. The research will draw upon techniques from graph theory, probability, optimization, and distributed computation.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

9.4.1.1. Professors / Researchers

Bernardo Amorim

Date: 4-8 April 2016

Institution: Federal Univ. of Rio de Janeiro (Brazil)

Vivek Borkar

Date: 26-29 May and 4-17 September 2016

Institution: IIT Mumbai (India)

Damiano Carra

Date: 22-27 February and 18-22 July 2016

Institution: Univ. of Verona (Italy)

Francesco De Pellegrini

Date: 19-22 December 2016

Institution: CREATE-NET (Italy)

Ioannis Dimitriou

Date: 5-10 September 2016

Institution: Univ. of Patras (Greece)

Daniel Figueiredo

Date: 4-8 April 2016

Institution: Federal Univ. of Rio de Janeiro (Brazil)

Michele Garetto

Date: 4-5 April 2016

Institution: Univ. of Torino (Italy)

Moshe Haviv

Date: 15-19 June 2016

Institution: Univ. of Jerusalem (Israel)

Nidhi Hegde

Date: 10-13 June 2016

Institution: Nokia Bell Labs (France)

Giulio Iacobelli

Date: 11-21 January and 4-8 April 2016

Institution: Federal Univ. of Rio de Janeiro (Brazil)

Philippe Jacquet
- Date: 1 December 2016
- Institution: Nokia Bell Labs (France)

Jean-Yves Le Boudec
- Date: 2 June 2016
- Institution: EPFL (Switzerland)

Emilio Leonardi
- Date: 6-16 December 2016
- Institution: Politecnico di Torino (Italy)

Nelly Litvak
- Date: 1-4 December 2016
- Institution: Univ. of Twente (Netherlands)

Natalia Markovich
- Date: 18-27 June 2016
- Institution: Russian Academy of Sciences (Russia)

Evzey Morozov
- Date: 21-29 July 2016
- Institution: Petrozavodsk Univ. (Russia)

Fernando Ordóñez
- Date: 27-30 September
- Institution: Univ. of Chile (Chile)

Sreenath Ramanath
- Date: 17-27 May 2016
- Institution: IIT Bombay (India)

Bruno Ribeiro
- Date: 10-20 June 2016
- Institution: Carnegie Mellon Univ. (USA)

Daniel Sadoc
- Date: 4-8 April 2016
- Institution: Federal Univ. of Rio de Janeiro (Brazil)

Matteo Sereno
- Date: until March 2016 and 28 Nov-2 Dec 2016
- Institution: Univ. of Torino (Italy)

Vinod Sharma
- Date: 15-30 November 2016
- Institution: IIS Bangalore (India)

Flora Spieksma
- Date: 5-7 July 2016
- Institution: Univ. of Leiden (Netherlands)

Rajesh Sundaresan
- Date: 05-26 May 2016
- Institution: IIS Bangalore (India)

Josh Taylor

Date: 24 June 2016

Institution: Univ. of Toronto (Canada)

Don Towsley

Date: 1-3 December 2016

Institution: Univ. of Massachusetts (USA)

Kavitha Voleti Veeraruna

Date: 17-27 May 2016

Institution: IIT Bombay (India)

Uri Yechiali

Date: 15-28 April 2016

Institution: Tel Aviv Univ. (Israel)

9.4.1.2. Post-doc / Ph.D. students

Víctor Bucarey López

Date: 27-30 September 2016

Institution: Univ. of Chile

Ricardo Coelho Silveira

Date: from Sep 2016 until Nov 2016

Institution: Univ. of Rio de Janeiro (Brazil)

Eduardo Hargreaves

Date: 20-23 June 2016

Institution: Univ. of Rio de Janeiro (Brazil)

Yahui Tian

Date: from Jun 2016 until Jul 2016

Institution: Univ. of Texas (USA)

9.4.1.3. Internships

Mikhail Kamalov

Date: from Jun 2016 until Jul 2016

Institution: Saint Petersburg State Univ. (Russia)

Supervisor: Konstantin Avrachenkov

Mohamed Lamghari

Date: from Apr 2016 until Aug 2016

Institution: UNS (France)

Supervisor: Giovanni Neglia

Maksim Mironov

Date: from Aug 2016 until Sept 2016

Institution: MIPT (Russia)

Supervisor: Konstantin Avrachenkov

9.4.2. Visits to International Teams

9.4.2.1. Research Stays Abroad

Konstantin Avrachenkov

Date: 4 - 8 April 2016

Institution: IIT Mumbai (India)

Date: 25 April - 5 May 2016

Institution: Moscow Institute of Physics and Technology and Yandex (Russia)

Date: 10-11 August 2016

Institution: Aaalto Univ. (Finland)

Alain Jean-Marie

Date: 5 - 16 December 2016

Institution: Univ. of Montreal (Canada)

Date: 28 March - 1 April 2016

Institution: Univ. National of Rosario (Argentina)

Date: 3 - 14 April 2016

Institution: Univ. de Chile (Chile)

Arun Kadavankandy

Date: 12-30 April 2016

Institution: Yandex (Russia)

Date: 12-17 July 2016

Institution: IIS Bangalore (India)

Giovanni Neglia

Date: 14 - 22 February; 1 - 4 April; 20 - 25 September; 7 - 10 and 25 - 30 October 2016

Institution: Univ. of Florence (Italy)

Dates: 11 - 16 May; 21 - 23 December 2016

Institution: Univ. of Palermo (Italy)

Dimitra Politaki

Date: 18 October - 2 November and 12 - 20 December 2016

Institution: Univ. of Torino (Italy)

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

- S. Alouf and A. Jean-Marie are the general chairs of the 13th SIGMETRICS/PERFORMANCE Joint International Conference on Measurement and Modeling of Computer Systems (ACM SIGMETRICS/IFIP PERFORMANCE 2016, Antibes Juan-les-Pins, France).

10.1.1.2. Member of the Organizing Committees

- A. Kadavankandy, J. Kazhuthuveettil Sreedharan, H. Mykhailenko, D. Politaki, and D. Tsigkari, were in the local organization committee of the 13th SIGMETRICS/PERFORMANCE Joint International Conference on Measurement and Modeling of Computer Systems (ACM SIGMETRICS/IFIP PERFORMANCE 2016, Antibes Juan-les-Pins, France).

- A. Kadavankandy, H. Mykhailenko, D. Politaki, D. Tsigkari, and A. Tuholukova were volunteer students at the 13th SIGMETRICS/PERFORMANCE Joint International Conference on Measurement and Modeling of Computer Systems (ACM SIGMETRICS/IFIP PERFORMANCE 2016, Antibes Juan-les-Pins, France).
- D. Politaki was a volunteer student at the Journées Cloud 2016, Nice, France.
- D. Politaki and E. Vatamidou are members of the organizing committee of the workshop "Monde des mathématiques industrielles (MOMI)", to be held on 27-28 February 2017 at Inria, Sophia Antipolis. Additional information:
- L. Vermeersch was the local organization chair of the 13th SIGMETRICS/PERFORMANCE Joint International Conference on Measurement and Modeling of Computer Systems (ACM SIGMETRICS/IFIP PERFORMANCE 2016, Antibes Juan-les-Pins, France).

10.1.1.3. Member of Conference Steering Committees

- E. Altman chairs the Steering Committee of the Intl. Conference on NETwork Games, COntrol and OPtimization (this year: NETGCOOP 2016, Avignon, France).

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

- 13th European Workshop on Performance Engineering (EPEW 2016, Chios, Greece) (**A. Jean-Marie**);
- IEEE Intl. Conference on Computer Communications (INFOCOM 2017, Atlanta, GA, USA) (**G. Neglia**);
- Intl. Conference on NETwork Games, COntrol and OPtimization (NETGCOOP 2016, Avignon, France) (**K. Avrachenkov**);
- 16th Intl. Conference on Next Generation Wired/Wireless Networking (NEW2AN 2016, St. Petersburg, Russia) (**K. Avrachenkov**);
- 10th Intl. Conference on Performance Evaluation Methodologies and Tools (VALUETOOLS 2016, Taormina, Italy) (**K. Avrachenkov**);
- 31st Intl. Symposium on Computer and Information Sciences (ISCIS 2016, Krakow, Poland) (**A. Jean-Marie**);
- 17th Intl. Symposium of Dynamic Games and Applications (ISDG 2016, Urbino, Italy) (**E. Altman**);
- Intl. Workshop on Bio-inspired Security, Trust, Assurance and Resilience (BioSTAR 2016, Fairmont, San Jose, CA, USA) (**E. Altman**);
- 9th Intl. Workshop on Multiple Access Communications (MACOM 2016, Aalborg, Denmark) (**K. Avrachenkov**);
- 5th International Conference on Computational Social Networks (CSoNet 2016, Ho Chi Minh City, Vietnam) (**K. Avrachenkov**);
- 1st Mini-Symposium on Stochastic Models: Methods and Applications (SAMMA 2016, Rhodes, Greece) (**E. Vatamidou**);
- 13th Workshop on Algorithms and Models for the Web Graph (WAW 2016, Montreal, Canada) (**K. Avrachenkov**).

10.1.2.2. Session organizer

- Session on Stochastic Modeling at the 17th Conference of the Société Française de Recherche Opérationnelle et d'Aide à la Décision (ROADEF 2016, Compiègne, France) (**A. Jean-Marie**).

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- *ACM Transactions on Modeling and Performance Evaluation of Computing Systems* (ToMPECS) (**K. Avrachenkov** since 2015).
- *Dynamic Games and Applications* (DGAA) (**E. Altman** since 2011);
- *Elsevier Computer Communications* (COMCOM) (**G. Neglia** since 2014);
- *IEEE/ACM Transactions on Networking* (ToN) (**E. Altman** since 2013);
- AIMS (American Institute of Mathematical Sciences) *Journal of Dynamics and Games* (JDG) (**E. Altman** since 2015);
- *Performance Evaluation* (PEVA) (**K. Avrachenkov** since 2008);
- *Wiley Transactions on Emerging Telecommunications Technologies* (ETT) (**S. Alouf** since July 2016).

10.1.3.2. Member of Advisory Boards

- E. Altman is Member of the advisory board of the international journal *IRAN Journal of Computer Science* published by University of Tabriz. Since 2016.

10.1.4. Invited Talks

MAESTRO members gave the following keynote lectures/plenary speeches (in alphabetical order):

- Eitan Altman gave a keynote talk at *The International Symposium on Ubiquitous Networking, UNet 2016*, Casablanca, May 30 – June 1st, 2016. Title: Game theory applied to SIS Epidemics in Networks.
- Eitan Altman gave a keynote lecture at *ITC 28* in Würzburg on 15 September 2015. Title: Dynamic Games for Analyzing Competition in the Internet.
- Alain Jean-Marie gave a keynote lecture at the *11th Workshop on Retrial Queues (WRQ11)*, in Amsterdam, 31 August – 2 September, 2016. Title: Impatient Customers and Optimal Control.

and the following invited talks (in alphabetical order):

- *Access-time aware cache algorithms*, at UCN'16 Workshop on Future challenges in User-Centric Networks, Antibes Juan-les-Pins, France, 14 June a workshop of ACM Sigmetrics / IFIP Performance 2016 (**G. Neglia**);
- *Distributed spectral decomposition and quantum random walk*, at Workshop on critical and collective effects in graphs and networks, MIPT, Moscow, April 2016 (**K. Avrachenkov**);
- *Distributed spectral decomposition and quantum random walk*, at the 20th Conference of the International Linear Algebra Society (ILAS), Leuven, Belgium, July 2016 (**K. Avrachenkov**);
- *Overview and comparison of random walk based techniques for estimating network averages*, at COSTNET Conference, Ribno, Slovenia, September 2016 (**K. Avrachenkov**);
- *Hitting Times in Markov Chains with Restart and their Applications to Ranking*, at Workshop dedicated to W. Stadje, Osnabruck, Germany, October 2016 (**K. Avrachenkov**).

10.1.5. Leadership within the Scientific Community

- E. Altman is a fellow member of IEEE (Class of 2010).
- E. Altman, A. Jean-Marie and P. Nain are (elected) members of IFIP WG7.3 on "Computer System Modeling". E. Altman is also Member of WG 6.3 of IFIP on Performance of Communication Systems.

10.1.6. Research Administration

E. Altman

- is co-responsible of one of the five themes of the SFR (Structure Fédérative de Recherche) AGORANTIC (in which Inria is a founding member) entitled "Digital Culture and Virtual Societies".

S. Alouf

- was member of the recruitment committee for junior Inria researchers (CR1, CR2);
- is member of the scientific committee of the joint laboratory Inria-Alstom since May 2014.

K. Avrachenkov

- together with Arnaud Legout (DIANA team) and Fabien Gandon (WIMMICS team) is co-responsible of the multi-disciplinary research theme (Action Transversale) "Semantic and Complex Networks" at Inria Sophia Antipolis - Méditerranée.

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 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 MAESTRO since October 2014;

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.

MAESTRO members are in the following committees of Inria Sophia Antipolis-Méditerranée

- CLFP: Training Committee (**S. Alouf**, since November 2014);
- CSD: Doctoral Committee (**S. Alouf**, since February 2006);
- MASTIC: a commission in charge of popularization and regional and internal scientific animation (**D. Politaki**, since July 2016);
- NICE: Invited Researchers Committee (**K. Avrachenkov**, since 2010).

MAESTRO members are in charge of the following tasks for the research center and the project-team:

- Supervision and validation of the project-teams' yearly activity reports (**K. Avrachenkov**, since 2010);
- Organizing the fortnightly PhD seminars of the research center (**D. Politaki**, since November 2016);
- Organizing the fortnightly MAESTRO internal meetings (**J. K. Sreedharan**, since November 2013).

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence:

G. Neglia, "Probability", 50.5H, 1st year Water Engineering degree (L3), niv. of Nice Sophia Antipolis (UNS), France.

D. Politaki, "Intro Web", 36H, (L1), UNS, France.

Master:

S. Alouf, "Performance Evaluation of Networks", 31.5H, M2 IFI Ubinet, UNS, France.

A. Jean-Marie, "Foundations of Network Modeling", 12H, MPRI, Univ. Paris Diderot/ENS Ulm/Univ. Paris Saclay, France.

G. Neglia, "Distributed Optimization and Games", 31.5H, M2 IFI Ubinet, UNS, France.

G. Neglia, responsible for the “Winter School on Complex Networks”, 22.5H, M1 Computer Science, UNS, France.

K. Avrachenkov, “Random-walk based algorithms for complex network analysis” at “Winter School on Complex Networks”, 2H, M1 Computer Science, UNS, France.

10.2.2. Supervision

- PhD defended:

  Alexandre Reiffers-Masson, “Competition over visibility and popularity in on line social networks”, UAPV, 12 January 2016, advisors: Eitan Altman and Yezekael Hayel.

  Jithin Kazhuthuveettil Sreedharan, “Sampling and Inference in Complex Networks”, Univ. Côte d’Azur, 2 December 2016, advisor: Konstantin Avrachenkov.

  Nessrine Trabelsi, “A Generic Framework for User Association and Interference Management in LTE Cellular Networks”, UAPV, 20 December 2016, advisors: Eitan Altman and Rachid El Azouzi.

- PhD in progress:

  Zaid Allybokus, 1 July 2016, advisors: Konstantin Avrachenkov and Lorenzo Maggi (Huawei).

  Arun Kadavankandy, “Random Matrix Theory and Complex Networks,” 5 March 2014, advisors: Konstantin Avrachenkov and Laura Cottatellucci (Eurecom).

  Hlib Mykhailenko, “Probabilistic approaches for big data analysis,” 1 May 2014, advisors: Fabrice Huet (SCALE team) and Philippe Nain.

  Dimitra Politaki, “Greening data center,” 1 February 2016, advisors: Sara Alouf and Fabien Hermenier (UNS).

  Alina Tuholukova, “Caching at the Edge: Distributed Phy-aware Caching Policies for 5G Cellular Networks,” 1 July 2016, advisors: Petros Elia (Eurecom) and Giovanni Neglia.

10.2.3. Juries

MAESTRO members participated in the Habilitation (HDR) thesis committees of (in alphabetical order):

- Patrick Loiseau, “Game theory and statistical learning in security, privacy and networks”, Univ. Pierre et Marie Curie (Paris), 8 December 2016 (**E. Altman** as reviewer and jury president);

and in the Ph.D. committees of (in alphabetical order):

- Alexandre Reiffers-Masson, “Competition over visibility and popularity in on line social networks”, UAPV, 12 January 2016 (**E. Altman** as advisor);
- Nesrine Ben Khalifa, “Evolutionary games with non-uniform interactions and delays”, UAPV, 16 December 2016 (**E. Altman** as examiner).
- Mikael Touati, “Cooperative Game Theory and Stable Matchings in Networks”, Telecom ParisTech, 1st December 2016 (**E. Altman** as advisor);
- Jithin Kazhuthuveettil Sreedharan, “Sampling and Inference in Complex Networks”, Univ. Côte d’Azur, 2 December 2016 (**K. Avrachenkov** as advisor, **A. Jean-Marie** as jury president);
- Nessrine Trabelsi, “A Generic Framework for User Association and Interference Management in LTE Cellular Networks”, UAPV, 20 December 2016 (**E. Altman** as advisor);
- Osti Prajwal, “Resource allocation in wireless access network: A queueing theoretic approach”, Aalto Univ., Helsinki, Finland, 11 August 2016 (**K. Avrachenkov** as opponent).

10.3. Popularization

Activities are presented in chronological order:

- S. Alouf delivered a conference titled “Comment marche le Web ?” at Lycée Pierre et Marie Curie, Menton, for one classe of high school students (25 November 2016).
- D. Politaki participated to the “Fête de la science” at the Campus Valrose, Nice (13 October 2016) and at the Congress Center, Antibes Juan-les-Pins (22 October 2016). She animated the game “Datagramme” and the programming of Thymio.
- D. Politaki managed two sessions MEDITES in two middle schools (22 November 2016).
- D. Politaki participated to the Thymio competition (26 November 2016) which was organized by Hackathon Women Creativity 2016 in Nice.

D. Politaki is a member of MASTIC, a commission in charge of popularization and regional and internal scientific animation (since July 2016).

10.4. Participation in scientific events

10.4.1. Conferences and workshops

MAESTRO members gave presentations at the following scientific events (in alphabetical order):

- 9th International Conference on Matrix Analytic Methods in Stochastic Models (MAM9), Budapest, Hungary, 28–30 June 2016 (**E. Vatamidou**).
- 4th International workshop on Big Data and Social Networking Management and Security (BDSN), Barcelona, Spain, 5-7 December 2016 (**H. Mykhailenko**).
- 1st International Conference on Reliability, Safety and Security of Railway Systems (RSSR 2016), Paris, France, 28-30 June 2016, (**A. Tuholukova**).
- 2016 Americal Control Conference (ACC 2016), Boston, USA, July 6-8 2016, (**G. Neglia**).

10.4.2. Schools and doctoral courses

MAESTRO members have attended the following events (list in alphabetical order):

- E3-RSD Summer School on “Efficacité Energétique des Réseaux et Systèmes Distribués” (20H), Dinard, France, 23-27 May 2016 (**S. Alouf**, **D. Politaki**);
- WAW 2015 School on complex networks and graph models (16H), Eindhoven, Netherlands, 7-8 December 2015 (**A. Kadavankandy** and **J. K. Sreedharan**).

11. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

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[2] J. K. SREEDHARAN.*Sampling and Inference in Complex Networks*, Université Côte d’Azur, 2016.

[3] N. TRABELSI.*A Generic Framework for User Association and Interference Management in LTE Cellular Networks*, UAPV, 2016.

Articles in International Peer-Reviewed Journal

[4] S. ALOUF, N. CHOUNGMO FOFACK, N. NEDKOV.*Performance models for hierarchy of caches: Application to modern DNS caches*, in "Performance Evaluation", March 2016, vol. 97, p. 57-82, Performance Evaluation Methodologies and Tools: Selected Papers from VALUETOOLS 2013.Free access to this article is provided until April 22, 2016 through this personal article link http://authors.elsevier.com/a/1SeQX_3oLTo1G2 [*DOI :* 10.1016/J.PEVA.2016.01.001], https://hal.inria.fr/hal-01258189.

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Project-Team MARELLE

Mathematical, Reasoning and Software

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Proofs and Verification

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Project-Team MARELLE

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7.6. - Computer Algebra
7.12. - Computer arithmetic

Other Research Topics and Application Domains:

6.1. - Software industry
9.4.1. - Computer science
9.4.2. - Mathematics

1. Members

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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. New Software and Platforms

4.1. Coq

The Coq Proof Assistant
KEYWORDS: Proof - Certification - Formalisation
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, ...

- Participants: Benjamin Gregoire, Enrico Tassi, Bruno Barras, Yves Bertot, Pierre Boutillier, Xavier Clerc, Pierre Courtieu, Maxime Dénès, Stephane Glondu, Vincent Gross, Hugo Herbelin, Pierre Letouzey, Assia Mahboubi, Julien Narboux, Jean-Marc Notin, Christine Paulin-Mohring, Pierre-Marie Pedrot, Loic Pottier, Matthias Puech, Yann Regis-Gianas, François Ripault, Matthieu Sozeau, Arnaud Spiwack, Pierre-Yves Strub, Benjamin Werner, Guillaume Melquiond and Jean-Christophe Filliatre
- Partners: CNRS - ENS Lyon - Université Paris-Diderot - Université Paris-Sud
- Contact: Matthieu Sozeau
- URL: http://coq.inria.fr/

The Marelle team, in collaboration with the pi.r2 team, plays an important role in the development of Coq. During this year, we contributed to the 8.6 version of Coq, released in December. As the *release manager*, Maxime Dénès led the implementation of a time-based release process, aiming at shorter and more predicitible release cycles. We successfully transitioned to 10-month cycles and hope to soon move to 6-month cycles, making it easier for users to benefit from the latest improvements.

At a more detailed level, members of the Marelle team attended the Coq developer meetings (organized in Paris by Maxime Dénès and Matthieu Sozeau) and contributed to the development of Coq concerning bug fixes for virtual machine execution (Benjamin Grégoire and Maxime Dénès), cleaning up the API for plug-in developers (Matej Košík), improving the State Transaction Machine (Enrico Tassi), setting up a package index based on OPAM (Enrico Tassi), introducing a system to discuss Coq Enhancement Proposals (Enrico Tassi), and implementing a new configurable system of warnings (Maxime Dénès).

We supervise of an engineer working at MIT on questions related to efficient proof construction and proof development environments, in cooperation with researchers from the pi.r2 team. The collaboration with MIT was also an occasion to reflect on the licence framework governing collaborations around the Coq system.

We also prepared the set-up of a consortium to gather intensive users and contributors to the development of Coq. This was an occasion to work with the promotors of the InriaSoft structure which is expected to host the consortium in the long run.

4.2. 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: Gilles Barthe, Benjamin Gregoire and Pierre-Yves Strub
- Contact: Benjamin Grégoire
- URL: https://www.easycrypt.info/trac/

This year, development on this software system concerned the development of new logical settings to work on differential privay problems: a Hoare logic based on union bound and a logic based on probabilistic couplings.

4.3. Math-Components

Mathematical Components library
FUNCTIONAL DESCRIPTION

The Mathematical Components library is a set of Coq libraries that cover the mechanization of the proof of the Odd Order Theorem.

- Participants: Andrea Asperti, Jeremy Avigad, Yves Bertot, Cyril Cohen, Francois Garillot, Georges Gonthier, Stéphane Le Roux, Assia Mahboubi, Sidi Ould Biha, Ioana Pasca, Laurence Rideau, Alexey Solovyev, Enrico Tassi, Laurent Théry and Russell O'Connor
- Contact: Assia Mahboubi
- URL: http://www.msr-inria.fr/projects/mathematical-components-2/

This year we contributed to the library by adding a new module to cover finite sets within potentially infinite finite types, organizing tutorials and schools to teach its usage:

- in January in Sophia Antipolis (one-week format) https://team.inria.fr/marelle/en/advanced-coq-winter-school-2016/ (organized by Enrico Tassi, with contributions by Cyril Cohen, Laurence Rideau, Laurent Théry)
- in August in Nancy (one-day tutorial format, colocated with the ITP conference, organized by Assia Mahboubi and Enrico Tassi, with contributions by Yves Bertot, Cyril Cohen, and Laurent Théry) https://github.com/math-comp/wiki/wiki/tutorial-itp2016
- in November in Sophia Antipols https://team.inria.fr/marelle/en/advanced-coq-winter-school-2016-2017/ (organized by Enrico Tassi, with contributions by Yves Bertot, Cyril Cohen, Laurence Rideau).

4.4. Ssreflect

FUNCTIONAL DESCRIPTION

Ssreflect is a tactic language extension to the Coq system, developed by the Mathematical Components team.

- Participants: Cyril Cohen, Yves Bertot, Laurence Rideau, Enrico Tassi, Laurent Thery, Assia Mahboubi and Georges Gonthier
- Contact: Yves Bertot
- URL: http://ssr.msr-inria.inria.fr/

This year we mainly performed maintenance operations on this software extension to the Coq system (Enrico Tassi).

4.5. Zoocrypt

FUNCTIONAL DESCRIPTION

ZooCrypt 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 year, we extended the tool to be able to deal with schemes based on cyclic groups and bilinear maps.

- Participants: Benjamin Gregoire, Gilles Barthe and Pierre-Yves Strub
- Contact: Benjamin Grégoire
- URL: https://www.easycrypt.info/zoocrypt/

5. New Results

5.1. Implementing Theorem Proving in Higher Order Logic Programming

Participants: Enrico Tassi, Cvetan Dunchev [University of Bologna], Ferruccio Guidi [University of Bologna], Claudio Sacerdoti Coen [University of Bologna].

We carried on our experiments with extensions of λ-prolog, based on the ELPI tool that we developed, in particular concerning implementations of higher-order logic and type theory in this context. This work lead to publication in June at LFMTP'16 [14] and to a preliminary report [25].

5.2. Coqoon: An IDE for interactive proof development in Coq

Participants: Enrico Tassi, Alexander Faithfull [ITU Copenhagen], Jesper Bengtson [ITU Copenhagen], Carst Tankink.

We carried on our experiments with the Coqoon integrated development environment. This lead to a preliminary report submitted for publication [24]

5.3. A book on mathematical components

Participants: Enrico Tassi, Yves Bertot, Laurence Rideau, Assia Mahboubi, Georges Gonthier.

As an effort to lower the entry barrier to use a structured library of formalized mathematics, we wrote a book explaining the principles of ssreflect and mathematical components. This book-in-the-making is available on github at https://math-comp.github.io/mcb/ and we plan to make it evolve as we teach schools on using the library and we gather feedback from readers and users.

5.4. Proofs of transcendence

Participants: Sophie Bernard, Yves Bertot, Laurence Rideau.

In the previous year, we developed formally verified proofs that e and π are transcendental. This result was published this year at the CPP conference (Certified Programs and Proofs) [12]. Since October, as part of the PhD of Sophie Bernard, we are working on the generalisation of these proofs, in order to prove the Lindemann theorem that states that no algebraic spans of exponentials of algebraic numbers can be equal to zero under some assumptions.

5.5. Cubical type theory and univalent foundations

Participants: Cyril Cohen, Anders Mörtberg, Benedikt Ahrens [ASCOLA project-team, Inria and LINA Nantes], Mark Bickford [Cornell Unversity, USA], Thierry Coquand [Chalmers and Göteborg University, Sweden], Ralph Matthes [CNRS, University of Toulouse].

This work mainly concerns Univalent Foundations and Homotopy Type Theory which builds on recently discovered connections between type theory and abstract homotopy theory. The main question we have been working on lately is finding a computational interpretation for the univalence axiom, the main fruit of this work is a recent paper on, and implementation of, cubical type theory [23] which provides a constructive justification for this axiom. The code is visible at https://github.com/mortberg/cubicaltt. The last year Anders Mörtberg has been working together with Mark Bickford at Cornell University and Thierry Coquand at University of Gothenburg and Chalmers University of Technology on the formal verification of this model in the Nuprl proof assistant, this code is visible at http://www.nuprl.org/wip/Mathematics/cubical!type!theory/index.html.

Anders Mörtberg also recently visited Thierry Coquand to start a collaboration on the formalization of this model in the UniMath system implemented in Coq. Together with Benedikt Ahrens in the Ascola team at Inria Nantes and Ralph Matthes at IRIT in Toulouse, Anders Mörtberg also worked on the formalization of a translation from binding signatures to monads for representing languages with binders in UniMath [21]. This work uses the new possibilities for representing category theory in type theory that univalence provides.

5.6. Formal study of double-word arithmetic algorithms

Participants: Laurence Rideau, Jean-Michel Muller [CNRS and ENS Lyon], Valentina Popescu [CNRS and ENS Lyon].

As part of the ANR Fastrelax project, we have started to formalize 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" [26].

5.7. Formal foundations of 3D geometry for robot manipulators

Participants: Cyril Cohen, Reynald Affeldt [AIST, Japan].

We formalized the 3D geometry concepts used in the description of kinematics chains, in particular: rotations, rigid body tranformations, screw motions, frame changes, and the Denavit-Hartenberg Convention. This lead to a publication to appear in the internaltional conference CPP 2017 [7].

5.8. Finites sets, finite maps, multisets, order types

Participant: Cyril Cohen.

We extend the Mathematical Components library with a module concerning finite sets (in potentially infinite types), finite maps and multisets. This module plays a crucial role in the formalization of nominal sets, multinomials, semi-algebraic sets, and many experimental developments.

We also extend the Mathematical Components library with a module concerning orders, lattices, and sets. This serves as an abstraction on various libraries, including the finite set library, semi-algebraic sets, finite reunions of intervals, and boolean predicates (in classical theories).

5.9. CoqEAL and modular large scale reflection

Participants: Cyril Cohen, Damien Rouhling.

Extending work by Guillaume Cano, Cyril Cohen, Maxime Dénès, Anders Mörtberg and Vincent Silès, we reimplemented the foundations of the CoqEAL library on Keller and Lasson's parametricity plug-in and provided a more robust translation mechanism. We illustrated the use of this enhanced version of CoqEAL on a new version of the traditional ring tactic. This lead to a publication at JFLA 2017 (Journées Francophones des Langages Applicatifs, the article actually is in English) [17].

5.10. Formalization of semi-algebraic sets

Participants: Yves Bertot, Cyril Cohen, Boris Djalal.

We developed the necessary results about first-order logical formulae to be able to define semi-algebraic sets and semi-algebraic functions in Coq. This required that we provide elements of language to describe quantification over blocks of variables. We show that the equality of semi-algebraic sets is decidable, thanks to the already formalized decision procedure based on quantifier elimination. We then show that our formalized semi-algebraic sets do satisfy general abstract interfaces for sets, as seen in section 5.8

In the long run this work will be instrumental to describe the output of cylindrical algebraic decomposition algorithms. Indeed, this output is usually made of semi-algebraic sets.

5.11. Formalizing the Spectral Theorem

Participant: Cyril Cohen.

We formalize the spectral theorem for normal, hermitian and unitary matrices (this work in progress is available at https://github.com/Barbichu/spectral) These results are useful in the study of rotations and rigid body transformations in dimension 3. This is a key ingredient of the singular value decomposition (useful in inverse kinematics, signal processing, and many other practical applications).

5.12. A formal proof of La Salle's invariance principle

Participants: Yves Bertot, Cyril Cohen, Damien Rouhling.

We started formalizing the proof of La Salle's invariance principle using the Coquelicot library, with the goal of using it to formalize the proof of stability of a control function for the inverted pendulum (a basic exercise that can serve as an introduction to problems in robotics). For now, I have proven a few properties of the set of limit points of a function.

5.13. Formalizing Delaunay triangulations

Participants: Yves Bertot, Wassim Haffaf.

We studied the applicability of the mathematical component library to describe Delaunay triangulation algorithms in the most abstract way. We also formalized a theorem on convex functions known as *Jensen's inequality*.

5.14. Formalizing Quantum Computing

Participant: Laurent Théry.

We have formalized an algorithm proposed by Peter Selinger to synthesize quantum gates. His approach mixes number theoretical notions and linear algebra, two aspects that are well covered by the Mathematical Components Library.

5.15. Formalizing De Bruijn Sequences

Participant: Laurent Théry.

De Bruijn sequences are combinatorial objects. We have shown how they can be generated by exhibiting a link with irreducible polynomials in finite fields, with a formal proof in Coq.

5.16. Formalizing Hanoi towers

Participant: Laurent Théry.

The problem of Hanoi towers is a standard example to explain recursion. While trying to write a formalization, we discovered that there exists an interesting generalisation. Starting with two arbitrary valid positions, the problem is to find an optimal solution to go from one to the other. The solution is somewhat counter-intuitive, and not always unique. We formalized it in Coq.

5.17. Implementation of Bourbaki's Theory of Sets in Coq

Participant: José Grimm.

A paper describing our implementation of the sets of natural numbers, of rational numbers and of real numbers has been published by the Journal of Formalized Reasoning [6].

We implemented Chapter 3, Section 7 (Inverse Limits and Direct Limits) and the start of Chapter 4 (Structures) of the Theory of Sets of Bourbaki, details are found in the Research Report [19]

5.18. Factorization of ordinal numbers

Participant: José Grimm.

Ordinal numbers have been designed at approximately the same time that the foundations of mathematics were being revisited, in the beginning of the 20th century. These objects cross the boundaries of set theory and pose especially difficult challenges when considering the task of formalizing mathematics. This is the reason why we concentrate on formal proofs concerning these objects.

An ordinal number x is said to be prime if $x > 1$ and for every factorisation $x = ab$, one of a or b is equal to x (the other factor is not necessarily equal to 1). Prime ordinals are of three kinds; a power of a power of ω, the successor of a power of ω, or a prime natural number. Every ordinal can uniquely be written as a product of primes, with the following restriction: if a is followed by b in the factor list then: if b is of the first kind, so is a and $a \geq b$, if a and b are natural numbers, then $a \leq b$. The proof can be found in an updated version of [20]

5.19. New logics for differential privacy

Participants: Benjamin Grégoire, Gilles Barthe [IMDEA], Noémie Fong [ENS], Marco Gaboardi [University at Buffalo], Justin Hsu [University of Pennsylvania], Pierre-Yves Strub [IMDEA].

We proposed new logics to work on examples from the differential privacy literature, a hoare logic based on the union bound [10] and a logic based on the deep connection between differential privacy and probabilistic couplings [11], [9].

5.20. Formalizing counter-measures for differential power analysis

Participants: Benjamin Grégoire, Gilles Barthe [IMDEA], Sonia Belaïd [Thales Communications & Security], François Dupressoir [IMDEA], Sebastian Faust [Ruhr Universität Bochum], Pierre-Alain Fouque [Université de Rennes and Institut Universitaire de France], François-Xavier Standaert [Université Catholique de Louvain], Pierre-Yves Strub [IMDEA], Rébecca Zucchini [ENS Cachan and Inria].

Differential power analysis (DPA) is a side-channel attack in which an adversary retrieves cryptographic material by measuring and analyzing the power consumption of the device on which the cryptographic algorithm under attack executes. We introduced new notions and models allowing to check the correctness of counter measures (known as *masking schemes*) [8], [22]. Based on this idea we have developed a compiler to transform an unmasked program into it masked version.

6. Partnerships and Cooperations

6.1. National Initiatives

6.1.1. ANR

We are currently members of two projects funded by the French national agency for research funding.

- 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.

6.2. International Initiatives

6.2.1. Inria International Partners

6.2.1.1. Informal International Partners

We work with the team of Adam Chlipala at MIT, in particular the engineer Paul Steckler, with whom we have regular meetings concerning the optimization of parts of the Coq system with respect to use cases provided by the MIT team, and the design of user-interface tools. This engineer had a visit of 6 weeks in France in April, three weeks in the pi.r2 team (mostly hosted by Matthieu Sozeau) and three weeks in the Marelle team, mostly hosted by Enrico Tassi and Maxime Dénès. The collaboration continues since that visit with a weekly phone conference.

6.3. International Research Visitors

6.3.1. Visits of International Scientists

We had visits by Gilles Barthe (IMDEA, Madrid, Spain) for 2 weeks, Benedikt Schmidt (IMDEA), for 2 weeks, François-Xavier Standaert (Université Catholique de Louvain, Crypto Group, Belgium), for 1 week, Sebastian Faust (Ruhr-University Bochum, Germany) for 1 week, François Dupressoir (IMDEA) for 1 week, Pierre-Yves Strub (IMDEA), for 1 week, and Peter Schwabe (Radboud University, Nijmegen, the Netherlands) for 3 days.

6.3.2. Visits to International Teams

Benjamin Grégoire visited IMDEA (Madrid, Spain) for two one-week trips.

Yves Bertot, Maxime Dénès, and Enrico Tassi visited Princeton University in June for the kick-off meeting of the *Expedition in Computing* entitled “the science of deep specification” funded by the NSF foundation.

Enrico Tassi visited the team of Jesper Bengtson at the IT-University of Copenhagen, Denmark.

Anders Mörtberg visited the team of Thierry Coquand at Chalmers and University of Göteborg in Sweden.

7. Dissemination

7.1. Promoting Scientific Activities

7.1.1. Scientific Events Selection

7.1.1.1. Chair of Conference Program Committees

Yves Bertot is program co-chair, with Viktor Vafeiadis from MPI-SWS in Germany for the ACM conference *Certified Programs and Proofs* (CPP) to be held in Paris in January 2017. Most of the editorial activities took place in 2016.

7.1.1.2. Member of the Conference Program Committees

- Yves Bertot and Laurent Théry were members of the conference program committee for the conference *Interactive Theorem Proving* (ITP) and *User-Interfaces for Theorem Provers* (UITP).
- Cyril Cohen was a member ot the program committee for the 8th Coq workshop.

7.1.1.3. Reviewer

Cyril Cohen was reviewer for the conferences CSL 2016 and ITP 2016. Laurent Théry was a reviewer for the conferences TACAS'17 and CPP'17. Benjamin Grégoire was a reviewer for TACAS. Benjamin Grégoire was a reviewer for PoPL 2017.

7.1.2. Journal

7.1.2.1. Reviewer - Reviewing Activities

Cyril Cohen was a reviewer for *Journal of Automated Reasoning*. Laurent Théry was a reviewer for *Journal of Automated Reasoning* and *Journal of Symbolic Computation*. Yves Bertot was a reviewer for *Journal of Automated Reasoning* and *Computational Geometry: Theory and Applications*.

7.1.3. Invited Talks

Laurent Théry gave an invited talk at MAP'16 (*Mathematics, Algorithms, and Proofs*).

Cyril Cohen gave an invited talk at the ELFIC seminar on the Paris-Saclay campus (Elfic stands for *Éléments finis formellement vérifiés*).

7.1.4. Leadership within the Scientific Community

Yves Bertot and Maxime Dénès have been working on setting up a Consortium of users for the Coq system. The consortium should start in the early days of 2017. Yves Bertot, Enrico Tassi, and Maxime Dénès were invited to the kick-off meeting of the *Expedition in Computing* entitled "the science of deep specification" funded by the NSF foundation, along with three other developers from the pi.r2 project-team, as expert developers of the Coq system. This kick-off meeting took place in June.

7.1.5. Scientific Expertise

- Laurent Théry evaluated projects for the French national agency for research funding (ANR),

7.1.6. Research Administration

- José Grimm is a member of the local committee for Hygiene and Work safety,
- Cyril Cohen served several times as secretary for the local committee of project-team leaders,
- Benjamin Grégoire is a member of the committee on computer tools usage (CUMI) for the Sophia-Antipolis Méditerranée Inria center.

7.2. Teaching - Supervision - Juries

7.2.1. Teaching

Licence : Cyril Cohen, mathematics oral exam, 30 hours, Classes préparatoires aux grandes écoles

Master : Laurent Théry gave a course at ENS Lyon (9 hours), a course at École des Mines (3 hours), and a course at University de Marseille (3 hours). Yves Bertot gave a one-week introductory course on Coq at University of Nice (21 hours). Enrico Tassi organized a one-week advanced course on Coq and Mathematical Components for students of ENS Lyon and University of Nice (30 hours). There were two instances of this school, in January and in November, teachers for this course were Enrico Tassi, Yves Bertot, Cyril Cohen, Laurence Rideau, and Laurent Théry.

7.2.2. Supervision

PhD in progress : Boris Djalal, started in October 2015, supervised by Yves Bertot and Cyril Cohen

PhD in progress : Cécile Baritel-Ruet, started in October 2016, supervised by Yves Bertot and Benjamin Grégoire

PhD in progress : Sophie Bernard, started in October 2016, supervised by Yves Bertot and Laurence Rideau

PhD in progress : Damien Rouhling, started in October 2016, supervised by Yves Bertot and Cyril Cohen.

7.2.3. Juries

Yves Bertot was member of the defense committee for the thesis of Jacques-Henri Jourdan.

7.3. Popularization

Laurent Théry gave talks in the context of “Fête de la science”.

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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 Medecine

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Team MATHNEURO

Creation of the Team: 2016 January 01

Keywords:

Computer Science and Digital Science:

6.1.1. - Continuous Modeling (PDE, ODE)
6.1.2. - Stochastic Modeling (SPDE, SDE)
6.1.4. - Multiscale modeling
6.2.1. - Numerical analysis of PDE and ODE
6.2.2. - Numerical probability
6.2.3. - Probabilistic methods
6.3.4. - Model reduction

Other Research Topics and Application Domains:

1.3. - Neuroscience and cognitive science
1.3.1. - Understanding and simulation of the brain and the nervous system
1.3.2. - Cognitive science
1.4. - Pathologies

1. Members

Research Scientists

Mathieu Desroches [Team leader, Inria, Researcher, HDR]
Pascal Chossat [CNRS, Senior Researcher, HDR]
Olivier Faugeras [Inria, Senior Researcher, HDR]
Maciej Krupa [Inria, Senior Researcher, Advanced Research Position]
Romain Veltz [Inria, Researcher]

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Elif Koksal Ersoz [Inria, relais thèse in Dec 2016]
Alex Dolcemascolo [Univ. Nice]
Pascal Helson [Inria, from Oct 2016]
Jamil Salhi [ENIT, until Mar 2016]

Post-Doctoral Fellows

Tomasz Gorski [Inria, from May 2016 until Aug 2016]
Audric Drogoul [Thales, until Nov 2016]
Alexandre Richard [Ecole Polytechnique, from Sep 2016]

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Marie-Cecile Lafont [Inria]

Others

Paul Bressloff [University of Utah, International Chair from 2014 until 2019]
Daniele Avitabile [University of Nottingham, Associate Member, from Nov 2016]
Cantin Baron [Master UNS, Internship, from Feb 2016 until Jul 2016]
Quentin Cormier [ENS Lyon, Internship, until Mar 2016]
Raphael Forquet [Master Polytech, Internship, from Oct 2016]

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 approaches
3. Neural fields
4. Slow-fast dynamics in neuronal models
5. Synaptic plasticity
6. Visual neuroscience

3. Research Program

3.1. Neural networks dynamics

The study of neural networks is certainly motivated by the long term goal to understand how brain is working. But, beyond the comprehension of brain or even of simpler neural systems in less evolved animals, there is also the desire to exhibit general mechanisms or principles at work in the nervous system. One possible strategy is to propose mathematical models of neural activity, at different space and time scales, depending on the type of phenomena under consideration. However, beyond the mere proposal of new models, which can rapidly result in a plethora, there is also a need to understand some fundamental keys ruling the behaviour of neural networks, and, from this, to extract new ideas that can be tested in real experiments. Therefore, there is a need to make a thorough analysis of these models. An efficient approach, developed in our team, consists of analysing neural networks as dynamical systems. This allows to address several issues. A first, natural issue is to ask about the (generic) dynamics exhibited by the system when control parameters vary. This naturally leads to analyse the bifurcations [8] [37] 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 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 [1] [36] 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.

3.3. Neural fields

Neural fields are a phenomenological way of describing the activity of population of neurons by delay 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 of 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], 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 [3], 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 [38]. This theory is based on center manifold and normal forms ideas.

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) 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 [35] — and numerical methods such as pseudo-arclength continuation [32]. 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) [30], [34])*, which represent an alternation between subthreshold and spiking behaviour, and *bursting oscillations* [31], [33], also corresponding to experimentally observed behaviour [29].

Selected publications on this topic: lien.

3.5. 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 [28]. 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, Hebbian-like or STDP, have strong effects on neuron dynamics complexity, such as dynamics complexity reduction, and spike statistics

3.6. Visual Neuroscience

Our group focuses on the visual system to understand how information is encoded and processed resulting in visual percepts. To do so, we propose functional models of the visual system using a variety of mathematical formalisms, depending on the scale at which models are built, such as spiking neural networks or neural fields. So far, our efforts have been focused on the study of retinal processing, edge and texture perception, motion integration at the level of V1 and MT cortical areas.

4. New Software and Platforms

4.1. New Software

4.1.1. Julia library LSODA.jl

LSODA.jl is a Julia package that interfaces to the liblsoda library, developed by Simon Frost (University of Cambridge), thereby providing a way to use the LSODA algorithm from Linda Petzold and Alan Hindmarsh from Julia.

4.1.2. Julia library PDMP.jl

PDMP.jl This is a joint work of Romain Veltz and Simon Frost.

PDMP.jl is a Julia package that allows simulation of Piecewise Deterministic Markov Processes (PDMP); this encompasses hybrid systems, comprising of continuous and discrete components, as well as processes with time-varying rates. It is based on an implementation of the True Jump Method for performing stochastic simulations of PDMP, and requires solving stiff ODEs in an efficient manner. Sundials.jl is used, but other solvers could be easily added.

5. New Results

5.1. Neural Networks as dynamical systems

5.1.1. A modular architecture for transparent computation in recurrent neural networks

Participants: Giovanni Carmantini [Plymouth University, UK], Peter Beim Graben [Humbolt University (Berlin), Germany], Mathieu Desroches [Inria MathNeuro], Serafim Rodrigues [Plymouth University, UK].

Computation is classically studied in terms of automata, formal languages and algorithms; yet, the relation between neural dynamics and symbolic representations and operations is still unclear in traditional eliminative connectionism. Therefore, we suggest a unique perspective on this central issue, to which we would like to refer as transparent connectionism, by proposing accounts of how symbolic computation can be implemented in neural substrates. In this study we first introduce a new model of dynamics on a symbolic space, the versatile shift, showing that it supports the real-time simulation of a range of automata. We then show that the Gödelization of versatile shifts defines nonlinear dynamical automata, dynamical systems evolving on a vectorial space. Finally, we present a mapping between nonlinear dynamical automata and recurrent artificial neural networks. The mapping defines an architecture characterized by its granular modularity, where data, symbolic operations and their control are not only distinguishable in activation space, but also spatially localizable in the network itself, while maintaining a distributed encoding of symbolic representations. The resulting networks simulate automata in real-time and are programmed directly, in the absence of network training. To discuss the unique characteristics of the architecture and their consequences, we present two examples: (i) the design of a Central Pattern Generator from a finite-state locomotive controller, and (ii) the creation of a network simulating a system of interactive automata that supports the parsing of garden-path sentences as investigated in psycholinguistics experiments.

This work has been published in Neural Networks and is available as [13].

5.1.2. Latching dynamics in neural networks with synaptic depression

Participants: Pascal Chossat [Inria MathNeuro], Martin Krupa [Inria MathNeuro], Frédéric Lavigne [Université de Nice - BCL].

Priming is the ability of the brain to more 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. 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 Hebbian learning, 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.

This work has been submitted for publication and is available as [23].

5.1.3. On the Hamiltonian structure of large deviations in stochastic hybrid systems

Participants: Paul Bressloff [University of Utah, USA], Olivier Faugeras [Inria MathNeuro].

We present a new derivation of the classical action underlying a large deviation principle (LDP) for a stochastic hybrid system, which couples a piecewise deterministic dynamical system in $\mathbb{R}^d$ with a time-homogeneous Markov chain on some discrete space Γ. We assume that the Markov chain on Γ is ergodic, and that the discrete dynamics is much faster than the piecewise deterministic dynamics (separation of timescales). Using the Perron-Frobenius theorem and the calculus-of-variations, we show that the resulting Hamiltonian is given by the Perron eigenvalue of a $|\Gamma|$-dimensional linear equation. The corresponding linear operator depends on the transition rates of the Markov chain and the nonlinear functions of the piecewise deterministic system. We compare the Hamiltonian to one derived using WKB methods, and show that the latter is a reduction of the former. We also indicate how the analysis can be extended to a multi-scale stochastic process, in which the continuous dynamics is described by a piecewise stochastic differential equations (SDE). Finally, we illustrate the theory by considering applications to conductance-based models of membrane voltage fluctuations in the presence of stochastic ion channels.

This work has been submitted for publication and is available as [22].

5.1.4. Large Deviations of a Spatially-Stationary Network of Interacting Neurons

Participants: Olivier Faugeras [Inria MathNeuro], James Maclaurin [University of Sydney, USA].

In this work we determine a process-level Large Deviation Principle (LDP) for a model of interacting neurons indexed by a lattice $\mathbb{Z}^d$. The neurons are subject to noise, which is modelled as a correlated martingale. The probability law governing the noise is strictly stationary, and we are therefore able to find a LDP for the probability laws Π^n governing the stationary empirical measure $\widehat{\mu}^n$ generated by the neurons in a cube of length $(2n+1)$. We use this LDP to determine an LDP for the neural network model. The connection weights between the neurons evolve according to a learning rule / neuronal plasticity, and these results are adaptable to a large variety of neural network models. This LDP is of great use in the mathematical modelling of neural networks, because it allows a quantification of the likelihood of the system deviating from its limit, and also a determination of which direction the system is likely to deviate. The work is also of interest because there are nontrivial correlations between the neurons even in the asymptotic limit, thereby presenting itself as a generalisation of traditional mean-field models.

This work has been submitted for publication and is available as [25].

5.1.5. The Period adding and incrementing bifurcations: from rotation theory to applications

Participants: Albert Granados [Technical University of Denmark, Denmark], Lluís Alsedà [Autonomous University of Barcelona, Spain], Martin Krupa [Inria MathNeuro].

This survey article is concerned with the study of bifurcations of piecewise-smooth maps. We review the literature in circle maps and quasi-contractions and provide paths through this literature to prove sufficient conditions for the occurrence of two types of bifurcation scenarios involving rich dynamics. The first scenario consists of the appearance of periodic orbits whose symbolic sequences and "rotation" numbers follow a Farey tree structure; the periods of the periodic orbits are given by consecutive addition. This is called the *period adding* bifurcation, and its proof relies on results for maps on the circle. In the second scenario, symbolic sequences are obtained by consecutive attachment of a given symbolic block and the periods of periodic orbits are incremented by a constant term. It is called the *period incrementing* bifurcation, in its proof relies on results for maps on the interval. We also discuss the expanding cases, as some of the partial results found in the literature also hold when these maps lose contractiveness. The higher dimensional case is also discussed by means of *quasi-contractions*. We also provide applied examples in control theory, power electronics and neuroscience where these results can be applied to obtain precise descriptions of their dynamics.

This work has been accepted for publication in SIAM Review and is available as [26].

5.2. Neural Fields Theory

5.2.1. Standing and travelling waves in a spherical brain model: the Nunez model revisited

Participants: Sid Visser [University of Nottingham, UK], Rachel Nicks [University of Nottingham, UK], Olivier Faugeras [Inria MathNeuro], Stephen Coombes [University of Nottingham, UK].

The Nunez model for the generation of electroencephalogram (EEG) signals is naturally described as a neural field model on a sphere with space-dependent delays. For simplicity, dynamical realisations of this model either as a damped wave equation or an integro-differential equation, have typically been studied in idealised one dimensional or planar settings. Here we revisit the original Nunez model to specifically address the role of spherical topology on spatio-temporal pattern generation. We do this using a mixture of Turing instability analysis, symmetric bifurcation theory, center manifold reduction and direct simulations with a bespoke numerical scheme. In particular we examine standing and travelling wave solutions using normal form computation of primary and secondary bifurcations from a steady state. Interestingly, we observe spatio-temporal patterns which have counterparts seen in the EEG patterns of both epileptic and schizophrenic brain conditions.

This work has been submitted for publication and is available as [27].

5.3. Slow-Fast Dynamics in Neuroscience

5.3.1. Canards, folded nodes and mixed-mode oscillations in piecewise-linear slow-fast systems

Participants: Mathieu Desroches [Inria MathNeuro], Antoni Guillamon [Polytechnic University of Catalunya, Spain], Enrique Ponce [University of Seville, Spain], Rafel Prohens [University of the Balearic Islands, Spain], Antonio E. Teruel [University of the Balearic Islands, Spain], Serafim Rodrigues [Plymouth University, UK].

Canard-induced phenomena have been extensively studied in the last three decades, from both the mathematical and the application viewpoints. Canards in slow-fast systems with (at least) two slow variables, especially near folded-node singularities, give an essential generating mechanism for mixed-mode oscillations (MMOs) in the framework of smooth multiple timescale systems. There is a wealth of literature on such slow-fast dynamical systems and many models displaying canard-induced MMOs, particularly in neuroscience. In parallel, since the late 1990s several papers have shown that the canard phenomenon can be faithfully reproduced with piecewise-linear (PWL) systems in two dimensions, although very few results are available in the three-dimensional case. The present paper aims to bridge this gap by analyzing canonical PWL systems that display folded singularities, primary and secondary canards, with a similar control of the maximal winding number as in the smooth case. We also show that the singular phase portraits are compatible in both frameworks. Finally, we show using an example how to construct a (linear) global return and obtain robust PWL MMOs.

This work has been published in SIAM Review and is available as [16].

5.3.2. Spike-adding in parabolic bursters: the role of folded-saddle canards

Participants: Mathieu Desroches [Inria MathNeuro], Martin Krupa [Inria MathNeuro], Serafim Rodrigues [Plymouth University, UK].

The present work develops a new approach to studying parabolic bursting, and also proposes a novel four-dimensional canonical and polynomial-based parabolic burster. In addition to this new polynomial system, we also consider the conductance-based model of the Aplysia R15 neuron known as the Plant model, and a reduction of this prototypical biophysical parabolic burster to three variables, including one phase variable, namely the Baer-Rinzel-Carillo (BRC) phase model. Revisiting these models from the perspective of slow-fast dynamics reveals that the number of spikes per burst may vary upon parameter changes, however the spike-adding process occurs in an explosive fashion that involves special solutions called canards. This spike-adding canard explosion phenomenon is analysed by using tools from geometric singular perturbation theory in tandem with numerical bifurcation techniques. We find that the bifurcation structure persists across all considered systems, that is, spikes within the burst are incremented via the crossing of an excitability threshold given by a particular type of canard orbit, namely the true canard of a folded-saddle singularity. However there can be a difference in the spike-adding transitions in parameter space from one case to another, according to whether the process is continuous or discontinuous, which depends upon the geometry of the folded-saddle canard. Using these findings, we construct a new polynomial approximation of the Plant model, which retains all the key elements for parabolic bursting, including the spike-adding transitions mediated by folded-saddle canards. Finally, we briefly investigate the presence of spike-adding via canards in planar phase models of parabolic bursting, namely the theta model by Ermentrout and Kopell.

This work has been published in Physica D and is available as [17].

5.3.3. Slow-fast transitions to seizure states in the Wendling-Chauvel neural mass model

Participants: Mathieu Desroches [Inria MathNeuro], Olivier Faugeras [Inria MathNeuro], Martin Krupa [Inria MathNeuro].

We revisit the Wendling-Chauvel neural mass model by reducing it to eight ODEs and adding a differential equation that accounts for a dynamic evolution of the slow inhibitory synaptic gain. This allows to generate dynamic transitions in the resulting nine-dimensional model. The output of the extended model can be related to EEG patterns observed during epileptic seizure, in particular isolated pre-ictal spikes and low-voltage fast oscillations at seizure onset. We analyse the extended model using basic tools from slow-fast dynamical systems theory and relate the main transitions towards seizure states to torus canards, a type of solutions that has been shown to explain the spiking to bursting transition in many neural models. We find that the original ten-dimensional Wendling-Chauvel model can be reduced to eight dimensions, two variables being scaled versions of two other variables of the model. We then obtain a model with four PSP blocks, which is consistent with the block-diagrams typically presented to describe this model. Instead of varying the slow inhibitory synaptic gain parameter B quasi-statically, or just performing numerical bifurcation analysis in B as the structure of the fast subsystem of an hypothetical extended system, we construct a true slow dynamics for B, depending sensitively on the main PSP output of the model, Y0. Near fold bifurcation of limit cycles of the original model, the solution to the extended model performs fast low-amplitude oscillations close to both attracting and repelling branches of limit cycles, which is the signature of a torus canard phenomenon.

This work has been published in Opera Medica & Physiologica and is available as [14].

5.3.4. Canards in a minimal piecewise-linear square-wave burster

Participants: Mathieu Desroches [Inria MathNeuro], Soledad Fernández-García [University of Seville, Spain], Martin Krupa [Inria MathNeuro].

We construct a piecewise-linear (PWL) approximation of the Hindmarsh-Rose (HR) neuron model that is minimal, in the sense that the vector field has the least number of linearity zones, in order to reproduce all the dynamics present in the original HR model with classical parameter values. This includes square-wave bursting and also special trajectories called canards, which possess long repelling segments and organise the transitions between stable bursting patterns with n and n?+?1 spikes, also referred to as spike-adding canard explosions. We propose a first approximation of the smooth HR model, using a continuous PWL system, and show that its fast subsystem cannot possess a homoclinic bifurcation, which is necessary to obtain proper square-wave bursting. We then relax the assumption of continuity of the vector field across all zones, and we show that we can obtain a homoclinic bifurcation in the fast subsystem. We use the recently developed canard theory for PWL systems in order to reproduce the spike-adding canard explosion feature of the HR model as studied, e.g., in Desroches et al., Chaos 23(4), 046106 (2013).

This work has been published in Chaos and is available as [15].

5.3.5. From Canards of Folded Singularities to Torus Canards in a Forced van der Pol Equation

Participants: John Burke [Boston University, USA], Mathieu Desroches [Inria MathNeuro], Albert Granados [Technical University of Denmark, Denmark], Tasso J. Kaper [Boston University, USA], Martin Krupa [Inria MathNeuro], Theodore Vo [Boston University, USA].

In this article, we study canard solutions of the forced van der Pol equation in the relaxation limit for low-, intermediate-, and high-frequency periodic forcing. A central numerical observation made herein is that there are two branches of canards in parameter space which extend across all positive forcing frequencies. In the low-frequency forcing regime, we demonstrate the existence of primary maximal canards induced by folded saddle nodes of type I and establish explicit formulas for the parameter values at which the primary maximal canards and their folds exist. Then, we turn to the intermediate- and high-frequency forcing regimes and show that the forced van der Pol possesses torus canards instead. These torus canards consist of long segments near families of attracting and repelling limit cycles of the fast system, in alternation. We also derive explicit formulas for the parameter values at which the maximal torus canards and their folds exist. Primary maximal canards and maximal torus canards correspond geometrically to the situation in which the persistent manifolds near the family of attracting limit cycles coincide to all orders with the persistent manifolds that lie near the family of repelling limit cycles. The formulas derived for the folds of maximal canards in all three frequency regimes turn out to be representations of a single formula in the appropriate parameter regimes, and this unification confirms the central numerical observation that the folds of the maximal canards created in the low-frequency regime continue directly into the folds of the maximal torus canards that exist in the intermediate- and high-frequency regimes. In addition, we study the secondary canards induced by the folded singularities in the low-frequency regime and find that the fold curves of the secondary canards turn around in the intermediate-frequency regime, instead of continuing into the high-frequency regime. Also, we identify the mechanism responsible for this turning. Finally, we show that the forced van der Pol equation is a normal form-type equation for a class of single-frequency periodically driven slow/fast systems with two fast variables and one slow variable which possess a non-degenerate fold of limit cycles. The analytic techniques used herein rely on geometric desingularisation, invariant manifold theory, Melnikov theory, and normal form methods. The numerical methods used herein were developed in Desroches et al. (SIAM J Appl Dyn Syst 7:1131–1162, 2008, Nonlinearity 23:739–765 2010).

This work has been published in Journal of Nonlinear Science and is available as [12].

5.3.6. Mixed-mode oscillations in a piecewise-linear system with multiple time scale coupling

Participants: Soledad Fernández-García [University of Seville, Spain], Martin Krupa [Inria MathNeuro], Frédérique Clément [Inria Mycenae].

In this work, we analyze a four dimensional slow?fast piecewise linear system with three time scales presenting Mixed-Mode Oscillations. The system possesses an attractive limit cycle along which oscillations of three different amplitudes and frequencies can appear, namely, small oscillations, pulses (medium amplitude) and one surge (largest amplitude). In addition to proving the existence and attractiveness of the limit cycle, we focus our attention on the canard phenomena underlying the changes in the number of small oscillations and pulses. We analyze locally the existence of secondary canards leading to the addition or subtraction of one small oscillation and describe how this change is globally compensated for or not with the addition or subtraction of one pulse.

This work has been published in Physica D and is available as [18].

5.4. Plasticity

5.4.1. Time-code neurotransmitter release at excitatory and inhibitory synapses

Participants: Serafim Rodrigues [Plymouth University, UK], Mathieu Desroches [Inria MathNeuro], Martin Krupa [Inria MathNeuro], Jesus M. Cortes [Biocruces Institute, Spain], Terrence J. Sejnowski [Salk Institute, USA], Afia B. Ali [University College London, UK].

Communication between neurons at chemical synapses is regulated by hundreds of different proteins that control the release of neurotransmitter that is packaged in vesicles, transported to an active zone, and released when an input spike occurs. Neurotransmitter can also be released asynchronously, that is, after a delay following the spike, or spontaneously in the absence of a stimulus. The mechanisms underlying asynchronous and spontaneous neurotransmitter release remain elusive. Here, we describe a model of the exocytotic cycle of vesicles at excitatory and inhibitory synapses that accounts for all modes of vesicle release as well as short-term synaptic plasticity (STSP). For asynchronous release, the model predicts a delayed inertial protein unbinding associated with the SNARE complex assembly immediately after vesicle priming. Experiments are proposed to test the model?s molecular predictions for differential exocytosis. The simplicity of the model will also facilitate large-scale simulations of neural circuits.

This work has been published in Proceedings of the National Academy of Sciences of the USA (PNAS) and is available as [20].

5.5. Vision in Neuroscience

5.5.1. The relative contribution of noise and adaptation to competition during tri-stable motion perception

Participants: Andrew Meso [Bournemouth University, UK], James Rankin [Center for Neural Science, NYU, USA], Olivier Faugeras [Inria MathNeuro], Pierre Kornprobst [Inria BioVision], Guillaume Masson [Institut de Neuroscience de la Timone, France].

Animals exploit antagonistic interactions for sensory processing and these can cause oscillations between competing states. Ambiguous sensory inputs yield such perceptual multi-stability. Despite numerous empirical studies using binocular rivalry or plaid pattern motion, the driving mechanisms behind the spontaneous transitions between alternatives remain unclear. In the current work, we used a tri-stable barberpole motion stimulus combining empirical and modelling approaches to elucidate the contributions of noise and adaptation to underlying competition. We first robustly characterised the coupling between perceptual reports of transitions and continuously recorded eye direction, identifying a critical window of 480ms before button presses within which both measures were most strongly correlated. Second, we identified a novel non monotonic relationship between stimulus contrast and average perceptual switching rate with an initially rising rate before a gentle reduction at higher contrasts. A neural fields model of the underlying dynamics introduced in previous theoretical work and incorporating noise and adaptation mechanisms was adapted, extended and empirically validated. Noise and adaptation contributions were confirmed to dominate at the lower, and higher, contrasts respectively. Model simulations with two free parameters, controlling adaptation dynamics and direction thresholds, captured the measured mean transition rates for participants. We verified the shift from noise dominated towards adaptation-driven in both the eye direction distributions and inter-transition duration statistics. This work combines modelling and empirical evidence to demonstrate the signal strength dependent interplay between noise and adaptation during tri- stability. We propose that the findings generalise beyond the barberpole stimulus case to ambiguous perception in continuous feature spaces.

This work has been published in Journal of Vision and is available as [19].

6. Partnerships and Cooperations

6.1. Regional Initiatives

Olivier Faugeras is a member of the scientific committee of the "Axe Interdisciplinaire de Recherche de l'Université de Nice Sophia Antipolis" entitled "Modélisation Théorique et Computationnelle en Neurosciences et Sciences Cognitives".

6.2. National Initiatives

6.2.1. ANR

6.2.1.1. SloFaDyBio

Title: a network for Slow-Fast Dynamics in the Biosciences

Programm: ANR “amorçage”

Duration: January 2015 - January 2017 (extension up to January 2018)

Coordinator: Inria

PI: Mathieu Desroches

Partners:
see the webpage of the project.

The SloFaDyBio project targets to gather European researchers from about 10 cost countries in order to build up a network project on “Multi-Scale Dynamics in Neuroscience” and to submit within two years a large-scale proposal to a European funding agency such as COST. The initial fund provided by the ANR is used to meet regularly over this period and write a complete proposal. We now have an operational team and we are in the process of writing a full proposal which will be submitted at the next COST call, that is, at the end of September 2017.

6.3. European Initiatives

6.3.1. FP7 & H2020 Projects

6.3.1.1. HBP

Title: The Human Brain Project

Programm: FP7

Duration: October 2013 - March 2016 (first part) and then : April 2016 - March 2018 (second part)

Coordinator: EPFL

Partners:
see the webpage of the project.

Inria contact: Olivier Faugeras (first part) and then : Romain Veltz (second part)

Understanding the human brain is one of the greatest challenges facing 21st century science. If we can rise to the challenge, we can gain profound insights into what makes us human, develop new treatments for brain diseases and build revolutionary new computing technologies. Today, for the first time, modern ICT has brought these goals within sight. The goal of the Human Brain Project, part of the FET Flagship Programme, is to translate this vision into reality, using ICT as a catalyst for a global collaborative effort to understand the human brain and its diseases and ultimately to emulate its computational capabilities. The Human Brain Project will last ten years and will consist of a ramp-up phase (from month 1 to month 36) and subsequent operational phases.
This Grant Agreement covers the ramp-up phase. During this phase the strategic goals of the project will be to design, develop and deploy the first versions of six ICT platforms dedicated to Neuroinformatics, Brain Simulation, High Performance Computing, Medical Informatics, Neuromorphic Computing and Neurorobotics, and create a user community of research groups from within and outside the HBP, set up a European Institute for Theoretical Neuroscience, complete a set of pilot projects providing a first demonstration of the scientific value of the platforms and the Institute, develop the scientific and technological capabilities required by future versions of the platforms, implement a policy of Responsible Innovation, and a programme of transdisciplinary education, and develop a framework for collaboration that links the partners under strong scientific leadership and professional project management, providing a coherent European approach and ensuring effective alignment of regional, national and European research and programmes. The project work plan is organized in the form of thirteen subprojects, each dedicated to a specific area of activity.
A significant part of the budget will be used for competitive calls to complement the collective skills of the Consortium with additional expertise.

6.4. International Research Visitors

6.4.1. Visits of International Scientists

Invitation of Martin Wechselberger, University of Sydney (Australia), June 2016

Invitation of Daniele Avitabile, University of Nottingham (UK), June 2016

Invitation of James MacLaurin, University of Sydney (Australia), December 2016

Invitation of Tim O'Leary, University of Cambridge (UK), December 2016

Invitation of Antonio Teruel, University of the Balearic Islands (Spain), December 2016

6.4.1.1. Internships

Cantin Baron (collaboration with H. Marie at IPMC, Feb-June 2016)

Raphaël Fourquet (collaboration with H. Marie at IPMC, Feb-June 2016)

6.4.2. Visits to International Teams

Visit of Mathieu Desroches to Daniele Avitabile (University of Nottingham, UK) in April 2016

Visit of Romain Veltz to Cian O'Donnell (University of Bristol, UK) in April 2016

Visit of Mathieu Desroches to Martin Wechselberger (University of Sydney, Australia) in August 2016

Visit of Mathieu Desroches to Vivien Kirk (University of Auckland, New Zealand) in September 2016

Visit of Mathieu Desroches to Daniele Avitabile (University of Nottingham, UK) in April 2016

Visit of Mathieu Desroches to Serafim Rodrigues (Plymouth University, UK) in October 2016

7. Dissemination

7.1. Promoting Scientific Activities

7.1.1. Scientific Events Organisation

7.1.1.1. General Chair, Scientific Chair

Romain Veltz was the General Chair of the 2nd International Conference on Mathematical Neuroscience, held in Antibe-Juan les Pins, May 30 - June 1 2016.

7.1.1.2. Member of the Organizing Committees

Mathieu Desroches was on the Organizing Committee of the MURPHYS-HSFS 2016 Workshop on Hysteresis and Slow-Fast Dynamics held at the Centre de Recerca Matemàtica (CRM) in Barcelona, June 13-17, 2016.

7.1.2. Scientific Events Selection

7.1.2.1. Member of the Conference Program Committees

Pascal Chossat and Martin Krupa were on the Program Committee of the 2nd International Conference on Mathematical Neuroscience, held in Antibe-Juan les Pins, May 30 - June 1 2016.

7.1.3. Journal

7.1.3.1. Member of the Editorial Boards

Olivier Faugeras is the co-editor in chief of the open access Journal of Mathematical Neuroscience.

7.1.3.2. Reviewer - Reviewing Activities

Mathieu Desroches acts as a reviewer for Physica D, SIAM Journal on Applied Dynamical Systems (SIADS), PLoS Computational Biology, Journal of Nonlinear Science, IMA Journal of Applied Mathematics, Journal of Mathematical Neuroscience.

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, Journal of the Royal Society Interface.

7.1.4. Invited Talks

R. Veltz, “Some applications of hybrid systems in neurosciences”, University of Bristol, April 2016

M. Desroches, “Simplifying singular perturbation theory in the canard regime with piecewise-linear dynamics; application to neuronal models”, Invited Plenary talk, *10th NoLineal Conference*, University of Seville (Spain), June 2016.

M. Desroches, “Canards, folded singularities and bursting”, Invited talk in the mini-symposium *Slow-fast dynamics in neuroscience* at the *10th ECMTB Conference*, Nottingham (UK), July 2016.

M. Desroches, “Spike-adding in parabolic bursters: the role of folded-saddle canards”, Invited talk in the workshop *Dynamics in Life Science, Neuroscience* at the *Volga Neuroscience meeting 2016*, St-Petersburg/Nizhny-Novgorod (Russia), July 2016.

M. Desroches, “Canards in piecewise-linear slow-fast systems”, Invited seminar talk, *Applied Mathematics Seminar*, University of Sydney (Australia), August 2016.

M. Desroches, “Canards in planar piecewise-linear slow-fast systems”, Invited seminar talk, *Applied Mathematics Seminar*, University of Auckland (New Zealand), September 2016.

M. Desroches, “Understanding synaptic mechanisms: why a multi-disciplinary approach is important”, Invited talk in the Symposia meeting *New Techniques in Electro- and Optophysiology*, SFN conference, San Diego (USA), November 2016.

7.2. Teaching - Supervision - Juries

7.2.1. 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, 30 hours, Paris, France.

7.2.2. Supervision

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: A. Dolcemascolo, "All optical neuromimetic devices", started in January 2016, co-supervised by Romain Veltz and S. Barland (INLN).

PhD completed: Lucile Mégret, “Explosions de cycles: Analyse qualitative, simulations numériques et modèles”, defended on 25 November 2016, co-supervised by Mathieu Desroches and J.-P. Françoise (UPMC).

PhD completed: Giovanni Carmantini, “Dynamical Systems Theory for Transparent Symbolic Computation in Neuronal Networks”, defended on 28 November 2016, co-supervised by Mathieu Desroches and S. Rodrigues (Plymouth University, UK).

PhD completed: Elif Köksal-Ersöz, “A mathematical study on coupled multiple timescale systems, synchronization of populations of endocrine neurons”, defended on 13 December 2016, co-supervised by Mathieu Desroches, J.-P. Françoise (UPMC) and F. Clément (Inria Paris).

7.2.3. Juries

Mathieu Desroches was a jury member for the PhD defence of Catalina Vich (University of the Balearic Islands, Spain) on 4 July 2016. He was also jury member for the PhD defence of Lucile Mégret (UPMC, France) on 25 November 2016 and that of Elif Köksal-Ersöz (Inria Paris / UPMC, France) on 13 December 2016.

8. Bibliography

Major publications by the team in recent years

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Project-Team MCTAO

Mathematics for Control, Transport and Applications

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THEME
Optimization and control of dynamic systems

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Project-Team MCTAO

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6.1.4. - Multiscale modeling
6.2.1. - Numerical analysis of PDE and ODE
6.2.6. - Optimization
6.4. - Automatic control
6.4.1. - Deterministic control
6.4.3. - Observability and Controlability
6.4.4. - Stability and Stabilization

Other Research Topics and Application Domains:

2.6. - Biological and medical imaging
5.2.3. - Aviation
5.2.4. - Aerospace
6.6. - Embedded systems

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2. Overall Objectives

2.1. Overall Objectives

The core endeavor of this team is to develop methods in control theory for finite-dimensional nonlinear systems, as well as in optimal transport, and to be involved in real applications of these techniques. Some mathematical fields like dynamical systems and optimal transport may benefit from control theory techniques. Our primary domain of industrial applications will be 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.

3. Research Program

3.1. Control Systems

Our effort is directed toward efficient methods for the *control* of real (physical) systems, based on a *model* of the system to be controlled. *System* refers to the physical plant or device, whereas *model* refers to a mathematical representation of it.

We mostly investigate nonlinear systems whose nonlinearities admit a strong structure derived from physics; the equations governing their behavior are then well known, and the modeling part consists in choosing what phenomena are to be kept in the model used for control design, the other phenomena being treated as perturbations; a more complete model may be used for simulations, for instance. We focus on systems that admit a reliable finite-dimensional model, in continuous time; this means that models are controlled ordinary differential equations, often nonlinear.

Choosing accurate models yet simple enough to allow control design is in itself a key issue; however, modeling or identification as a theory is not per se in the scope of our project.

The extreme generality and versatility of linear control do not contradict the often heard sentence "most real life systems are nonlinear". Indeed, for many control problems, a linear model is sufficient to capture the important features for control. The reason is that most control objectives are local, first order variations around an operating point or a trajectory are governed by a linear control model, and except in degenerate situations (non-controllability of this linear model), the local behavior of a nonlinear dynamic phenomenon is dictated by the behavior of first order variations. Linear control is the hard core of control theory and practice; it has been pushed to a high degree of achievement –see for instance some classics: [64], [55]– that lead to big successes in industrial applications (PID, Kalman filtering, frequency domain design, H^∞ robust control, etc...), it is taught to future engineers, and it is still a topic of ongoing research.

Linear control by itself however reaches its limits in some important situations:

1. **Non local control objectives.** Steering the system from a region to a reasonably remote other one, as in path planning and optimal control, is outside the scope of information given by a local linear approximation. It is why these are by essence nonlinear.

   Stabilisation with a basin of attraction larger than the region where the linear approximation is dominant also needs more information than one linear approximation.
2. **Local control at degenerate equilibria.** Linear control yields local stabilization of an equilibrium point based on the tangent linear approximation if the latter is controllable. It is *not* the case at interesting operating points of some physical systems; linear control is irrelevant and specific nonlinear techniques have to be designed. This is an extreme case of the second part of the above item: the region where the linear approximation is dominant vanishes.
3. **Small controls.** In some situations, actuators only allow a very small magnitude of the effect of control compared to the effect of other phenomena. Then the behavior of the system without control plays a major role and we are again outside the scope of linear control methods.

3.2. Structure of nonlinear control systems

In most problems, choosing the proper coordinates, or the right quantities that describe a phenomenon, sheds light on a path to the solution. In control systems, it is often crucial to analyze the structure of the model, deduced from physical principles, of the plant to be controlled; this may lead to putting it via some transformations in a simpler form, or a form that is most suitable for control design. For instance, equivalence to a linear system may allow to use linear control; also, the so-called "flatness" property drastically simplifies path planning [59], [70].

A better understanding of the "set of nonlinear models", partly classifying them, has another motivation than facilitating control design for a given system and its model: it may also be a necessary step towards a theory of "nonlinear identification" and modeling. Linear identification is a mature area of control science; its success is mostly due to a very fine knowledge of the structure of the class of linear models: similarly, any progress in the understanding of the structure of the class of nonlinear models would be a contribution to a possible theory of nonlinear identification.

These topics are central in control theory, but raise very difficult mathematical questions: static feedback classification is a geometric problem which is feasible in principle, although describing invariants explicitly is technically very difficult; and conditions for dynamic feedback equivalence and linearization raise unsolved mathematical problems, that make one wonder about decidability [0].

3.3. Optimal control and feedback control, stabilization

3.3.1. Optimal control.

Mathematically speaking, optimal control is the modern branch of the calculus of variations, rather well established and mature [39], [68], [46], [76]. Relying on Hamiltonian dynamics is now prevalent, instead of the standard Lagrangian formalism of the calculus of variations. Also, coming from control engineering, constraints on the control (for instance the control is a force or a torque, which are naturally bounded) or the state (for example in the shuttle atmospheric re-entry problem there is a constraint on the thermal flux) are imposed; the ones on the state are usual but these on the state yield more complicated necessary optimality conditions and an increased intrinsic complexity of the optimal solutions. Also, in the modern treatment, ad-hoc numerical schemes have to be derived for effective computations of the optimal solutions.

[0] Consider the simple system with state $(x, y, z) \in I\!R^3$ and two controls that reads $\dot{z} = (\dot{y} - z\dot{x})^2 \dot{x}$ after elimination of the controls; it is not known whether it is equivalent to a linear system, or flat; this is because the property amounts to existence of a formula giving the general solution as a function of two arbitrary functions of time and their derivatives up to a certain order, but no bound on this order is known a priori, even for this very particular example.

What makes optimal control an applied field is the necessity of computing these optimal trajectories, or rather the controls that produce these trajectories (or, of course, close-by trajectories). Computing a given optimal trajectory and its control as a function of time is a demanding task, with non trivial numerical difficulties: roughly speaking, the Pontryagin Maximum Principle gives candidate optimal trajectories as solutions of a two point boundary value problem (for an ODE) which can be analyzed using mathematical tools from geometric control theory or solved numerically using shooting methods. Obtaining the *optimal synthesis* –the optimal control as a function of the state– is of course a more intricate problem [46], [51].

These questions are not only academic for minimizing a cost is *very* relevant in many control engineering problems. However, modern engineering textbooks in nonlinear control systems like the "best-seller" [61] hardly mention optimal control, and rather put the emphasis on designing a feedback control, as regular and explicit as possible, satisfying some qualitative (and extremely important!) objectives: disturbance attenuation, decoupling, output regulation or stabilization. Optimal control is sometimes viewed as disconnected from automatic control... we shall come back to this unfortunate point.

3.3.2. Feedback, control Lyapunov functions, stabilization.

A control Lyapunov function **(CLF)** is a function that can be made a Lyapunov function (roughly speaking, a function that decreases along all trajectories, some call this an "artificial potential") for the closed-loop system corresponding to *some* feedback law. This can be translated into a partial differential relation sometimes called "Artstein's (in)equation" [42]. There is a definite parallel between a CLF for stabilization, solution of this differential inequation on the one hand, and the value function of an optimal control problem for the system, solution of a HJB equation on the other hand. Now, optimal control is a quantitative objective while stabilization is a qualitative objective; it is not surprising that Artstein (in)equation is very under-determined and has many more solutions than HJB equation, and that it may (although not always) even have smooth ones.

We have, in the team, a longstanding research record on the topic of construction of CLFs and stabilizing feedback controls.

3.4. Optimal Transport

We believe that matching optimal transport with geometric control theory is one originality of our team. We expect interactions in both ways.

The study of optimal mass transport problems in the Euclidean or Riemannian setting has a long history which goes from the pioneer works of Monge [72] and Kantorovitch [65] to the recent revival initiated by fundamental contributions due to Brenier [52] and McCann [71].

The same transportation problems in the presence of differential constraints on the set of paths —like being an admissible trajectory for a control system— is quite new. The first contributors were Ambrosio and Rigot [40] who proved the existence and uniqueness of an optimal transport map for the Monge problem associated with the squared canonical sub-Riemannian distance on the Heisenberg groups. This result was extended later by Agrachev and Lee [37], then by Figalli and Rifford [56] who showed that the Ambrosio-Rigot theorem holds indeed true on many sub-Riemannian manifolds satisfying reasonable assumptions. The problem of existence and uniqueness of an optimal transport map for the squared sub-Riemannian distance on a general complete sub-Riemannian manifold remains open; it is strictly related to the regularity of the sub-Riemannian distance in the product space, and remains a formidable challenge. Generalized notions of Ricci curvatures (bounded from below) in metric spaces have been developed recently by Lott and Villani [69] and Sturm [80]. A pioneer work by Juillet [62] captured the right notion of curvature for subriemannian metric in the Heisenberg group; Agrachev and Lee [38] have elaborated on this work to define new notions of curvatures in three dimensional sub-Riemannian structures. The optimal transport approach happened to be very fruitful in this context. Many things remain to be done in a more general context.

3.5. Small controls and conservative systems, averaging

Using averaging techniques to study small perturbations of integrable Hamiltonian systems dates back to H. Poincaré or earlier; it gives an approximation of the (slow) evolution of quantities that are preserved in the non-perturbed system. 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; see for instance [41], [79].

When the "perturbation" is a control, these techniques may be used after deciding how the control will depend on time and state and other quantities, for instance it may be used after applying the Pontryagin Maximum Principle as in [44], [45], [53], [60]. Without deciding the control a priori, an "average control system" may be defined as in [43].

The focus is then on studying into details this simpler "averaged" problem, that can often be described by a Riemannian metric for quadratic costs or by a Finsler metric for costs like minimum time.

This line of research stemmed out of applications to space engineering, see section 4.1.

4. Application Domains

4.1. Space engineering, satellites, low thrust control

Space engineering is very demanding in terms of safe and high-performance control laws (for instance optimal in terms of fuel consumption, because only a finite amount of fuel is onboard a satellite for all its "life"). It is therefore prone to real industrial collaborations.

We are especially interested in trajectory control of space vehicles using their own propulsion devices, outside the atmosphere. Here we discuss "non-local" control problems (in the sense of section 3.1 point 1): orbit transfer rather than station keeping; also we do not discuss attitude control.

In the geocentric case, a space vehicle is subject to
- gravitational forces, from one or more central bodies (the corresponding acceleration is denoted by $F_{\text{grav.}}$ below),
- a thrust, the control, produced by a propelling device; it is the $G\,u$ term below; assume for simplicity that control in all directions is allowed, *i.e.*G is an invertible matrix
- other "perturbating" forces (the corresponding acceleration is denoted by F_2 below; in simplified models, it is not present). In position-velocity coordinates, its dynamics can be written as

$$\ddot{x} \;=\; F_{\text{grav.}}(x,t) \;+\; F_2(x,\dot{x},t) \;+\; G(x,\dot{x})\,u\;, \qquad \|u\| \le u_{\max}. \tag{8}$$

In the case of a single attracting central body (the earth) and in a geocentric frame, $F_{\text{grav.}}$ does not depend on time, or consists of a main term that does not depend on time and smaller terms reflecting the action of the moon or the sun, that depend on time. The second term is often neglected in the design of the control at first sight; it contains terms like atmospheric drag or solar pressure. G could also bear an explicit dependence on time (here we omit the variation of the mass, that decreases proportionally to $\|u\|$.

4.1.1. Low thrust

Low thrust means that $u_{\max}$ is small, or more precisely that the maximum magnitude of $G\,u$ is small with respect to the one of $F_{\text{grav.}}$ (but in general not compared to F_2). Hence the influence of the control is very weak instantaneously, and trajectories can only be significantly modified by accumulating the effect of this low thrust on a long time. Obviously this is possible only because the free system is somehow conservative. This was "abstracted" in section 3.5.

Why low thrust ? The common principle to all propulsion devices is to eject particles, with some relative speed with respect to the vehicle; conservation of momentum then induces, from the point of view of the vehicle alone, an external force, the “thrust” (and a mass decrease). Ejecting the same mass of particles with a higher relative speed results in a proportionally higher thrust; this relative speed (specific impulse, I_{sp}) is a characteristic of the engine; the higher the I_{sp}, the smaller the mass of particles needed for the same change in the vehicle momentum. Engines with a higher I_{sp} are highly desirable because, for the same maneuvers, they reduce the mass of "fuel" to be taken on-board the satellite, hence leaving more room (mass) for the payload. “Classical” chemical engines use combustion to eject particles, at a somehow limited speed even with very efficient fuel; the more recent electric engines use a magnetic field to accelerate particles and eject them at a considerably higher speed; however electrical power is limited (solar cells), and only a small amount of particles can be accelerated per unit of time, inducing the limitation on thrust magnitude.

Electric engines theoretically allow many more maneuvers with the same amount of particles, with the drawback that the instant force is very small; sophisticated control design is necessary to circumvent this drawback. High thrust engines allow simpler control procedures because they almost allow instant maneuvers (strategies consist in a few burns at precise instants).

4.1.2. Typical problems

Let us mention two.

- *Orbit transfer or rendez-vous*. It is the classical problem of bringing a satellite to its operating position from the orbit where it is delivered by the launcher; for instance from a GTO orbit to the geostationary orbit at a prescribed longitude (one says rendez-vous when the longitude, or the position on the orbit, is prescribed, and transfer if it is free). In equation (1) for the dynamics, $F_{\mathrm{grav.}}$ is the Newtonian gravitation force of the earth (it then does not depend on time); F_2 contains all the terms coming either from the perturbations to the Newtonian potential or from external forces like radiation pressure, and the control is usually allowed in all directions, or with some restrictions to be made precise.
- *Three body problem*. This is about missions in the solar system leaving the region where the attraction of the earth, or another single body, is preponderant. We are then no longer in the situation of a single central body, $F_{\mathrm{grav.}}$ contains the attraction of different planets and the sun. In regions where two central bodies have an influence, say the earth and the moon, or the sun and a planet, the term $F_{\mathrm{grav.}}$ in (1) is the one of the restricted three body problem and dependence on time reflects the movement of the two “big” attracting bodies.

  An issue for future experimental missions in the solar system is interplanetary flight planning with gravitational assistance. Tackling this global problem, that even contains some combinatorial problems (itinerary), goes beyond the methodology developed here, but the above considerations are a brick in this puzzle.

4.1.3. Properties of the control system.

If there are no restrictions on the thrust direction, i.e., in equation (1), if the control u has dimension 3 with an invertible matrix G, then the control system is “static feedback linearizable”, and a fortiori flat, see section 3.2. However, implementing the static feedback transformation would consist in using the control to “cancel” the gravitation; this is obviously impossible since the available thrust is very small. As mentioned in section 3.1, point 3, the problem remains fully nonlinear in spite of this “linearizable” structure [0].

4.2. Quantum Control

These applications started by a collaboration between B. Bonnard and D. Sugny (a physicist from ICB) in the ANR project Comoc (now ended). The problem was the control of the orientation of a molecule

[0] However, the linear approximation around *any* feasible trajectory is controllable (a periodic time-varying linear system); optimal control problems will have no singular or abnormal trajectories.

using a laser field, with a model that does take into account the dissipation due to the interaction with the environment, molecular collisions for instance. The model is a dissipative generalization of the finite dimensional Schrödinger equation, known as Lindblad equation. It is a 3-dimensional system depending upon 3 parameters, yielding a very complicated optimal control problem that we have solved for prescribed boundary conditions. In particular we have computed the minimum time control and the minimum energy control for the orientation or a two-level system, using geometric optimal control and appropriate numerical methods (shooting and numerical continuation) [49], [48].

More recently, based on this project, we have reoriented our control activity towards Nuclear Magnetic Resonance (MNR). In MNR medical imaging, the contrast problem is the one of designing a variation of the magnetic field with respect to time that maximizes the difference, on the resulting image, between two different chemical species; this is the "contrast". This research is conducted with Prof. S. Glaser (TU-München), whose group is performing both in vivo and in vitro experiments; experiments using our techniques have successfully measured the improvement in contrast between materials chemical species that have an importance in medicine, like oxygenated and de-oxygenated blood, see [47]; this is however still to be investigated and improved. The model is the Bloch equation for spin $\frac{1}{2}$ particles, that can be interpreted as a sub-case of Lindblad equation for a two-level system; the control problem to solve amounts to driving in minimum time the magnetization vector of the spin to zero (for parameters of the system corresponding to one of the species), and generalizations where such spin $\frac{1}{2}$ particles are coupled: double spin inversion for instance.

A reference book by B. Bonnard and D. Sugny has been published on the topic [50].

4.3. Swimming at low-Reynolds number

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. This feature, known as the scallop theorem in that context needs to be circumvented when one wants to swim with strokes that produce a net motion of the swimmer. In this regime, it turns out that the dynamic of a micro-swimmer could be expressed as an ordinary differential equation. First of all, by stating that the swimmer controls its own shape, we focus on finding the best strategy to swim (by minimizing a time or an energy). Moreover, we work on the control and optimal control of magnetic micro-swimmers. The latter micro-device is charged in order to be deformed by an external magnetic field. In this case, the control functions are the external magnetic field. And we wonder whether it is possible to control the position of the swimmer by acting on this external magnetic field. We are also interested in the associated optimal control problem (acting on the magnetic field in such a way that the swimmer reaches a desired position as soon as possible).

4.4. Applications of optimal transport

Optimal Transportation in general has many applications. Image processing, biology, fluid mechanics, mathematical physics, game theory, traffic planning, financial mathematics, economics are among the most popular fields of application of the general theory of optimal transport. Many developments have been made in all these fields recently. Three more specific examples:
- In image processing, since a grey-scale image may be viewed as a measure, optimal transportation has been used because it gives a distance between measures corresponding to the optimal cost of moving densities from one to the other, see e.g. the work of J.-M. Morel and co-workers [73].
- In representation and approximation of geometric shapes, say by point-cloud sampling, it is also interesting to associate a measure, rather than just a geometric locus, to a distribution of points (this gives a small importance to exceptional "outlier" mistaken points); this was developed in Q. Mérigot's PhD [74] in the GEOMETRICA project-team. The relevant distance between measures is again the one coming from optimal transportation.

- The specific to the type of costs that we have considered in some mathematical work, i.e. these coming from optimal control, are concerned with evolutions of densities under state or velocity constraints. A fluid motion or a crowd movement can be seen as the evolution of a density in a given space. If constraints are given on the directions in which these densities can evolve, we are in the framework of non-holonomic transport problems.

4.5. Applications to some domains of mathematics.

Control theory (in particular thinking in terms of inputs and reachable set) has brought novel ideas and progresses to mathematics. For instance, some problems from classical calculus of variations have been revisited in terms of optimal control and Pontryagin's Maximum Principle [63]; also, closed geodesics for perturbed Riemannian metrics where constructed in [66], [67] using control techniques.

Inside McTAO, a work like [58], [57] is definitely in this line, applying techniques from control to construct some perturbations under constraints of Hamiltonian systems to solve longstanding open questions in the field of dynamical systems.

5. New Software and Platforms

5.1. Hampath

KEYWORDS: Geometric control - Second order conditions - Differential homotopy - Ordinary differential equations

FUNCTIONAL DESCRIPTION

Hampath is an open-source software developed to solve optimal control problems by coupling shooting and homotopy methods. More generally, it can be used to solve general Hamiltonian boudary value problems. It also implements an efficient computation of Jacobi fields (allowing in particular second order optimality condition checks) based on the repeated use of automatic differentiation.

- Participants: Jean-Baptiste Caillau, Olivier Cots and Joseph Gergaud
- Contact: Oliver Cots
- URL: http://www.hampath.org

6. New Results

6.1. Advances in optimal control

6.1.1. Algebraic and geometric techniques in medical resonance imaging

Participants: Bernard Bonnard, Jean-Charles Faugère [EPI PolSys], Alain Jacquemard [Univ. de Bourgogne], Mohab Safey El Din [EPI PolSys], Thibaut Verron [EPI PolSys].

In the framework of the ANR-DFG project Explosys (see Section 8.3) we use computer algebra methods to analyze the controlled Bloch equations, modeling the contrast problem in MRI. The problem boils down to analyzing the so called singular extremals associated to the problem. Thanks to the linear dependance of the problem with respect to the state variables and the relaxation parameters the problem is algebraic and is equivalent to determining equilibrium points and eigenvalues of the linearized system at such points together with the algebraic classification of the surface associated to the switches between bang and singular arcs. Preliminary results are described in ISSAC paper [12] using Grobner basis and stratifications of singularities of determinantal varieties. This work was a part of T. Verron's PhD and is continuing in particular with him (Post doc APO-ENSEEIHT).

6.1.2. Local minima, second order conditions

Participants: Jean-Baptiste Caillau, Zheng Chen, Yacine Chitour [Univ. Paris-Sud], Ariadna Farrés [Univ. Barcelona].

It is well known that the PMP gives necessary conditions for optimality, but curves satisfying this condition may be local minima or critical sadle points. Roughly speaking, the PMP is a first order condition. Higher order conditions give finer necessary conditions (and sufficient in some special cases), but they require differentiability that is not always satisfied when commutations occur. Furthermore, these local conditions cannot distinguish local from global minima. In [4] and [19], we make contributions respectively to extending higher order conditions to non-smooth cases and to exploring local and global minima on an example of interest.

Second order systems whose drift is defined by the gradient of a given potential are considered, and minimization of the L^1-norm of the control is addressed in [4]. An analysis of the extremal flow emphasizes the role of singular trajectories of order two [78], [81]; the case of the two-body potential is treated in detail. In L^1-minimization, regular extremals are associated with bang-bang controls (saturated ocnstraint on the norm); in order to assess their optimality properties, sufficient conditions are given for broken extremals and related to the no-fold conditions of [75]. Two examples of numerical verification of these conditions are proposed on a problem coming from space mechanics.

In another direction, we have been studying the structure of local minima for time minimization in the controlled three-body problem. In [19], several homotopies are systematically used to unfold the structure of these local minimizers, and the resulting singularity of the path associated with the value function is analyzed numerically.

6.1.3. Solving chance-constrained optimal control problems in aerospace engineering via Kernel Density Estimation

Participants: Jean-Baptiste Caillau, Max Cerf [Airbus Industries], Achille Sassi, Emmanuel Trélat [Univ. P. & M. Curie], Hasna Zidani [ENSTA ParisTech].

The goal of [30] is to show how non-parametric statistics can be used to solve chance-constrained optimization and optimal control problems by reformulating them into deterministic ones, focusing on the details of the algorithmic approach. We use the Kernel Density Estimation method to approximate the probability density function of a random variable with unknown distribution, from a relatively small sample. In the paper it is shown how this technique can be applied to a class of chance-constrained optimization problem, focusing on the implementation of the method. In particular, in our examples we analyze a chance-constrained version of the well known problem in aerospace optimal control: the Goddard problem.

6.2. Averaging and filtering for optimal control in Space mechanics

Participants: Jean-Baptiste Caillau, Thierry Dargent, Florentina Nicolau, Jean-Baptiste Pomet, Jérémy Rouot.

Investigating averaging in optimal control for space mechanics with low thrust, or more generally with conservative systems with “small” controls is an ongoing subject in the team. It is also central in the research contract with CNES mentioned in Section 7.1.

6.2.1. Convergence properties of the Maximum principle

Part of Jérémy Rouot’s PhD [2] was devoted to convergence properties in the Hamiltonian system resulting from Pontryagin’s Maximum principle when the small parameter representing the ratio between slow and fast velocities tends to zero. The difference with previous work is that we give a clear method to sort fast and slow variables in the adjoint variables, and we provide convergence of these under some conditions. A more complete publication is under preparation.

6.2.2. Approximation by filtering in optimal control and applications

Minimum time control of slow-fast systems is considered. In the case of only one fast angle, averaging techniques are available for such systems. The approach introduced in [54] and [43] is recalled, then extended to time dependent systems by means of a suitable filtering operator. The process relies upon approximating the dynamics by means of sliding windows. The size of these windows is an additional parameter that provides intermediate approximations between averaging over the whole fast angle period and the original dynamics. The method was applied to problems coming from space mechanics, and is exposed in [31].

6.2.3. Averaging with reconstruction of the fast variable

We have been studying a way to modify the initial condition of the average equation in order to approach better (but in the mean) the slow variable while reconstructing asymptotically the fast variable. This follows an idea that was shown to work numerically in [54].

In [32], we give a construction for Cauchy problems. It is lighter than second order averaging, in that oscillating signals and ODEs are not used, and still provides a second order error *in the mean*, together with convergence of the fast variable. This remains to be developed for two-point boundary value problems like in optimal control.

6.3. Fully controlled slender microswimmers

6.3.1. The N-link micro-swimmer

Participants: François Alouges [École Polytechnique], Antonio Desimone [SISSA Trieste], Laetitia Giraldi, Marta Zopello [Univ. di Padova].

We discussed a reduced model to compute the motion of slender swimmers which propel themselves by changing the curvature of their body. Our approach is based on the use of Resistive Force Theory for the evaluation of the viscous forces and torques exerted by the surrounding fluid, and on discretizing the kinematics of the swimmer by representing its body through an articulated chain of N rigid links capable of planar deformations. The resulting system of ODEs, governing the motion of the swimmer, is easy to assemble and to solve, making our reduced model a valuable tool in the design and optimization of bio-inspired artificial microdevices. We prove that the swimmer composed by almost 3 segments is controllable in the whole plane. As a direct result, there exists an optimal swimming strategy to reach a desired configuration in minimum time. Numerical experiments for in the case of the Purcell swimmer suggest that the optimal strategy is periodic, namely a sequence of identical strokes. Our results indicate that this candidate for an optimal stroke, indeed gives a better displacement speed than the classical Purcell stroke.

This is presented in [36] (accepted as a Book chapter in Multi-scale Models in Mechano and Tumor Biology: Modeling, Homogenization and Applications, Lecture Notes in Computational Science and Engineering. June 2016).

6.3.2. Optimal periodic strokes for the Copepod and Purcell micro-swimmers

Participants: Piernicola Bettiol [Uni. Bretagne Ouest], Bernard Bonnard, Alice Nolot, Jérémy Rouot.

We have analyzed the problem of optimizing the efficiency of the displacement of two micro swimmers with slender links, namely the following two models: the symmetric micro swimmer introduced by Takagi (see [29]); this is a model to describe the locomotion of the micro crustaceans named copepod, and the historical three link Purcell swimmer. The problems are studied in the framework of optimal control theory and SR geometry vs the standard curvature control point of view. Our contributions are to determine the optimal solutions combining geometric analysis and adapted numerical scheme. In particular the nilpotent models introduced in SR geometry allow to make a neat analysis of the problem of determining optimal strokes with small amplitudes and numerical continuation methods are then applied to compute more general stroke. This approach is completely original in optimal control. Also necessary and sufficient optimality conditions are applied to select the topology of optimal strokes (simple loops) and to determine the optimal solution in both cases. For the references see [17] and [27]. Also note that in collaboration with D. Takagi and M. Chyba this approach is currently at the experimental level at the university of Hawaii using a robot micro swimmer mimicking a copepod, see above. More theoretical issues in relation with SR geometry are investigated in the framework of A. Nolot's starting PhD (started August, 2016). Other publication relating these advances are [25], [26], [11].

6.4. Modelization and Controllability of "Magneto-elastic" Micro-swimmers

Participants: François Alouges [École Polytechnique], Antonio Desimone [SISSA Trieste], Laetitia Giraldi, Pierre Lissy [Univ. Paris Dauphine], Clément Moreau [ENS Cachan and York University], Jean-Baptiste Pomet, Marta Zopello [Univ. di Padova].

It is not realistic for *artificial* micro-swimmers built as micro-robots, to have an actuator at each joint. A possibility is as follows: each link of the swimmer bears is magnetized and the movement is controlled via an exterior magnetic field. These models also bear an internal elastic force, that can be modelled as a torsional spring at each joint and tends to asymptotically restore the straight shape in the absence of other forces.

Control strategies for these models have been proved successful numerically. It can also be proved mathematically via an asymptotic analysis that it is possible to steer the swimmer along a chosen direction with some well chosen oscillating magnetic field, provided some obstruction, like symmetries, are avoided. This is exposed in [23] for a Purcell magnetic swimmer (3 links).

For the smallest magneto-elastic micro-swimmer (2 links), we have been able to prove a strong local controllability result (weaker than STLC) around the straight position of the swimmer, again except for values of the parameters that correspond to symmetries preventing controllability. This is exposed in [8], and a note is under preparation, that shows that STLC is indeed *not* satisfied. This analysis is difficult because the straight position corresponds to the equilibria but is very degenerate from the control point of view.

To avoid this degeneracy, a possibility is to "twist" one of the torsional springs so that the equilibria no longer occur for a straight shape. This is exposed in [34] for a 3-link magnetic microswimmer (local controllability has not been proved for this system without the twist). A local partial controllability result around the equilibrium is proved in that case and a constructive method to find the magnetic field that allows the swimmer to move along a prescribed trajectory is described.

6.5. Sub-Riemannian Geometry and Optimal Transport

Participants: Zeinab Badreddine, André Belotto Da Silva [University of Toronto], Ludovic Rifford.

We have studied the Sard Conjecture and its link with the problem of existence and uniqueness of an optimal transport map for a cost given by the square of a sub-Riemannian distance. Given a totally non-holonomic distribution on a smooth manifold, the Sard Conjecture is concerned with the the size of the set of points that can be reached by singular horizontal paths starting from a same point. In the setting of rank-two distributions in dimension three, the Sard conjecture states that that set should be a subset of the so-called Martinet surface of 2-dimensional Hausdorff measure zero. In [24], A. Belotto da Silva and L. Rifford proved that the conjecture holds in the case where the Martinet surface is smooth. Moreover, they address the case of singular real-analytic Martinet surfaces and show that the result holds true under an assumption of non-transversality of the distribution on the singular set of the Martinet surface. The methods rely on the control of the divergence of vector fields generating the trace of the distribution on the Martinet surface and some techniques of resolution of singularities. In a work in progress, the control on the divergence of this "generating" vector field is the key ingredient used by Z. Badreddine to obtain results of existence and uniqueness of optimal transport map for rank-two distribution in dimension four.

6.6. Geometric Control and Dynamics

Participants: Ayadi Lazrag, Ludovic Rifford, Rafael Ruggiero [PUC-RIO].

Following [77], [57] and [58], we apply techniques from geometric control to the study of perturbations of Hamiltonian flows. In [9], we prove a uniform Franks' lemma at second order for geodesic flows and apply the result in persistence theory.

7. Bilateral Contracts and Grants with Industry

7.1. CNES - Inria - UB Contract

Contract number: 130777/00. Call Number: R-S13/BS-005-012

"Perturbations and averaging for low thrust" (Poussée faible et moyennation).
Research contract between CNES and McTAO (both the Inria and the Université de Bourgogne parts). It runs for the period 2014-2017. It concerns averaging techniques in orbit transfers around the earth while taking into account many perturbations of the main force (gravity for the earth considered as circular). The objective is to validate numerically and theoretically the approximations made by using averaging, and to propose methods that refine the approximation. It has co-funded the PhD thesis of Jeremy Rouot [2] (also co-funded by Région PACA) and fully funded the postdoc of Florentina Nicolau [32], [31].

8. Partnerships and Cooperations

8.1. Regional Initiatives

The PhD thesis of Jeremy Rouot [2] has been co-funded by Région PACA.

8.2. National Initiatives

8.2.1. ANR

Weak KAM beyond Hamilton-Jacobi (WKBHJ). Started 2013 (decision ANR-12-BS01-0020 of December 19, 2012), duration: 4 years. L. Rifford is in the scientific committee.

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.

8.2.2. Others

The McTAO team participates in the GdR MOA, a CNRS network on Mathematics of Optimization and Applications.

PEPS project of AMIES Labex, "Dealing with exclusion constraints in orbital transfer" with Thalès Alenia Space (PI J.-B. Caillau). This project funded two master internships during summer 2016 (M. Brunengo and Y. El Alaoui Faris, co-supervised with T. Dargent from Thalès).

PGMO grant (2016-2017) on "Metric approximation of minimizing trajectories and applications" (PI J.-B. Caillau). This project involves colleagues from Université Paris Dauphine and has funding for one year, including one intership (M2 level).

J.-B. Caillau is associate researcher of the team Optimization & Control at ENSTA-Paristech and of the CNRS team Parallel Algorithms & Optimization team at ENSEEIHT, Univ. Toulouse.

8.3. European Initiatives

8.3.1. Collaborations in European Programs, other than FP7 & H2020

8.3.1.1. 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

8.3.1.2. Bilateral 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 is in the (scientific committee).

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. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

The cut locus: A bridge over differential geometry, optimal control and transport, Bangkok, August 2016 (B. Bonnard, J.-B. Caillau, K. Kondo, L. Rifford, M. Tanaka). The conference was organized with the support of the Thai KMITL University and gathered 30 people mostly from Japan, Thailand and France.

9.1.1.2. Member of the Organizing Committees

Séminaire de géométrie hamiltonienne, Paris 6 (J.-B. Caillau). Bi-mensual seminar.

Journée McTAO, Inria Sophia, January 2016. One day event organized by the team with four invited speakers.

10th International Young Researcher Workshop on Geometry, Mechanics and Control, Paris (IHP), January 2016 (J.-B. Caillau). The workshop gathered 50 people for conferences and mini-courses.

Journées SMAI-MODE, Toulouse, March 2016 (J.-B. Caillau). The conference gathered 140 researchers, and was coupled with a series of two mini-courses co-organized with GdR MOA.

Journée MokaTAO, Inria Paris, October 2016. Two-day event co-organized by Mokaplan (Inria Paris) and McTAO teams, with talks by members of these teams. The two teams share common interests in optimization and optimal transportation.

Groupe de travail "Optimisation et applications", Inria Sophia Antipolis, November 2016 (J.-B. Caillau). One day event with four invited speakers.

9.1.2. Books

9.1.2.1. Springer briefs

B. Bonnard and J. Rouot, together with M. Chyba, have written the series of notes [28], submitted as Springer briefsPublications. They were the basis of courses at the Phd level given at the University of Burgundy and at the institute of Mathematics for industry at Fukuoka (Japan)

9.1.2.2. Springer Maths and Industry

B. Bonnard, together with M. Chyba, served as an editor of the volume [18], which gather contributions on the subject by specialists of both academics and space agencies.

9.1.2.3. Radon Series on Comput. and Applied Math.

J.-B. Caillau, together with M. Bergounioux, G. Peyré, C. Schnörr and T. Haberkorn, served as an editor for the volume [21]. With a focus on the interplay between mathematics and applications of imaging, the first part covers topics from optimization, inverse problems and shape spaces to computer vision and computational anatomy. The second part is geared towards geometric control and related topics, including Riemannian geometry, celestial mechanics and quantum control.

9.1.3. Journals

9.1.3.1. Member of the Editorial Boards

L. Rifford has been a member of the Editorial Board of the journal "Discrete and Continuous Dynamical Systems - A" since 2014.

9.1.3.2. Reviewer - Reviewing Activities

The team members have reviewed articles in 2016 for the following journals: SIAM J. Control & Optim., ESAIM Control Optim. and Calc. Var., Automatica, J. Dyn. Control Syst., J. Optim. Theory Appl., J. Math. Pures Appl., Inventiones Mathematicae, Mathematische Zeitschrift, Advances in Differential Equations, Memoirs of the American Mathematical Society, Annales Scientifiques de l'ENS, Nonlinear Analysis, Communications in Mathematical Physics

9.1.4. Invited Talks

J.-B. Caillau
03/2016: *Séminaire Géométrie et dynamique*, Nice
04/2016: *Séminaire de Géométrie hamiltonienne*, Paris
05/2016: *Emerging Trends in Applied Mathematics and Mechanics*, Perpignan
06/2016: *Alicante-Limoges-Elche Meeting on Optimization*, Cartagena
08/2016: *The cut locus: A bridge over differential geometry, optimal control and transport*, Bangkok
09/2016: *Séminaire Astrogéo*, Observatoire de la côte d'azur, Sophia

L. Giraldi
11/2016: *Controllability and hysteresis*, Trento, Italie

L. Rifford
02/2016: *Rencontre d'Analyse Mathématique et ses Applications*, Ouargla (Algeria)
02/2016: *Séminaire de Calculs des Variations et EDP*, Aix-Marseille University
03/2016: *CIMPA Research School "Géométrie et Analyse"*, Abidjan (Ivory Coast)
03/2016: *Séminaire Bourbaki*, Institut Henri Poincaré, Paris

04/2016: *Colloquium de l'Institut de Mathématiques*, University of Neuchâtel (Switzerland)
04/2016: *International Conference of the GE2MI*, Hammamet (Tunisia)
05/2016: *Colloquium du Département de Mathématiques*, University of Orsay
05/2016:*Geometric control and sub-Riemannian geometry*, Course given at the University of Isfahan (Iran)
06/2016: *Analysis, Geometry, and Optimal Transport*, KIAS, Seoul (South Korea)
08/2016: *The cut locus*, KIMTL, Bangkok (Thailand)
11/2016: *Dynamical Systems Seminar*, ETH Zurich
11/2016: *Dynamics and Geometry Seminar*, University Nice Sophia Antipolis
12/2016: *Seminar of Hamiltonian Geometry*, Paris VI
12/2016: *2016 Analysis School in Benin*, IMPS, Benin

9.1.5. Leadership within the Scientific Community

J.-B. Caillau has been head of the SMAI-MODE group (2014-2016), the group on optimization of the French Society for Applied and Industrial Mathematics.

L. Rifford has been executive director of CIMPA since September 2016.

9.1.6. Scientific Expertise

J.-B. Caillau is member of the scientific committees of the "Institut de Mécanique Céleste de Calcul des Éphémérides" and of the GdR Calcul, and corresponding member in Dijon for the Labex AMIES.

J.-B. Pomet is a member of the steering committee of "C4PO", a structuring project of the IDEX UCA$^{\text{JEDI}}$.

9.1.7. Research Administration

J.-B. Caillau is the joint head of the CNRS team Statistique, Probabilités, Optimisation & Contrôle at the Math. Institute of Univ. Bourgogne & Franche-Comté.

J.-B. Pomet has been an elected member of the Inria Evaluation Committee (commission d'évaluation) since 2014.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

J.-B. Caillau has managed L1 math and the master of applied mathematics (M2 MIGS) of Univ. Bourgogne Franche-Comté (2014-2016). He has been a designated member of the Conseil pédagogique du Département de Mathématiques at UBFC (2014-2016), and of the Conseil de l'UFR Mathématiques & Informatique at Univ. Paris I (2014-2016). His teaching duties in 2016 include:

Licence : cours d'analyse (analysis), 100 H équivalent TD, niveau L1, Univ. Bourgogne Franche-Comté, France

Master : approximation géométrique (geometric approximation), 50 H équivalent TD, niveau M1, Univ. Bourgogne Franche-Comté, France

Master : optimisation, 50 H équivalent TD, niveau M2, Univ. Bourgogne Franche-Comté, France

Master : contrôle optimal (optimal control), 20 H équivalent TD, niveau M2, ENSTA-Paristech, France

L. Giraldi is responsible of the following courses:

Licence : *"colles de mathématiques", MPSI and MP*, 4 H équivalent TD/week, L1 L2, Lycée International de Valbonne,

Licence : numerical analysis, 20 H équivalent TD, L3, Polytech Nice Sophia,

Master : numerical analysis project, 30 H équivalent TD, M1, Polytech Nice Sophia.

9.2.2. Supervision

PhD: Zheng Chen, L^1-minimization in space mechanics, Univ. Paris Saclay, defended September, 2016, J.-B. Caillau (co-supervised with Y. Chitour) [1]

PhD: Jérémy Rouot, , Univ. Nice Sophia Antipolis, Geometric and numerical methods in optimal control and application to orbit transfer and swimming at low Reynolds number. Defended November, 2016, co-supervised by B. Bonnard and J.-B. Pomet. [2]

PhD in progress: Achille Sassi, to be defended 01/2017, Numerical methods for hybrid control and chance-constrained optimization problems, Univ. Paris Saclay, J.-B. Caillau (co-supervised with M. Cerf, E. Trélat and H. Zidani)

PhD in progress: Michaël Orieux, started 10/2015, Dynamical systems and optimal control, Univ. Paris Dauphine, J.-B. Caillau (co-supervised with J. Féjoz)

PhD in progress: Zeinab Badreddine, started 09/2014, Sub-Riemannian Geometry and Optimal Transport, co-supervised by L. Rifford and B. Bonnard.

PhD in progress: Sébastien Fueyo, started 09/2016, Testing stability of nonlinear amplifier by frequency-domain methods. J.-B. Pomet (co-supervised with L. Baratchart).

PhD in progress: Alice Nolot, started 09/2016, Sub-Riemannian geometry and optimal swimming at low Reynolds number. B. Bonnard.

9.2.3. Juries

In 2016, J.-B. Caillau referee for Jiamin Zhu (Univ. Paris 6) and Maxime Chupin (Univ. Paris 6) PhD theses, for the HDR of Aude Rondepierre (Univ. Toulouse), and jury member for the PhD thesis of Clément Royer (Univ. Toulouse).

9.3. Popularization

Conference for high school students, "Ne votez pas, jugez !" (J.-B. Caillau), semaine des maths 2016, Lycée Charles de Gaulle (Dijon) and MASTIC initiative (Inria Sophia Antipolis).

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[2] J. ROUOT. *Geometric and numerical methods in optimal control and application to orbit transfer and swimming at low Reynolds number*, Universite Nice Sophia Antipolis, November 2016, https://hal.inria.fr/tel-01402516.

Articles in International Peer-Reviewed Journal

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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

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Computer Science and Digital Science:

3.4. - Machine learning and statistics
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3.4.2. - Unsupervised learning
3.4.4. - Optimization and learning
3.4.6. - Neural networks
3.4.7. - Kernel methods
3.4.8. - Deep learning
5.3. - Image processing and analysis
5.3.2. - Sparse modeling and image representation
5.3.4. - Registration
5.4.1. - Object recognition
5.4.3. - Content retrieval
5.4.4. - 3D and spatio-temporal reconstruction
5.4.5. - Object tracking and motion analysis
5.4.6. - Object localization
5.9. - Signal processing
5.9.3. - Reconstruction, enhancement
5.9.5. - Sparsity-aware processing
5.9.6. - Optimization tools
6.1. - Mathematical Modeling
6.1.1. - Continuous Modeling (PDE, ODE)
6.1.2. - Stochastic Modeling (SPDE, SDE)
6.3.1. - Inverse problems

Other Research Topics and Application Domains:

1.1. - Biology
1.1.3. - Cellular biology
1.1.4. - Developmental biology
2.6. - Biological and medical imaging

1. Members

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]
Florence Besse [CNRS, Researcher, 50%]
Caroline Medioni [CNRS, Researcher, 20%]

Faculty Member

Cedric Richard [Univ. Nice, Professor, from Mar 2016 until Aug 2016]

Technical Staff

Sébastien Schaub [CNRS, IR, 20%]
Djampa Kozlowski [Inria, from Sep. 2016]
Gaël Michelin [Inria, from Nov. 2016]

PhD Students

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Lola-Xiomara Bautista Rozo [Univ. Nice]
Anca-Ioana Grapa [Univ. Nice, from Sep 2016]
Emmanuelle Poulain [GEMS, Cifre]
Agustina Razetti [Univ. Nice]
Emmanuel Soubies [Univ. Nice, until Oct 2016]

Visiting Scientists

Mohammed Lamine Benomar [Laboratoire Génie Biomédical (G.B.M) Université Abou Bekr Belkaid Tlemcen / Algérie, from Sep 2016]
Hibetallah Ouazaa [National Engineering School of Tunis, from May 2016 until Jun 2016]

Administrative Assistants

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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. New Software and Platforms

4.1. SPADE: Small PArticle DEtection

FUNCTIONAL DESCRIPTION SPADE is an algorithm primarily designed to detect objects whose size is smaller than a few pixels (particles) on fluorescence microscopy images. It is a simplified version of a marked point process based on a shape dictionnary.

- Participants: N. Cedilnik, E. Debreuve, and X. Descombes
- Contact: Xavier Descombes

5. New Results

5.1. Multi-Angle TIRF reconstruction for studying the cell adhesion phenomenon

Participants: Emmanuel Soubies, Laure Blanc-Féraud, Sébastien Schaub.

This work is made in collaboration with Agata Radwanska and Ellen Van Obberghen-Schilling from Institut de Biologie Valrose (iBV) at Nice.

Understanding cell adhesion mechanism is of a major importance in biology for example in the context of tumoral angiogenesis [0]. However, this process occurs at the vicinity of the cell membrane within a layer of a few hundred nanometer making classical microscopy devices unable to image such biological structures due to their lack of resolution in the axial direction. An interesting alternative would be to use a multi-angle total internal reflection illumination together with numerical reconstruction algorithms in order to reach a nanoscale precision in the axial direction.

Following this idea, we made use of our previous work on MA-TIRF reconstruction to produce color-coded maps (see the example on Figure 1), with an axial resolution of 20 nm, of biological samples provided by Agata Radwanska and Ellen Van Obberghen-Schilling from the Institut de Biologie Valrose. The information obtained from the study of the reconstructed images have confirmed known behaviors of some proteins involved in the cell adhesion process allowing us, by this way, to complete the validation of our reconstruction method. Moreover, the 3D reconstructions have provided new information concerning the axial position of the observed biological proteins, information which was unavailable for previous studies conducted with other microscopy systems.

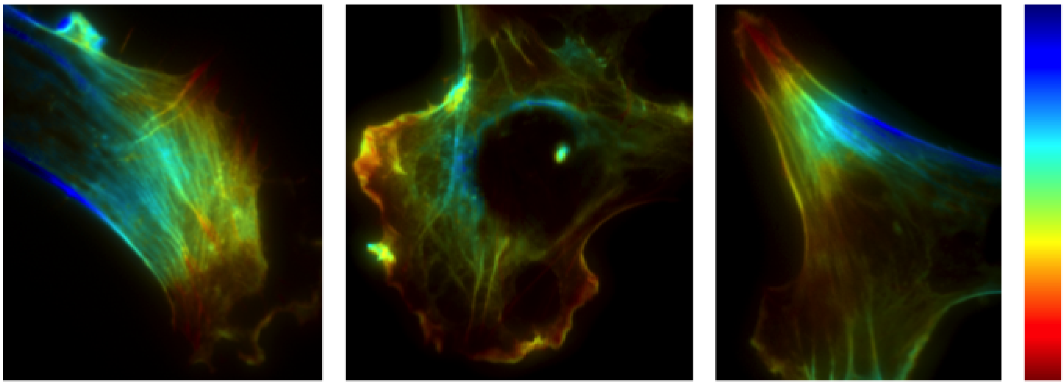

Figure 1. Example of color-coded representations for the reconstructed samples. The colors correspond to the depth (in the axial direction) of the biological structures (in the colorbar on the right: red = 0 nm and dark blue = 400 nm).

5.2. Exact continuous penalties for ℓ_2-ℓ_0 minimization: Application to Photo Activated Localization Microscopy (PALM)

Participants: Simon Gazagnes, Emmanuel Soubies, Laure Blanc-Féraud.

In conventional microscopy techniques, the spatial resolution of an image is limited by the diffraction phenomena. Recent methods like photo-activated localization microscopy (PALM) allow high-precision molecule localization by sequentially activating and imaging a small random set of fluorescent molecules in the sample. However, the quality of this super-resolved image is related to the density of emitters activated at each acquisition and the numerical method used to locate molecules.

Applications for these microscopy techniques are then mainly restricted by the number of acquisitions required to obtain the superresolved image. One way to overcome this limitation is to increase the density of emitters activated at each acquisition. Nevertheless, it will cause overlapping for a certain number of spots on the acquired image which makes the localization of the underlying molecules a harder task. Considering such

[0] Process of blood vessels creation from existing ones.

a high density setting, we have proposed to perform the molecules localization by solving a ℓ_0-penalized least squares criteria through the minimization of the Continuous Exact ℓ_0 (CEL0) relaxation that we have previously proposed. The method has provided interesting results, competing with state of the art methods, as shown on Figure 2. This work has been submitted for the conference ISBI 2017.

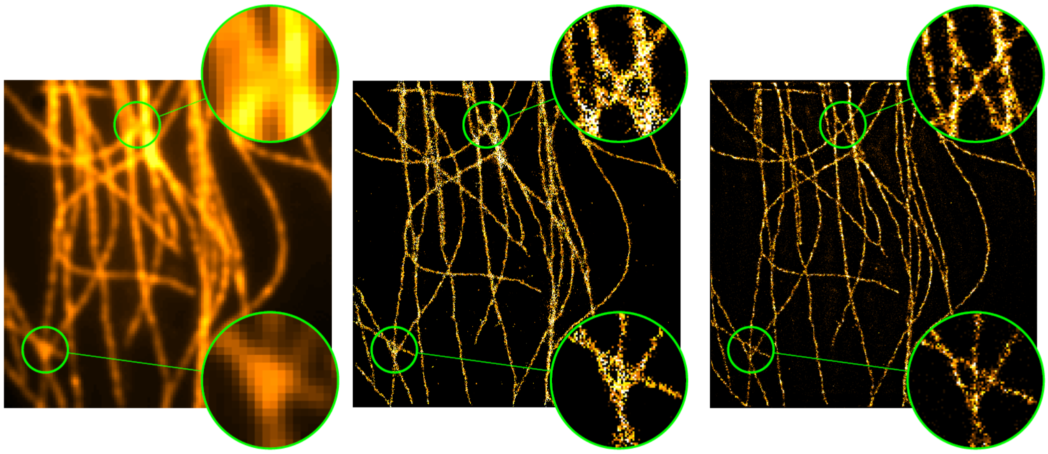

Figure 2. From left to right: Conventional Wide Field image, PALM with DAOSTORM (state of the art algorithm) reconstruction, PALM with the proposed reconstruction.

5.3. Exact continuous penalties for ℓ_2-ℓ_0 minimization: Application to Channel and Direction Of Arrival (DOA) estimation problems

Participants: Emmanuel Soubies, Laure Blanc-Féraud.

This work is made in collaboration with Adilson Chinatto, Cynthia Junqueira, João M. T. Romano (University of Campinas, Brazil) and Pascal Larzabal, Jean-Pierre Barbot (ENS Cachan, SATIE Lab).

In this work, we have proposed to extend the Continuous Exact ℓ_0 (CEL0) penalty, which we initially introduced for the real single measurement vector (SMV) case, to complex SMV and complex multiple measurement vector (MMV) situations involving structured sparsity. Such an extension is necessary to address sparse signal processing estimation problems like augmented resolution channel estimation and direction of arrival (DOA) estimation for which the mixture matrix do not verify restrict isometry property (RIP) and incoherence conditions. We thereby have derived a row-structured version of the CEL0 penalty and showed that the relations between minimizers of the resulting relaxation and those of the initial ℓ_0-penalised least squares criteria, that we previously showed in the real SMV case, are still valid for complex SMV and MMV situations using the proposed row-structured CEL0 penalty. Finally, we have employed state of the art nonsmooth nonconvex algorithms to minimize the proposed relaxation and we have compared the results obtained by our method with those provided by the well known iterative hard thresholding (IHT) algorithm as well as some classical algorithms for the studied problems. We have shown that minimizing the row-structured CEL0 relaxation provides better estimation results than IHT, which minimizes directly with the initial ℓ_0-penalized least-squares criteria, and than classical algorithms used for such problems where the mixture matrix is highly correlated. Moreover, the proposed method is able to reach the oracle RMSE in some cases. This work has been submitted to the IEEE Transaction on Signal Processing journal.

5.4. Phase estimation in Differential Interference Contrast (DIC) microscopy

Participants: Lola-Xiomara Bautista Rozo, Laure Blanc-Féraud.

We address the problem of estimating the phase from color images acquired with differential-interference-contrast microscopy. In particular, we consider the nonlinear and nonconvex optimization problem obtained by regularizing a least-squares-like discrepancy term with a total variation functional, possibly smoothed with the introduction of a positive constant. We deeply investigate the analytic properties of the resulting objective function, proving the existence of minimum points, and several optimization methods able to address the minimization problem. Besides revisiting the conjugate gradient method proposed in the literature for this problem and comparing it with standard conjugate gradient approaches, we introduce more recent effective optimization tools able to obtain both in the smooth and in the non smooth case accurate reconstructions with a reduced computational demand.

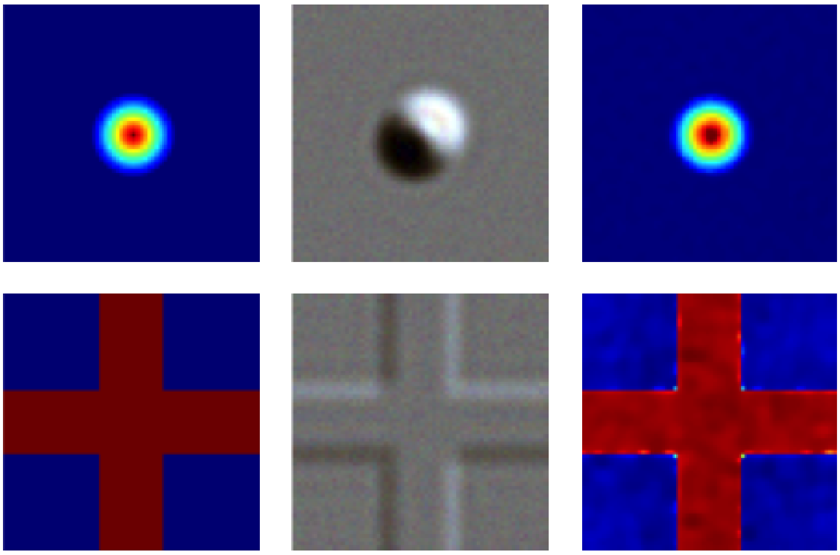

Figure 3. Data and results for the cone (top row) and cross (bottom row) objects. From left to right: true object, noisy DIC color image taken at shear angle $\frac{\pi}{4}$ rad *and corrupted with white Gaussian noise at SNR = 4.5 dB, and reconstructed phase with the LMSD method from observations at shear angles equal to* $-\pi/4$ rad *and* $\pi/4$ rad.

5.5. White Blood Cells Segmentation and Classification in Bone Marrow Images

Participants: Mohammed Lamine Benomar, Xavier Descombes.

This work is made in collaboration with Chikh Amine and Mourtada Benazzouz from GBM Lab. (Tlemcen University). Our experiments were performed on an image database acquired in the Hemobiology service of the Tlemcen Hospital (Algeria).

The differential count of white blood cells (WBC) for medical diagnosis requires a careful observation in peripheral blood and bone marrow microscopic images in order to detect abnormal or suspicious cells. However, this process (screening) is time consuming, requiring concentration, experience and competence of the expert. The diagnosis depends on the correct recognition of cells. For that, computer analysis image system is required to automate the process in order to help experts, reduce the time and increase the accuracy. The main important steps in such systems are segmentation and classification of white blood cells.

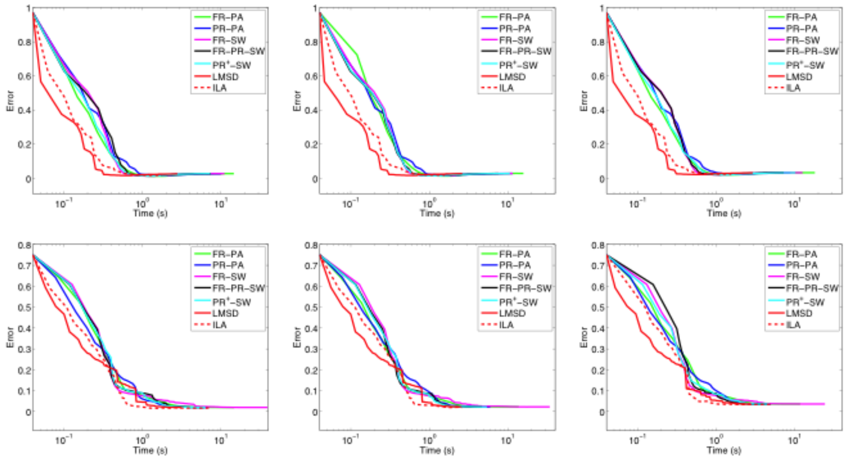

Figure 4. Error versus computational time plots for the cone (top row) and cross (bottom row) objects. From left to right: noise-free data, SNR = 9 dB and SNR = 4.5 dB.

The proposed approach to locate WBC in bone marrow microscopic smear could be divided into three main steps: pre-processing, segmentation and classification. The main concept of the segmentation and classification algorithm employed uses WBCs color, texture and morphological properties.

The first step is to reveal chromatic characteristics of the WBC by applying decorrelation stretch to multi-channel RGB image, simple color transformation and Otsu thresholding to suppress background and most of the red blood cells. In the segmentation step, two techniques have been used which are Marker Controlled Watershed followed by MLE (Maximum Likelihood Estimator) to differentiate between WBC, the grouped red blood cells and artifacts using shape, color and texture features. Then Otsu thresholding based on HSL color space to separate WBC nucleus and cytoplasm (see Figure 5). Finally, white blood cells were classified into two categories related to the type of Myeloma, this step is based on features extraction and then applying a classifier.

5.6. Classification of the extracellular matrix

Participants: Raphael Meunier, Anca-Ioana Grapa, Laure Blanc-Féraud, Xavier Descombes, Sébastien Schaub.

This work is made in collaboration with Ellen Van Obberghen eand Georgios Efthymiou (iBV).

Cells of multicellular organisms interact continually with their local environment which is largely determined by the extracellular matrix (ECM). The biochemical, topological and physical properties (stiffness, elasticity) of the ECM regulate many physiological processes (embryonic development and tissue repair) and their dysregulation plays a key role in the evolution of inflammatory, fibrotic and tumoral diseases. Fibronectin (FN) is a major component of the ECM. The biologists at iBV have identified certain molecular mechanisms involved in the assembly of FN into fibrillar arrays (FN fibrillogenesis) on the cell surface. The resulting fibrillar networks display variable densities and organizations that convey specific biological signals to the cells that encounter them (see figure 6).

We have developed a classification scheme that consists in clustering features extracted from the images to define a texture dictionary. The extracellular matrix are then classified with respect to their signature on this dictionary. We have compared two sets of features that are SIFT histograms and the curvelet coefficients. The

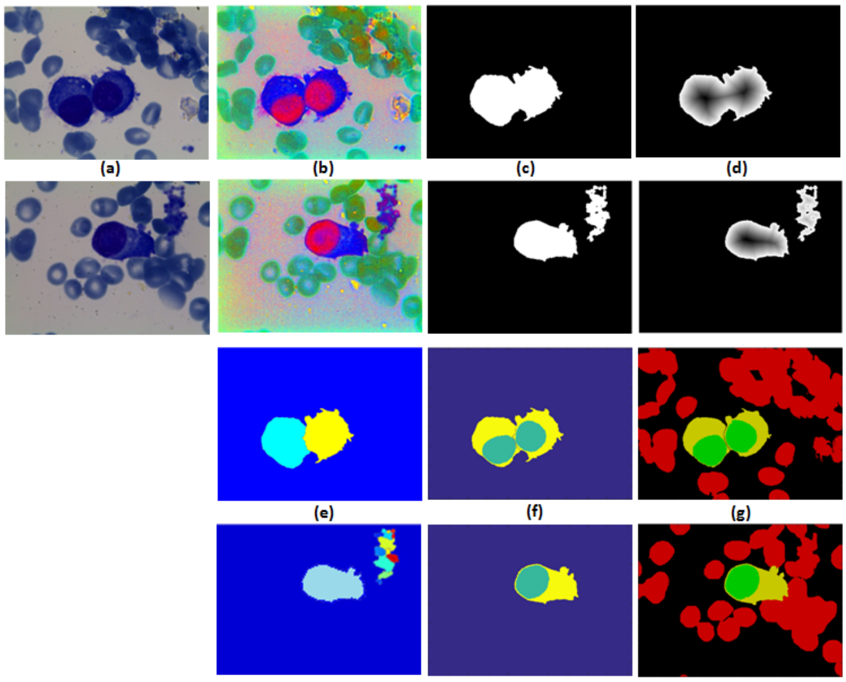

Figure 5. Image segmentation step: (a) Input image, (b) RGB Decorrelation stretch, (c) Binary mask, (d) Distance transform, (e) Watershed, (f) Segmented cell, (g) Ground truth.

SIFT approach appears to be more discriminant for classification purposes but the curvelet approach is better suited for modeling the texture. Next step will consists in modeling the extracellular matrix.

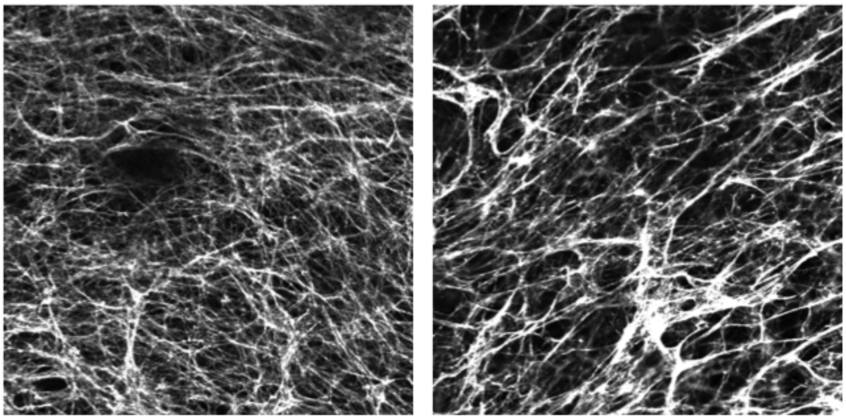

Figure 6. Two examples of extracellular matrices.

5.7. CNuclei/cytoplasm detection and classification in genome-wide RNAi screens

Participants: Eric Debreuve, Djampa Kozlowski, Florence Besse, Xavier Descombes.

This work is made in collaboration with Fabienne De Graeve (iBV).

The work described hereafter is part of the RNAGRIMP ANR project which started in January 2016 and lasts 48 months (see Section 7.2.1). A pilot genome-wide RNAi (Ribonucleic Acid interference) screen on Drosophila cultured cells has been performed with different mutant conditions. The purpose is to study the density and repartition of cytoplasmic RNP (RiboNucleoprotein Particles) granules containing the IMP protein (IGF-II mRNA-binding protein where IGF stands for Insulin-like Growth Factor).

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). A first task that must be accomplished is to detect the nuclei on the DAPI images, and to learn a classification procedure into *living cell* or *dead cell* based on morphologic and radiometric nuclei properties. A CellProfiler [0] pipeline has been developed to automatically detect the nuclei and compute some properties on them. The detection was based on the following main steps: intensity re-scaling, Kapur-based thresholding, and small object discarding. For each detected nucleus, the computed properties were (non-exhaustive list) average intensity, area, granularity, circularity ...

Then, a learning set has been built where a significant number of nuclei were manually assigned their correct (*living* or *dead*) class by a biologist of the team. This learning set was fed to CellProfiler Analyst [0] in order to learn a decision tree for automatic nuclei (hence, cell) classification (see Fig 7, left).

Once the living cell nuclei have been identified on the DAPI images, the next step is to segment (*i.e.*, extract automatically the region of) their cytoplasm on the GFP images. Indeed, the target RNP-IMP granules appear in that compartment of the cell and are visible through their GFP response. We are developing an active contour-based segmentation method relying on local image contrast. The current version still has to be robustified in order to be applicable batchwise (see Fig 7, right).

[0] http://cellprofiler.org
[0] http://cellprofiler.org/cp-analyst

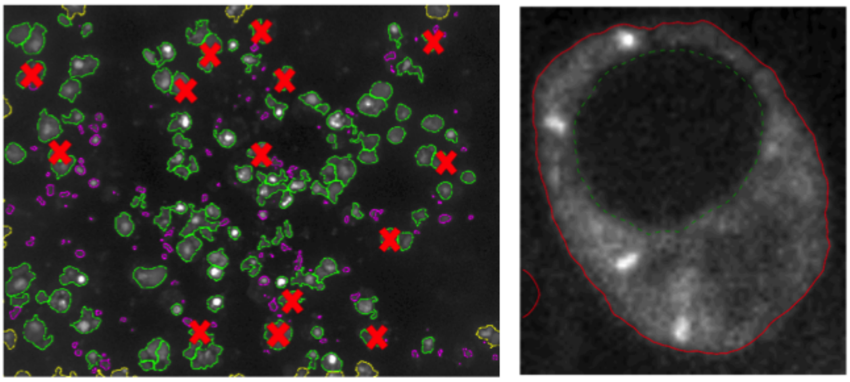

Figure 7. Left: automatic classification of the detected nuclei into living (encircled in green) or dead (with a red cross); objects encircled in yellow are cropped by the field of view, and objects encircled in purple are too small ; they are all discarded. Right: active contour segmentation of the cytoplasm of a cell (previously classified as a living cell); red contour: cytoplasm external boundary; green, dashed contour: nucleus boundary (also cytoplasm internal boundary).

5.8. Small Particle Detection

Participants: Nicolas Cedilnik, Xavier Descombes, Eric Debreuve, Florence Besse.

This work is made in collaboration with Fabienne De Graeve (iBV).

One task of the RNAGRIMP project is to detect RNA granules from fluorescent images. These granules have their size close to the image resolution, they typically represent very few pixels. At this scale, shape parametric models are only crude approximations of the object geometry and not adapted for a detection task. To overcome this difficulty we have defined a shape dictionary consisting of all the shapes included in a five by five tile and satisfying some properties of regularity and convexity. Then we are mimicking the marked point process framework by defining an energy function on the finite sets of shapes as the sum of a data term, applied on each object, and a non overlapping constraint between neighboring objects. The solution minimizing the energy is approximated by a greedy algorithm. We have compared different data terms and shown better performances than the traditional threshold approaches and the wavelet based approach as provided by the software Icy.

5.9. Inter-individual spatio-temporal registration strategies applied to 3D microscopy image sequences of Arabidopsis floral meristems

Participants: Gaël Michelin, Grégoire Malandain.

This work is made in collaboration with Yassin Refahi (Sainsbury Lab., University of Cambridge), Jan Traas (ENS Lyon) and Christophe Godin (Inria Virtual Plants team, Montpellier).

In developmental biology, the study of model organisms such as the plant *Arabidopsis thaliana* aims at understanding genetic mechanisms responsible of morphogenesis. Today, fluorescent confocal microscopy is a means for *in vivo* imaging of organs of interest such as Arabidopsis floral meristems at cell level with a high spatio-temporal resolution. To handle such 3D+t image sequences, adapted computer-assisted methods are highly desirable. Moreover, the inter-individual development variability quantification requires the ability to register spatio-temporal image sequences from a population of individuals.

In the related work, we propose a dedicated tool for the inter-individual spatio-temporal sequence-to-sequence registration applied to developing Arabidopsis flower meristems. We also discuss the different strategies that may be adopted by the user for the method application in order to assist the choice of parameters for the registration method such as:

- the image primitives to be registered;
- the initialization of the image-to-sequence registration optimization process;
- the initialization "propagation" strategy for sequence-to-sequence registration;
- the parameters selection for the optimization step.

Figure 8 shows the result of the temporal registration between three interpolated image sequences of developing Arabidopsis floral meristems. Figure 9 shows an example of spatial registration between two images from different floral meristems at the same developing stage.

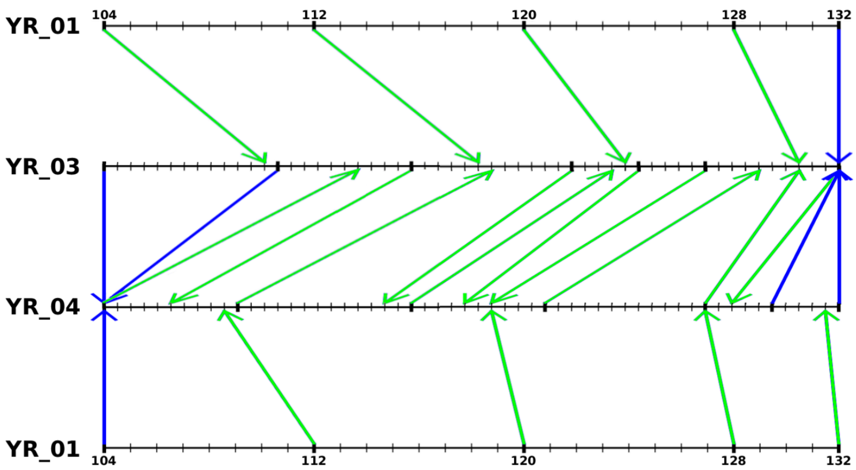

Figure 8. Inter-individual temporal registration result between three floral meristem 3D+t interpolated image sequences. Blue arrows correspond to border registrations.

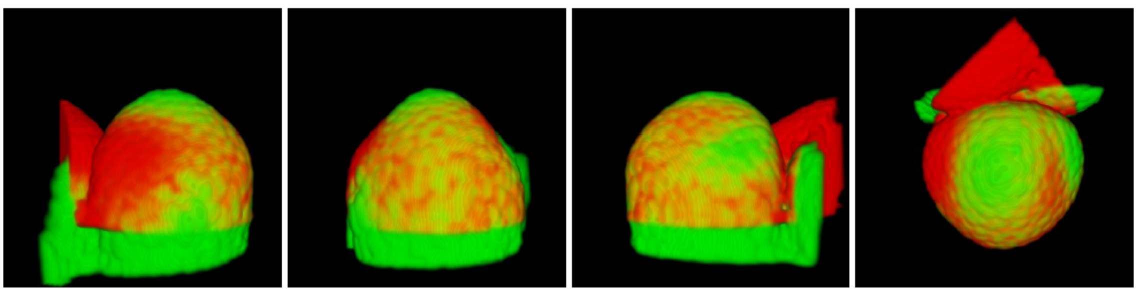

Figure 9. 3D views of the spatial registration of images from two flower meristems (in red and green) at the same developing stage.

5.10. Coherent temporal extrapolation of labeled images

Participants: Gaël Michelin, Grégoire Malandain.

In developmental imaging, 3D+t series of microscopic images allows to follow the organism development at the cell level and has become the standard way of imaging the development of living organs. Dedicated tools for cell segmentation in 3D images as well as cell lineage calculation from 3D+t sequences have been proposed to analyze these data. For some applications (such as section 5.9), it may be desirable to interpolate images at intermediary time-points. However, the known methods do not allow to locally handle the topological changes (ie cell. division).

In the present work, we propose an extrapolation method that coherently deformed the images to be interpolated so that to guarantee a topological continuity of borders (see figure 10).

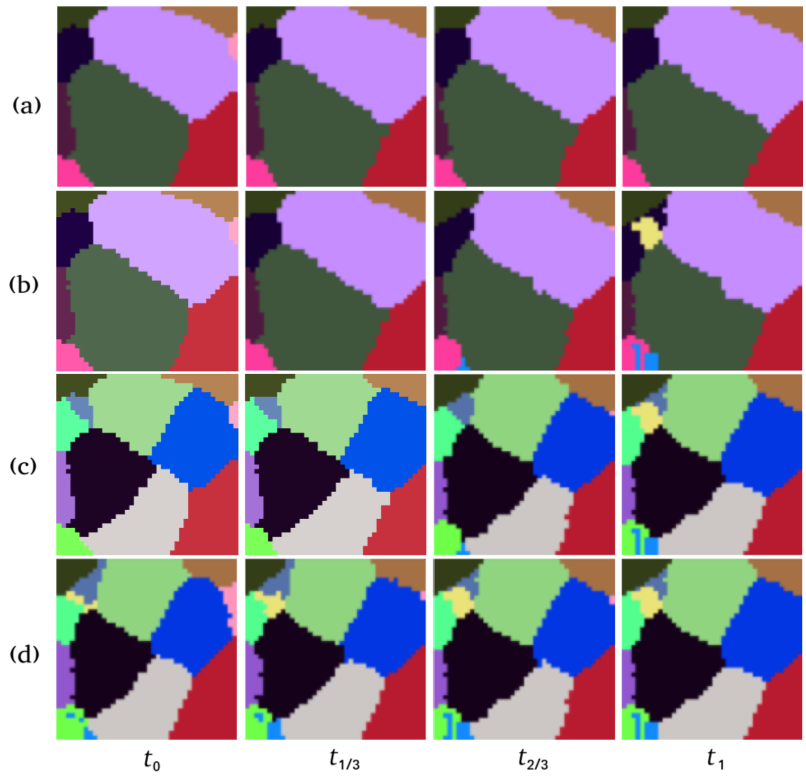

Figure 10. Images compounded of labeled regions at increasing time. (a) and (d) are the original sequences. One can see that the region borders of the corresponding groups of regions of these sequences do not superimpose perfectly. (b) and (c) are the images of transformed regions respectively from the sequences (a) and (d) so that the corresponding region borders superimpose perfectly with the constraint that the image of (a) at t_0 and the image of (d) at t_1 are not modified.

5.11. 3D/2D Coronary Arteries dynamic registration

Participants: Emmanuelle Poulain, Grégoire Malandain.

This work is made in collaboration with Régis Vaillant (GE-Healthcare, Buc, France) and Nicholas Ayache (Inria Asclepios team).

Integrating vessel information, extracted from pre-operative 3D CT angiography images, into a live fluoroscopic 2D sequence can greatly improve the guidance of percutaneous coronary interventions. We are developing a framework aiming at deformed a vessel 3D from the CT so that it moves along the cardiac cycle observed through the 2D angiographic sequence.

The vessel is approximated by a spline which will be deformed thanks to a gradient descent with a length constraint. The length preservation of the vessel allows us to provide a realistic movement, i.e any point will keep its curvilinear abscissa along the spline. This is exemplified by figure 11 where the vessel projection and a remarkable point is tracked at 3 different cardiac phases.

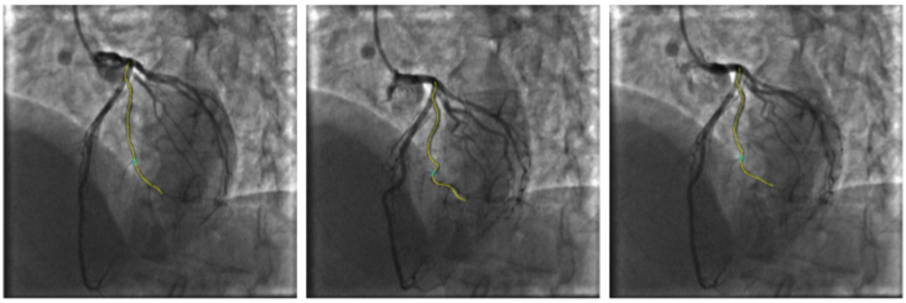

Figure 11. The 3 images show the projection of a 3D vessel in yellow and a remarkable point on the vessel (bifurcation) in blue at 3 different phases of the cardiac cycle.

5.12. Modelling axon growth from in vivo data

Participants: Agustina Razetti, Xavier Descombes, Caroline Medioni, Florence Besse.

During the first part of this work, we focused at identifying the main morphological features that allow to describe and discriminate genetically different Drosophila Gamma neurons, as well as to automatically assess a quantification of the overall morphological distance between them [8]. The second part, developed this year, approaches the process of neuron growth and morphogenesis in pupal stage. Important advances have already been achieved in identifying the main factors involved in neuron development. The next step that has to be done is concerning how we approach the question.

In this work we intend to close the gap between classic in vitro experimental assumptions and real in vivo situations, where the final neuronal morphology is acquired through a dynamic and environmental-dependent process. In particular, the branch formation process - how or why branches are created - has been belittled or over-simplified by neuron development models. In our opinion, this represents a constraint in the general understanding of neuron development, hierarchy of the neuronal tree and adult functionality.

Our goal is to bring light to the mechanisms of branch formation during development in realistic conditions. We study the particular case of Drosophila Gamma neuron remodeling and analyze, for the first time to our knowledge, the mechanical situation of a whole population of Gamma neurons (650 individuals) growing together in a constraint space (i.e. medial lobe of the Mushroom Body). We hypothesize that one kind of branches are born when the growing tip encounters a mechanical obstacle (i.e. other neurons or the lobe limits), enhancing the probability that at least one neurite reaches the end of the lobe. We model the neurites growth by a Gaussian Markov chain, and the parameters of the model –which account for axon elasticity and guiding cues attractiveness- are estimated from data.

Our database is composed by different sets –wild type and mutations- of confocal images of a single neuron that we treated, segmented and normalized. We show that the proposed mechanistic branch generation process is plausible, and explore unsolved problems concerning the understanding of some particular Gamma neuron mutation phenotypes. This approach allows us also to analyze dynamic aspects of the Gamma neuron collective growth process such as speed and density in function of space and time, which help to explain several characteristics of the Gamma neuron morphology and behavior during development. Figure 12 shows examples of wild type as well as imp mutant neurons of our database and contrasts them with neurons from simulations that are morphologically close.

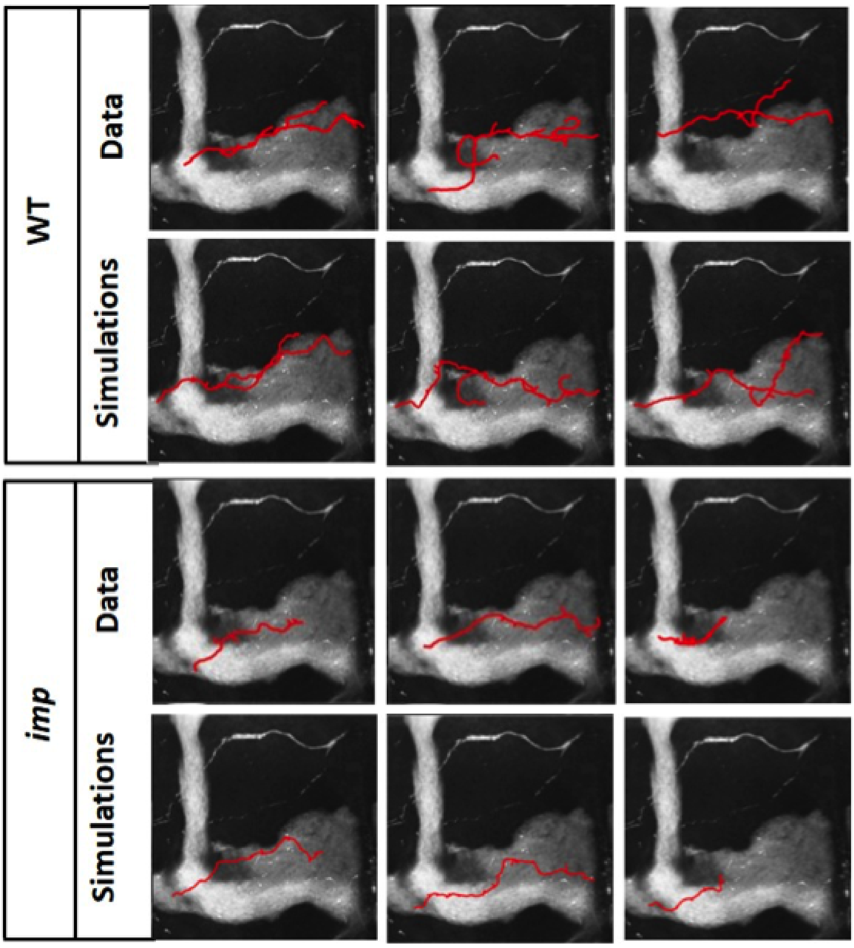

Figure 12. Wild type and imp mutant neurons from the database, contrasted to very similar neurons from our simulations.

6. Bilateral Contracts and Grants with Industry

6.1. 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. In December, we signed a collaboration contract with Bayer, Lyon, to fund a Master 2 internship with some overhead on the topic of automatic cell classification. The intern will start working on the subject in January 2017.

7. Partnerships and Cooperations

7.1. Regional Initiatives

7.1.1. LABEX SIGNALIFE

The MORPHEME team is member of the SIGNALIFE Laboratory of Excellence.

Florence Besse and Xavier Descombes are members of the Scientific Committee.

Florence Besse and Xavier Descombes participated in the selection committee for LabeX PhD program students.

7.2. National Initiatives

7.2.1. ANR RNAGRIMP

Participants: Florence Besse [PI], Xavier Descombes, Eric Debreuve, Djampa Kozlowski, Nicolas Cedilnik.

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.

7.2.2. 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.

7.2.3. 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.

7.2.4. ANR PhaseQuant

Participants: Grégoire Malandain, Eric Debreuve.

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.

7.2.5. Inria Large-scale initiative Morphogenetics

Participants: Grégoire Malandain, Xavier Descombes, Gaël Michelin.

This action gathers the expertise of three Inria research teams (Virtual Plants, Morpheme, and Evasion) and other groups (RDP (ENS-CNRS–INRA, Lyon), RFD (CEA-INRA-CNRS, Grenoble)) and aimed at understanding how shape and architecture in plants are controlled by genes during development. To do so, we will study the spatio-temporal relationship between genetic regulation and plant shape utilizing recently developed imaging techniques together with molecular genetics and computational modeling. Rather than concentrating on the molecular networks, the project will study plant development across scales. In this context we will focus on the Arabidopsis flower, currently one of the best-characterized plant systems.

7.2.6. 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).

7.3. European Initiatives

7.3.1. Collaborations in European Programs, Except FP7 & H2020

- COST Action (The COST Program is supported by the EU Framework Program H2020). We are part of a consortium of teams which submitted in December a COST Action proposal on machine learning and intelligent systems for the marine and aquatic sciences.

7.4. International Research Visitors

7.4.1. Visits of International Scientists

7.4.1.1. Internships

Mohammed Lamine Benomar, PhD, Université Abou Bekr Belkaid Tlemcen, Algérie, from October 2016 until April 2017.

Hibetallah Ouazaa, PhD, National Engineering School of Tunis, from May 2016 until Jun 2016

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. Member of the Organizing Committees

Florence Besse was a co-organizer of the SIgnalife Maths-Bio workshop (Sophia, Nov 2016)

8.1.2. Scientific Events Selection

8.1.2.1. Member of the Conference Program Committees

Laure Blanc-Féraud was associate editor of the workshops: New Computational Methods in Inverse Problems - NCMIP 2016 (NCMIP) in ENS Cachan, and Optimization Techniques for Inverse Problems III, Modena Italy 1-21 September 2016

Eric Debreuve: Advanced Concepts for Intelligent Vision Systems (ACIVS) and Reconnaissance des Formes et l'Intelligence Artificielle (RFIA)

Grégoire Malandain was in charge of a special session "Approches RF et vision en imagerie biologique et médicale" at RFIA.

8.1.2.2. Reviewer

Laure Blanc-Féraud was a reviewer for the conference ICIP.

Eric Debreuve was a reviewer for the conferences IEEE International Conference on Image Processing (ICIP) and International Symposium on Biomedical Imaging (ISBI)

Xavier Descombes was reviewer for the conferences ISBI, ICASSP and ICIP.

Grégoire Malandain was reviewer for the conferences EMBC, ISBI, ICPR, MICCAI, and the Second Workshop on BioImage Computing at ECCV 2016.

8.1.3. Journal

8.1.3.1. Member of the Editorial Boards

Laure Blanc-Féraud is Associate Editor of SIAM Journal Imaging Sciences and Traitement du Signal Journal.

Xavier Descombes is associated editor of DSP (Digital Signal Processing).

8.1.3.2. Reviewer - Reviewing Activities

Laure Blanc-Féraud was reviewer for the Journal Signal Processing.

Eric Debreuve was reviewer for the journals IEEE Transactions on Medical Imaging, Signal Processing: Image Communication (Elsevier), and Digital Signal Processing (Elsevier).

Xavier Descombes was reviewer for the journals IEEE on IP, Pattern Recognition and DSP.

Grégoire Malandain was reviewer for the journals CVIU NeuroImage and MedIA.

8.1.4. Invited Talks

Laure Blanc-Féraud was invited to give a talk at the workshops: NCMIP'16 in Cachan in May, ATLAS Workshop organized by the GdR MaDICS in Grenoble in May, and Optimization Techniques for Inverses Problems III in Modena Italy in September.

Xavier Descombes was invited to give a talk at the workshop “Mathématiques et Biologie” organized within the labex Signalife programm.

8.1.5. Leadership within the Scientific Community

Florence Besse is a member of the scientific council (CAC) of the University Cote d'Azur (UCA), a member of the scientific council of the IDEX JEDI Academy 2, and a member of the scientific council of the LabeX Signalife program.

Laure Blanc-Féraud is director of GdR 720 ISIS of CNRS, a group for the animation of research at national french level on the thematics Signal Image and Vision. This group includes around 160 academic laboratories and twenty industrial partners totaling almost 3,000 members. She heads the scientific committee of academy 1 of UCA (COMUE université Côte d'Azur) and Idex UCA JEDI.

Xavier Descombes is member of the Scientific Committee of the competitivness pole Optitech, member of IEEE BISP (Biomedical Imaging Signal Processing) Technical Committee and member of the Scientific Committee of Labex SIGNALIFE.

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.

8.1.6. Scientific Expertise

Laure Blanc-Féraud is part of the scientific committee of the Institut des Technologies Avancées en sciences du Vivant" (ITAV, USR CNRS 3505). She headed the HCERES expert committee (18 members) of LabSTICC Lab in Brest and headed the recruitment panel "Comité de sélection" of a MCF at University Paris Descartes in section 26. Sha was member of the scientific committee of the "rencontres du numériques" of ANR. She is expert member of the MIUR: Italian Ministry for Education, University and Research (Italy) and expert for the Fund for Scientific Research - FNRS (Belgium). She was expert for an application at a director of research position in ONERA DTIM.

Xavier Descombes is an expert for the DRRT within the CIR ("Crédit Impot Recherche") and JEI ("Jeunes Entreprise Innovantes") programs.

8.1.7. Research Administration

Laure Blanc-Féraud was member of the steering committee of the "défi 7" of the ANR. She was member of the CNRS admission for chargé de recherche at INS2I of CNRS. She is member of the academic council of UCA (COMUE université Côte d'Azur).

Xavier Descombes is member of the "comité des projets" and the "comité de centre" of Inria CRI-SAM.

Grégoire Malandain is the head of the committee "Comité de suivi doctoral" of the Inria CRI-SAM.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Master: Florence Besse, Genetic control of neuronal branching, 2h, Université Côte d'Azur, France.

Master: Florence Besse, Dissection of neuronal circuits, 4h, Université Côte d'Azur, France.

Master: Florence Besse, Post-transcriptional regulation of neuronal development and maturation, 2h, Nancy, France.

Master : Laure Blanc-Féraud, Fluorescence image restoration, 18h Eq. TD, M2 Computational Biology , University Nice Sophia Antipolis, France.

Master : Laure Blanc-Féraud, Traitement numérique des images, 12h Eq. TD, M2 VIM , EPU University Nice Sophia Antipolis, France.

Master/Engineer: Eric Debreuve, Data Mining, 27.5h équivalent TD, M2/Engineer 5th year, Université Côte d'Azur, France

Master: Eric Debreuve, Introduction to Inverse Problems in Image Processing, 28.5h équivalent TD, International M2, Université Côte d'Azur, France

Master: Xavier Descombes, Traitement d'images, Analyse de données, Techniques avancées de traitement d'images, 10h Eq. TD, Niveau M2, ISAE, France.

Master: Xavier Descombes, Traitement d'images, master 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: Gaël Michelin, Traitement Numérique des Images, 8h Eq. TD, Niveau M2, EPU, Université Côte d'Azur, France.

IUT : A. Razetti, initiation à la mesure du signal, 30h Eq. TD, IUT Nice Côte d'Azur, Université Côte d'Azur, France.

Licence : Emmanuel Soubies, Images et Filtres, 54h Eq.TD, Niveau L3 , EPU, Université Côte d'Azur, France.

8.2.2. Supervision

PhD: Emmanuel Soubies, Sur quelques problèmes de reconstruction en imagerie MA-TIRF et en optimisation parcimonieuse par relaxations continue exacte de critères pénalisés en norme ℓ_0, Université Côte d'Azur, 14 october 2016.

PhD: Gaël Michelin, Outils d'analyse d'images et recalage d'individus pour l'étude de la morphogénèse animale et végétale, 28 october 2016.

PhD in progress: Lola Baustista, DIC microscopy image reconstruction, 1st november 2013, Laure Blanc-Féraud.

PhD in progress: Agustina Razetti, Modelling and characterizing axon growth from in vivo data, 1st november 2014, Xavier Descombes (advisor), Florence Besse (co-supervisor).

PhD in progress: Emmanuelle Poulain, Fluoroscopy/CTA dynamic registration, 1st february 2016, Grégoire Malandain.

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.

8.2.3. Internships

Nicolas Cedilnik: M1 BIM, UNS, Small particle detection. Supervisors: X. Descombes.

Simon Gazagnes: M2 INSA Lyon. Sparse 3D reconstruction for TIRF-PALM Imaging. Supervisors: L. Blanc-Féraud, E. Soubies.

Djampa Kozlowski: M2 BIM, UNS, Nuclei detection and classification in genome-wide RNAi screens. Supervisors: X. Descombes, F. Besse, F. de Graeve (iBV).

Raphaël Meunier: M1 INSA Toulouse. Classification of the extracellular matrix. Supervisors: X. Descombes, L. Blanc-Féraud.

8.2.4. Juries

Laure Blanc-Féraud participated to the PhD thesis committee of Sébastien Combrexelles (IRIT Toulouse), as reviewer of the HDR of Gabriele Facciolo (ENS Cachan) and reviewer of the 2 PhD thesis: Fred NGole MBoula (CEA Saclay), Meriem Ben Abdallah (CRAN Nancy).

Xavier Descombes participated to the PhD thesis committee of A. Sarr (Univ. de Bretagne)

Grégoire Malandain participated as chair to the PhD thesis committee of D. Chen (Paris Dauphine univ.), G. Michelin (Côte d'Azur univ.) as reviewer to the PhD thesis committee of O. Merveille (Paris Est univ.), A. Sironi (EPFL), and as committee head to the PhD thesis committee of P. Samarakoon (Grenoble Alpes univ.).

8.3. Popularization

Xavier Descombes was invited to give a talk at "La fête de la science" in Juan Les Pins.

The Morpheme team has animated a stand during the "fête de la science" in Juan Les Pins.

9. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journal

[1] X. Descombes.*Multiple objects detection in biological images using a marked point process framework*, in "Methods", 2016 [*DOI :* 10.1016/j.ymeth.2016.09.009], https://hal.inria.fr/hal-01383165.

[2] A. Halimi, P. Honeine, M. Kharouf, C. Richard, J.-Y. Tourneret.*Estimating the Intrinsic Dimension of Hyperspectral Images Using a Noise-Whitened Eigengap Approach*, in "IEEE Transactions on Geoscience and Remote Sensing", July 2016, vol. vol. 54, n^{o} n° 7, p. 3811-3821 [*DOI :* 10.1109/TGRS.2016.2528298], https://hal.archives-ouvertes.fr/hal-01325467.

[3] E. Soubies, L. Blanc-Féraud, G. Aubert.*ERRATUM: A Continuous Exact l0 penalty (CEL0) for least squares regularized problem*, in "SIAM J. on Imaging Science (SIIMS)", March 2016, vol. 9, n^{o} 1, p. 490–494. [*DOI :* 10.1137/15M1038384], https://hal.inria.fr/hal-01267679.

Invited Conferences

[4] L. Blanc-Féraud, E. Soubies, G. Aubert.*Some results on sparse L2-L0 reconstruction: Continuous Exact L0 penalties*, in "NCMIP 2016 - New Computational Methods for Inverse Problem", Cachan, France, ENS Cachan, April 2016, https://hal.inria.fr/hal-01349670.

[5] L. Blanc-Féraud, E. Soubies, G. Aubert.*Some results on sparse L2-L0 reconstruction: Continuous Exact L0 penalties*, in "Workshop ATLAS on mathematical and algorithmimcal approaches for high dimensional problems in data sciences", Grenoble, France, GdR MaDICS, May 2016, https://hal.archives-ouvertes.fr/hal-01358112.

International Conferences with Proceedings

[6] L. BAUTISTA, S. REBEGOLDI, L. BLANC-FÉRAUD, M. PRATO, L. ZANNI, A. PLATA.*Phase Estimation in Differential-Interference-Contrast (DIC) Microscopy*, in "IEEE International Symposium on Biomedical Imaging (ISBI)", Prague, Czech Republic, April 2016, p. 136-139, https://hal.inria.fr/hal-01255004.

[7] G. MICHELIN, Y. REFAHI, R. WIGHTMAN, H. JÖNSSON, J. J. TRAAS, C. GODIN, G. MALANDAIN.*Spatio-temporal registration of 3D microscopy image sequences of Arabidopsis floral meristems*, in "ISBI - International Symposium on Biomedical Imaging", Prague, Czech Republic, April 2016 [*DOI :* 10.1109/ISBI.2015.7163872], https://hal.inria.fr/hal-01251151.

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[9] E. SOUBIES, S. SCHAUB, A. RADWANSKA, E. VAN OBBERGHEN-SCHILLING, L. BLANC-FÉRAUD, G. AUBERT.*A Framework for Multi-angle Tirf Microscope Calibration*, in "ISBI - International Symposium on Biomedical Imaging", Prague, Czech Republic, IEEE, April 2016, 4 [*DOI :* 10.1109/ISBI.2016.7493355], https://hal.inria.fr/hal-01257736.

[10] A. ZUBIOLO, E. DEBREUVE, D. AMBROSETTI, P. POGNONEC, X. DESCOMBES.*Is the Vascular Network Discriminant Enough to Classify Renal Cell Carcinoma?*, in "International Workshop on Content-based Multimedia Indexing (CBMI)", Bucarest, Romania, June 2016 [*DOI :* 10.1109/CBMI.2016.7500255], https://hal.archives-ouvertes.fr/hal-01344247.

Conferences without Proceedings

[11] S. REBEGOLDI, L. BAUTISTA, L. BLANC-FÉRAUD, M. PRATO, L. ZANNI, A. PLATA.*Accelerated gradient-based methods for phase estimation in differential-interference-contrast microscopy*, in "SIMAI 2016: Società Italiana di Matematica Aplicata e Industriale", Milan, Italy, September 2016, https://hal.inria.fr/hal-01426330.

[12] S. REBEGOLDI, L. BAUTISTA, M. PRATO, L. ZANNI, L. BLANC-FÉRAUD, A. PLATA.*An efficient gradient-based method for differential-interference-contrast microscopy*, in "NUMTA 2016: Numerical Computations: Theory and Algorithms", Calabria, Italy, June 2016, https://hal.inria.fr/hal-01426337.

Other Publications

[13] Y. QUÉAU, R. MECCA, J.-D. DUROU, X. DESCOMBES.*Photometric Stereo with Only Two Images: A Theoretical Study and Numerical Resolution*, November 2016, working paper or preprint [*DOI :* 10.1016/J.IMAVIS.2016.11.006], https://hal.archives-ouvertes.fr/hal-01334657.

[14] S. REBEGOLDI, L. BAUTISTA, L. BLANC-FÉRAUD, M. PRATO, L. ZANNI, A. PLATA.*Optimization methods for phase estimation in differential-interference-contrast (DIC) microscopy*, September 2016, Workshop on Optimization Techniques for Inverse Problems III, Poster, https://hal.inria.fr/hal-01426317.

[15] E. SOUBIES, L. BLANC-FÉRAUD, G. AUBERT.*A unified view of exact continuous penalties for l2-l0 minimization*, February 2016, working paper or preprint, https://hal.inria.fr/hal-01267701.

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

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Project-Team NACHOS

Creation of the Project-Team: 2007 July 01

Keywords:

Computer Science and Digital Science:

6.2.1. - Numerical analysis of PDE and ODE
6.2.7. - High performance computing

Other Research Topics and Application Domains:

5.3. - Nanotechnology
5.5. - Materials

1. Members

Research Scientists

Loula Fezoui [Inria, Senior Researcher]
Marie-Hélène Lallemand Tenkes [Inria, Researcher]
Stephane Lanteri [Team leader, Inria, Senior Researcher, HDR]

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Claire Scheid [LJAD, Université Nice Sophia Antipolis, Associate Professor]

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Tristan Cabel [Inria, ADT SIMON, until Aug 2016]
Raphaël Léger [Inria, granted by FP7 HPC4E project]
Ludovic Moya [Inria, granted by FP7 PRACE-4IP project]
Jonathan Viquerat [Inria, ADT DIOGENeS]

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Alexis Gobé [Inria, from Nov 2016]
Nikolai Schmitt [Université Nice Sophia Antipolis]
Van Hieu Nguyen [Université Nice Sophia Antipolis]

Post-Doctoral Fellow

Alexandra Christophe Argenvillier [Inria, until Oct 2016]

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Liang Li [UESTC, Chengdu, China, from Mar 2016 until Feb 2017]
Hao Wang [UESTC, Chengdu, China, Visiting PhD student, from Sep 2015 until Aug 2017]
Antonio Tadeu Gomez [LNCC, Petropolis, Brazil, from Dec 2016 until Feb 2017]
Frédéric Valentin [LNCC, Petropolis, Brazil, from Dec 2016 until Feb 2017]

Administrative Assistant

Montserrat Argente [Inria]

Others

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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 [49] 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 [54] 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 [44] 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 [53] 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 [41]- [42]- [43]- [48]:

- 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 [13]. 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 [10]-[11] and hybrid structured/unstructured meshes [6], their coupling with hybrid explicit/implicit time integration schemes in order to improve their efficiency in the context of locally refined meshes [4]-[19]-[18]. A high order DG method has also been proposed for the numerical resolution of the elastodynamic equations modeling the propagation of seismic waves [2]-[9].

- **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 [8]. 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.*[46] 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 [15]-[16].
- **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 [4]-[19]-[18] 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 [14]. 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 [21]. In the context of seismic wave propagation, we are interested by the intrinsic attenuation of the medium [20]. 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

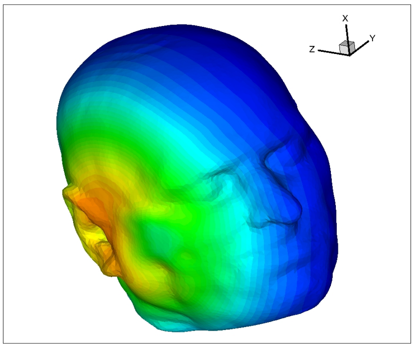
Two main reasons motivate our commitment to consider this type of problem for the application of the numerical methodologies developed in the NACHOS project-team:

- 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 [54]. 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 [12].

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



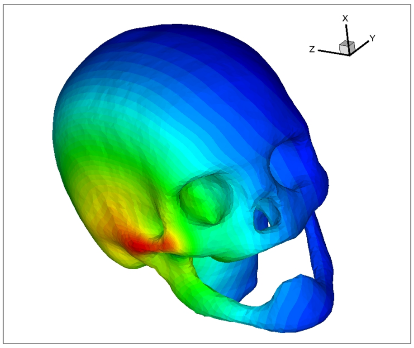


Figure 1. Exposure of head tissues to an electromagnetic wave emitted by a localized source. Top figures: surface triangulations of the skin and the skull. Bottom figures: contour lines of the amplitude of the electric field.

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 [47]- [55].

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 [52]. 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 [50]- [51]- [45]. 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.

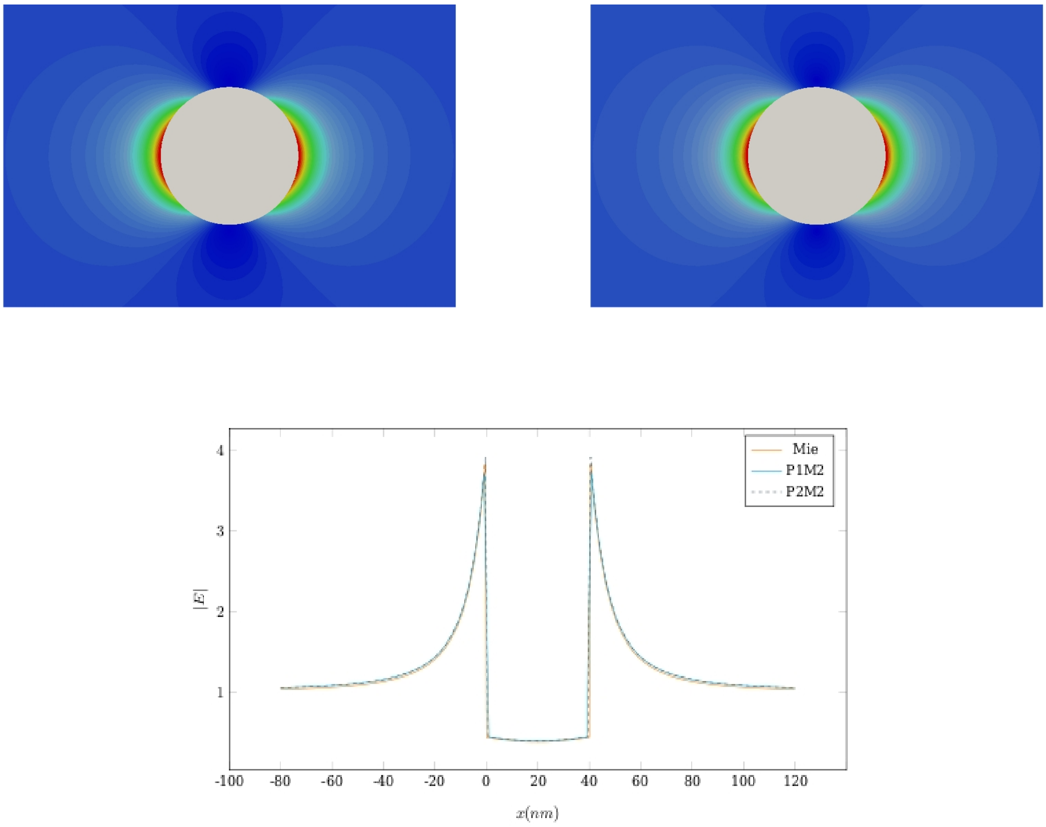


Figure 2. Scattering of a 20 nanometer radius gold nanosphere by a plane wave. The gold properties are described by a Drude dispersion model. Modulus of the electric field in the frequency-domain. Top left figure: Mie solution. Top right figure: numerical solution. Bottom figure: 1d plot of the electric field modulus for various orders of approximation (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, in particular in the context of 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 [53] and based on the first order velocity-stress hyperbolic system of elastic waves equations, which is an extension of the scheme derived by Yee [54] 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 initiated a close collaboration with CETE Méditerranée http://www.cete-mediterranee.fr/gb which is a regional technical and engineering centre whose activities are concerned with seismic hazard assessment studies, and IFSTTAR http://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.

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.

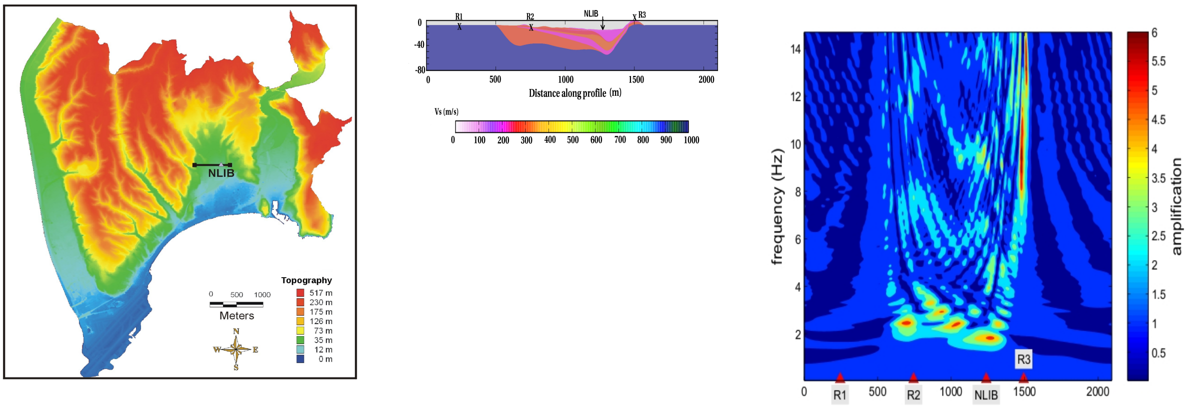


Figure 3. Propagation of a plane wave in a heterogeneous model of Nice area (provided by CETE Méditerranée). Left figure: topography of Nice and location of the cross-section used for numerical simulations (black line). Middle figure: S-wave velocity distribution along the cross-section in the Nice basin. 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).

5. New Software and Platforms

5.1. DIOGENeS

DIscOntinuous GalErkin Nanoscale Solvers
KEYWORDS: High-Performance Computing - Computational electromagnetics - Discontinuous Galerkin - Computational nanophotonics
FUNCTIONAL DESCRIPTION

DIOGENeS is a software suite dedicated to the numerical modeling of light interaction with nanometer scale structures with applications to nanophotonics and nanoplasmonics. DIOGENeS relies on a two layer architecture. The core of the suite is a library of generic software components (data structures and algorithms) for the implementation of high order DG (Dicontinuous Galerkin) and HDG (Hybridizable Dicontinuous Galerkin) schemes formulated on unstructured tetrahedral and hybrid structured/unstructured (cubic/tetrahedral) meshes. This library is used to develop dedicated simulation software for time-domain and frequency-domain problems relevant to nanophotonics and nanoplasmonics, considering various material models.

- Contact: Stéphane Lanteri
- URL: http://www-sop.inria.fr/nachos/index.php/Software/DIOGENeS

5.2. GERShWIN

discontinuous GalERkin Solver for microWave INteraction with biological tissues
KEYWORDS: High-Performance Computing - Computational electromagnetics - Discontinuous Galerkin - Computational bioelectromagnetics
FUNCTIONAL DESCRIPTION

GERShWIN is based on a high order DG method formulated on unstructured tetrahedral meshes for solving the 3D system of time-domain Maxwell equations coupled to a Debye dispersion model.

- Contact: Stéphane Lanteri
- URL: http://www-sop.inria.fr/nachos/index.php/Software/GERShWIN

5.3. HORSE

High Order solver for Radar cross Section Evaluation

KEYWORDS: High-Performance Computing - Computational electromagnetics - Discontinuous Galerkin

FUNCTIONAL DESCRIPTION

HORSE is based on a high order HDG (Hybridizable Discontinuous Galerkin) method formulated on unstructured tetrahedral and hybrid structured/unstructured (cubic/tetrahedral) meshes for the discretization of the 3D system of frequency-domain Maxwell equations, coupled to domain decomposition solvers.

- 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. Numerical study of the non-linear Maxwell equations for Kerr media

Participants: Loula Fezoui, Stéphane Lanteri.

The system of Maxwell equations describes the evolution of the interaction of an electromagnetic field with a propagation medium. The different properties of the medium, such as isotropy, homogeneity, linearity, among others, are introduced through *constitutive laws* linking fields and inductions. In the present study, we focus on non-linear effects and address non-linear Kerr materials specifically. In this model, any dielectric may become non-linear provided the electric field in the material is strong enough. As a first setp, we considered the one-dimensional case and study the numerical solution of the non-linear Maxwell equations thanks to DG methods. In particular, we make use of an upwind scheme and limitation techniques because they have a proven ability to capture shocks and other kinds of singularities in the fluid dynamics framework. The numerical results obtained in this preliminary study gave us confidence towards extending them to higher spatial dimensions. This year, we have completed the development of a first version a parallel DGTD solver for the three-dimensional based on our past contributions on DGTD methods for the case of linear propagation media.

6.1.2. Numerical treatment of non-local dispersion for nanoplasmonics

Participants: Stéphane Lanteri, Claire Scheid, 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 can be excited and cause extreme local field enhancements (surface plasmon polariton electromagnetic waves). 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 effects due to electron collisions have to be taken into account. Non-locality leads to additional, in general non-linear, partial differential equations and is significantly more difficult to treat, though. In this work, we study a DGTD method able to solve the system of Maxwell equations coupled to a linearized non-local dispersion model relevant to nanoplasmonics. This year, we have developed a parallel DGTD solver for the three-dimentional Maxwell equations coupeld to a non-local Drude model. Both centered flux-based and upwind flux-based DG schemes have been considered, in combination with with leap-frog and Runge-Kutta time stepping respectively.

6.1.3. Corner effects in nanoplasmonics

Participants: Camille Carvalho [ENSTA, POEMS project-team], Patrick Ciarlet [ENSTA, POEMS project-team], Claire Scheid.

In this work, we study nanoplasmonic structures with corners (typically a diedral/truangular 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. Travelling waves for the non-linear Schrödinger equation in 2D

Participants: David Chiron [J.A. Dieudonné Laboratory, Université Nice Sophia Antipolis], Claire Scheid, Serge Nicaise [Université de Valenciennes et du Hainaut-Cambrésis], Claire Scheid.

We are interested in the numerical study of the two-dimensional travelling waves of the non-linear Schrödinger equation for a general non-linearity and with nonzero condition at infinity. This equation is appearing in models of nonlinear optics. It has a variational structure that we propose to exploit to design a numerical method. We continue the sudy initiated in [1] and investigate excited states of the Kadomtsev-Petviashvili-I (KP-I) and Gross-Pitaevskii (GP) equations in dimension 2. We address numerically the question of the Morse index of some explicit solutions of KP-I. The results confirm that the lump solitary wave has Morse index one and that the other explicit solutions correspond to excited states. We then turn to the 2D GP equation which in some long wave regime converges to the KP-I equation. We finally perform numerical simulations showing that the other explicit solitary waves solutions to the KP-I equation give rise to new branches of travelling waves of GP corresponding to excited states.

In this ongoing work, we are interested in fundamental properties of the non local linearized hydrodynamic Drude model introduced in the context of nanoplasmonics. We propose an existence and detailed (polynomial/exponential) stability study for these models. We also investigate the discrete stability results. We propose to study the impact of the DG schemes developped in the team on these properties. This study complements the numerical approach that we already propose in the context of the PhD of Nikolai Schmitt for this model, towards a thorough understanding of its fundamentals properties.

6.1.5. A structure preserving numerical discretization framework for the Maxwell Klein Gordon equation in 2D.

Participants: Snorre Christiansen [Department of Mathematics, University of Oslo, Norway], Claire Scheid.

Toward a better understanding of non-linear optical phenomena, we focus on the case of the Maxwell Klein Gordon (MKG) equation in dimension 2. This equation appears in the context of quantum electrodynamics but also in relativity. We propose to develop a numerical discretization framework that takes advantage of the Hamiltonian structure of the equation. The gauge invariance is recovered at the discrete level with the help of the Lattice Gauge theory. We then propose a fully discrete scheme and prove its convergence. The strategy of proof, based on discrete energy principle, is developed in a more general context and next applied in the particular case of MKG equation. This work has been conducted and finalized during a of five month's stay of C. Scheid at the University of Oslo through an invitation in the contexty of the ERC Starting Grant project STUCCOFIELD of S. Christiansen.

6.1.6. Multiscale DG methods for the time-domain Maxwell equations

Participants: Stéphane Lanteri, Raphaël Léger, Diego Paredes Concha [Instituto de Matemáticas, Universidad Católica de Valparaiso, Chile], Claire Scheid, Frédéric Valentin [LNCC, Petropolis, Brazil].

Although the DGTD method has already been successfully applied to complex electromagnetic wave propagation problems, its accuracy may seriously deteriorate on coarse meshes when the solution presents multiscale or high contrast features. In other physical contexts, such an issue has led to the concept of multiscale basis functions as a way to overcome such a drawback and allow numerical methods to be accurate on coarse meshes. The present work, which is conducted in the context of the HOMAR Associate Team, is concerned with the study of a particular family of multiscale methods, named Multiscale Hybrid-Mixed (MHM) methods. Initially proposed for fluid flow problems, MHM methods are a consequence of a hybridization procedure which caracterize the unknowns as a direct sum of a coarse (global) solution and the solutions to (local) problems with Neumann boundary conditions driven by the purposely introduced hybrid (dual) variable. As a result, the MHM method becomes a strategy that naturally incorporates multiple scales while providing solutions with high order accuracy for the primal and dual variables. The completely independent local problems are embedded in the upscaling procedure, and computational approximations may be naturally obtained in a parallel computing environment. In this study, a family of MHM methods is proposed for the solution of the time-domain Maxwell equations where the local problems are discretized either with a continuous FE method or a DG method (that can be viewed as a multiscale DGTD method). Preliminary results have been obtained in the two-dimensional case.

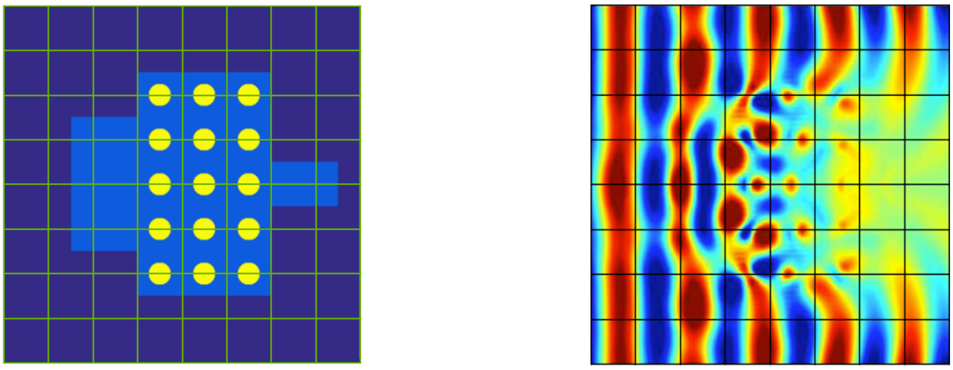


Figure 4. Light propagation in a photonic crystal structure using a MHM-DGTD method for solving the 2D Maxwell's equations. Left: quadrangular mesh. Right: contour lines of the amplitude of the electric field.

6.1.7. HDG methods for the time-domain Maxwell equations

Participants: Alexandra Christophe-Argenvillier, Stéphane Descombes, Stéphane Lanteri.

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.

6.1.8. HDG methods for the frequency-domain Maxwell equations

Participants: Alexis Gobé, Stéphane Lanteri, Ludovic Moya.

In the context of the ANR TECSER project, we continue our efforts towards the development of scalable high order HDG methods for the solution of the system of 3D frequency-domain Maxwell equations. We aim at fully exploiting the flexibiity of the HDG discretization framework with regards to the adaptation of the interpolation order (p-adaptivity) and the mesh (h-adaptivity). In particular, we study the formulation of

HDG methods on a locally refined non-conforming tetrahedral mesh and on a non-confoming hybrid cubic/tetrahedral mesh. We also investigate the coupling between the HDG formulation and a BEM (Boundary Element Method) discretization of an integral representation of the electromagnetic field in the case of propagation problems theoretically defined in unbounded domains. The associated methodological contributions are implemented in the HORSE simulation software.

6.1.9. HDG methods for the frequency-domain plasmonics

Participants: Stéphane Lanteri, Liang Li [UESTC, Chengdu, China], Asger Mortensen [DTU Fotonik, Technical University of Denmark], Martijn Wubs [DTU Fotonik, Technical University of Denmark].

In this colleaboration with physicists at DTU Fotonik, we study HDG methods for solving the frequency-domain Maxwell's equations coupled to the Nonlocal Hydrodynamic Drude (NHD) and Generalized Nonlocal Optical Response (GNOR) models, which are employed to describe the optical properties of nanoplasmonic scatterers and waveguides. The formulations of the HDG method for these two models are exetnsion of our previous works for classical microwave applications. In teh present case, two conservativity conditions are globally enforced to make the problem solvable and to guarantee the continuity of the tangential component of the electric field and the normal component of the current density. Numerical results show that the proposed HDG methods converge at optimal rate. These new HDG formulations hace been implemented and numerically assessed for two-dimensional problems.

6.1.10. Exponential time integrators for a DGTD method

Participants: Stéphane Descombes, Stéphane Lanteri, Bin Li [UESTC, Chengdu, China], Hao Wang [UESTC, Chengdu, China], Li Xu [UESTC, Chengdu, China].

The objective of this study is to design efficient and (high order) accurate time integration strategies for the system of time-domain Maxwell equations discretized in space by a high order discontinuous Galerkin scheme formulated on locally refined unstructured meshes. A new family of implicit-explicit (IMEX) schemes using exponential time integration is developed. The Lawson procedure is applied based on a partitioning of the underlying tetrahedral mesh in coarse and fine parts, allowing the contruction of a time advancing strategy that combines an exact integration of the semi-discrete system for the problem unknowns associated to the elements of the fine part, with an arbitrary high order explicit time integration scheme for the Lawson-transformed system.

6.2. Elastodynamic wave propagation

6.2.1. HDG method for the frequency-domain elastodynamic equations

Participants: Hélène Barucq [MAGIQUE-3D project-team, Inria Bordeaux - Sud-Ouest], Marie Bonnasse, Julien Diaz [MAGIQUE-3D project-team, Inria Bordeaux - Sud-Ouest], Stéphane Lanteri.

One of the most used seismic imaging methods is the full waveform inversion (FWI) method which is an iterative procedure whose algorithm is the following. Starting from an initial velocity model, (1) compute the solution of the wave equation for the N sources of the seismic acquisition campaign, (2) evaluate, for each source, a residual defined as the difference between the wavefields recorded at receivers on the top of the subsurface during the acquisition campaign and the numerical wavefields, (3) compute the solution of the wave equation using the residuals as sources, and (4) update the velocity model by cross correlation of images produced at steps (1) and (3). Steps (1)-(4) are repeated until convergence of the velocity model is achieved. We then have to solve $2N$ wave equations at each iteration. The number of sources, N, is usually large (about 1000) and the efficiency of the inverse solver is thus directly related to the efficiency of the numerical method used to solve the wave equation. Seismic imaging can be performed in the time-domain or in the frequency-domain regime. In this work which is conducted in the framework of the Depth Imaging Partnership (DIP) between Inria and TOTAL, we adopt the second setting. The main difficulty with frequency-domain inversion lies in the solution of large sparse linear systems which is a challenging task for realistic 3D elastic media, even with the progress of high performance computing. In this context, we study novel high order HDG methods formulated on unstructured meshes for the solution of the frency-domain elastodynamic equations. Instead of solving a linear system involving the degrees of freedom of all volumic cells of the mesh, the principle of a HDG formulation is to introduce a new unknown in the form of Lagrange multiplier representing the trace of the numerical solution on each face of the mesh. As a result, a HDG formulation yields a global linear system in terms of the new (surfacic) unknown while the volumic solution is recovered thanks to a local computation on each element.

6.2.2. Multiscale DG methods for the time-domain elastodynamic equations

Participants: Marie-Hélène Lallemand, Raphaël Léger, 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.

6.3. High performance numerical computing

6.3.1. Poring a DGTD solver for bioelectromagnetics to the DEEP-ER architecture

Participants: Alejandro Duran [Barcelona Supercomputing Center, Spain], Stéphane Lanteri, Raphaël Léger, Damian A. Mallón [Juelich Supercomputing Center, Germany].

We are concerned here with the porting of the GERShWIN DGDT solver for computational bioelectromagnetics to the novel heterogeneous architecture proposed in the DEEP-ER european project on exascale computing. This architecture is based on a Cluster/Booster division concept (see Fig. 5). The Booster nodes are based on the Intel Many Integrated Core (MIC) architecture. Therfore, one objective of our efforts is the algorithmic adaptation of the DG kernels in order to leverage the vectorizing capabilities of the MIC processor. The other activities that are undertaken in the context of our contribution to this project aim at exploiting the software environments and tools proposed by DEEP-ER partners for implementing resiliency strategies and high performance I/O operations. In particular, the Cluster nodes are used for running some parts of the pre- and post-processing phases of the DGTD solver which do not lend themselves well to multithreading, as well as I/O intensive routines. One possibility to achieve this is to consider a model in which these less scalable and I/O phases are reverse-offloaded from Booster processes to Cluster processes in a one-to-one mapping. This is achieved by exploiting the OmpSs offload functionality, developed at Barcelona Supercomputing Center for the DEEP-ER platform.

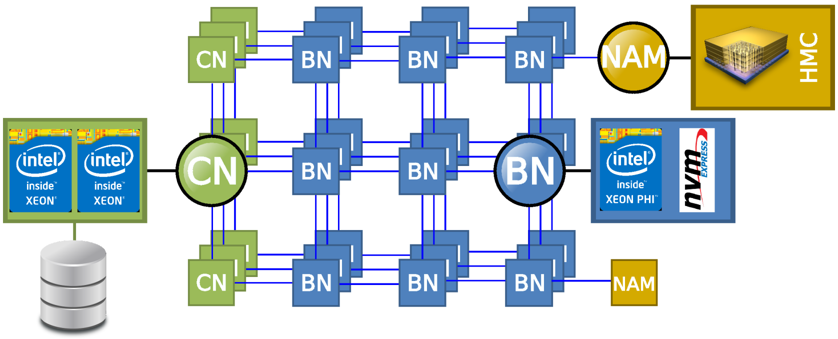


Figure 5. DEEP-ER hardware architecture sketch.

6.3.2. High order HDG schemes and domain decomposition solvers for frequency-domain electromagnetics

Participants: Emmanuel Agullo [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, Ludovic Moya, Olivier Rouchon [CINES, Montpellier].

This work is undertaken in the context of the ANR TECSER project on one hand, and PRACE 4IP project on the other hand, and is concerned with 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 use the MaPHyS (Massively Parallel Hybrid Solver) developed in the HIEPACS project-team at Inria Bordeaux - Sud-Ouest.

6.4. Applications

6.4.1. Light diffusion in nanostructured optical fibers

Participants: Wilfried Blanc [Optical Fibers team, LPMC, Université Nice Sophia Antipolis, Nice], Stéphane Lanteri, Paul Loriot, Claire Scheid.

Optical fibers are the basis for applications that have grown considerably in recent years (telecommunications, sensors, fiber lasers, etc.). Despite these undeniable successes, it is necessary to develop new generations of amplifying optical fibers that will overcome some limitations typical of silica. In this sense, the amplifying Transparent Glass Ceramics (TGC), and particularly the fibers based on this technology, open new perspectives that combine the mechanical and chemical properties of a glass host and the augmented spectroscopic properties of embedded nanoparticles, particularly rare earth-doped oxide nanoparticles. Such rare earth-doped silica-based optical fibers with transparent glass ceramic (TGC) core are fabricated by the Optical Fibers team of the Laboratory of Condensed Matter Physics (LPMC) in Nice. The objective of this collaboration with Wilfried Blanc at LPMC is the study of optical transmission terms of loss due to scattering through the numerical simulation of light propagation in a nanostructured optical fiber core using a high order DGTD method developed in the team.

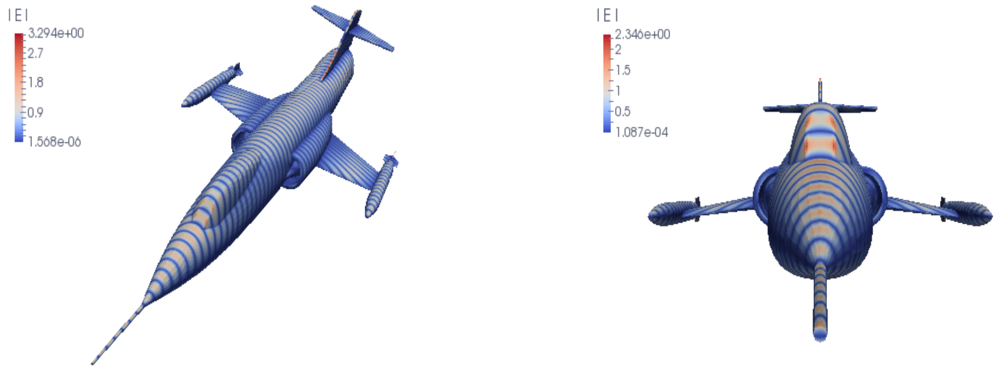


Figure 6. Scattering of a plane wave by a Lockheed F-104 Starfighter. Contour lines of the amplitude of the electric field. Simulations are performed with a HDG scheme based on a cubic interpolation of the electric and magnetic field unknowns, combined with a PDE-based domain decomposition solver.

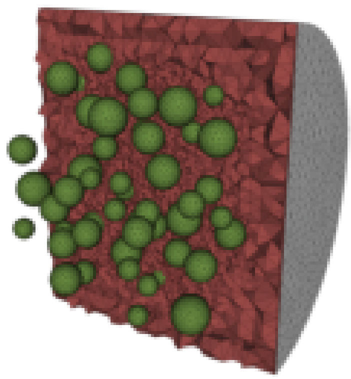


Figure 7. Unstructured tetrahdral mesh of a nanostructured optical fiber core.

6.4.2. Gap-plasmon confinement with gold nanocubes

Participants: Stéphane Lanteri, Antoine Moreau [Institut Pascal, Université Blaise Pascal], Claire Scheid, 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. 8). The behavior of single nanocubes on metallic plates has been simulated, for lateral sizes c ranging from 50 to 80 nm, and spacer thicknesses δ from 3 to 22 nm. The absorption efficiency in the cube Q_{cube} at the resonance frequency is retrieved from the results of each computation (see Fig. 9).

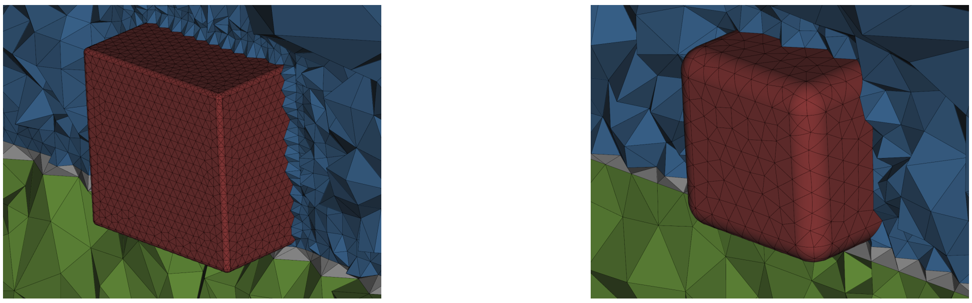
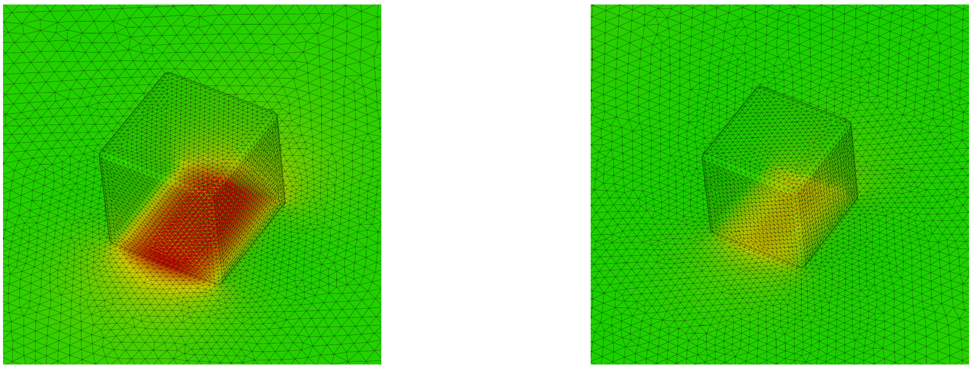


Figure 8. Meshes of rounded nanocubes with rounding radii ranging from 2 to 10 nm. Red cells correspond to the cube. The latter lies on the dielectric spacer (gray cells) and the metallic plate (green). Blue cells represent the air surrounding the device.

6.4.3. Dielectric reflectarrays

Participants: Maciej Klemm [Centre for Communications Research, University of Bristol], Stéphane Lanteri, Claire Scheid, Jonathan Viquerat.

In the past few years, important efforts have been deployed to find alternatives to on-chip, low-performance metal interconnects between devices. Because of the ever-increasing density of integrated components, intra- and inter-chip data communications have become a major bottleneck in the improvement of information processing. Given the compactness and the simple implantation of the devices, communications *via* free-space optics between nanoantenna-based arrays have recently drawn more attention. Here, we focus on a specific low-loss design of dielectric reflectarray (DRA), whose geometry is based on a periodic repartition of dielectric cylinders on a metallic plate. When illuminated in normal incidence, specific patterns of such resonators provide a constant phase gradient along the dielectric/metal interface, thus altering the phase of the incident wavefront. The gradient of phase shift generates an effective wavevector along the interface, which



$c = 70$ nm, $\delta = 12$ nm $c = 60$ nm, $\delta = 18$ nm

Figure 9. Amplitude of the discrete Fourier transform of the magnetic field for different nanocube configurations. All field maps are scaled identically for better comparison. The obtained field is more intense for configurations that yield high Q_{cube} values.

is able to deflect light from specular reflection. However, the flaws of the lithographic production process can lead to discrepancies between the ideal device and the actual resonator array. Here, we propose to exploit our DGTD solver to study the impact of the lithographic flaws on the performance of a 1D reflectarray (see Fig. 10). Efficient computations are obtained by combining high-order polynomial approximation with curvilinear meshing of the resonators, yielding accurate results on very coarse meshes (see Fig. 11). The study is continued with the computation of the reflection of a 2D reflectarray. This work constitutes the base of a wider study in collaboration with Maciej Klemm at the Centre for Communications Research, University of Bristol.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. Nucletudes

Participants: Patrick Breuilh [Nuclétudes, Les Ulis, France], Alexis Gobé, Stéphane Lanteri.

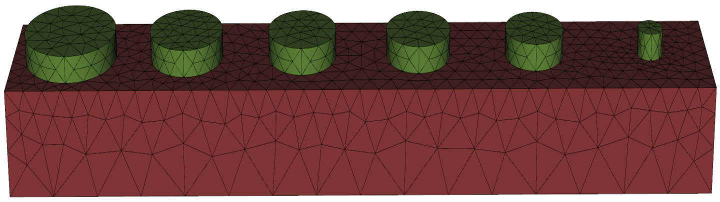
The objective of this collaboration with the Nucletudes company that has been initiated this year is to design a high order HDG formulation able to deal with non-conforming hybrid cubic/tetrahedral meshes, for the simulation of time-domain electromagnetic wave propagation problems with applications to radiation hardening. This first part of this study has been concerned with the specification and development of a preprocessing tool for the construction of such hybrid structured/unstructured meshes.

8. Partnerships and Cooperations

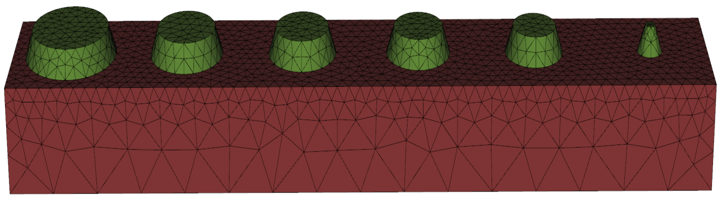
8.1. National Initiatives

8.1.1. Inria Project Lab

8.1.1.1. C2S@Exa (Computer and Computational Sciences at Exascale)

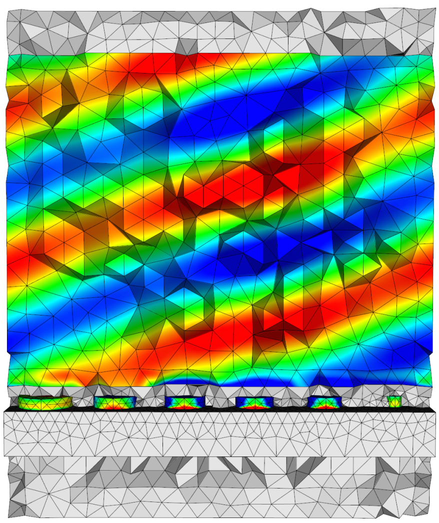


Ideal reflectarray

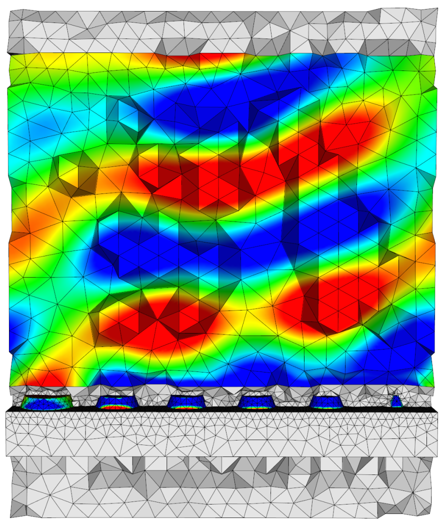


Realistic reflectarray

Figure 10. Ideal and realistic 1D dielectric reflectarray meshes. The red tetrahedra correspond to silver, while the green ones are made of an anisotropic dielectric material. The device is surrounded by air and terminated by a PML above and below, and by periodic boundary conditions on the lateral sides.



Ideal reflectarray



Realistic reflectarray

Figure 11. Time-domain snapshot of E_y component for ideal and realistic 1D dielectric reflectarrays. Solution is obtained in established regime at $t = 0.1$ ps. Fields are scaled to $[-1, 1]$.

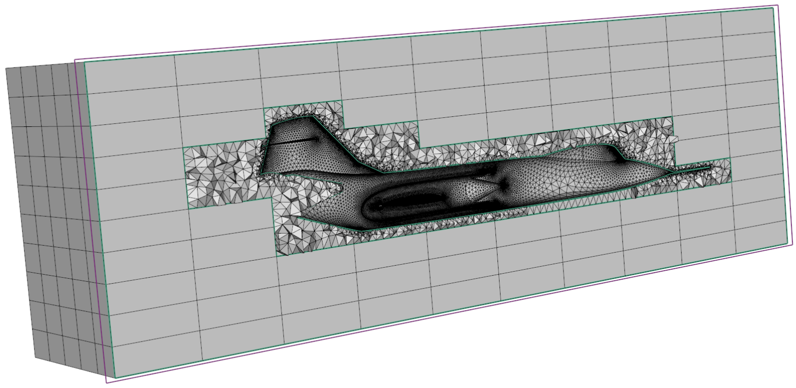


Figure 12. Non-confoming hybrid cubic/tetrahedral mesh around a jet fighter for Radar Cross Section evaluation using a frequency-domain Maxwell solver based on a HDG method.

Participants: Olivier Aumage [STORM project-team, Inria Bordeaux - Sud-Ouest], Philippe Helluy [TONUS project-team, Inria Nancy - Grand-Est], Luc Giraud [HIEPACS project-team, Inria Bordeaux - Sud-Ouest], Stéphane Lanteri [Coordinator of the project], Jean-François Méhaut [CORSE project-team, Inria Grenoble - Rhône-Alpes], Christian Perez [AVALON project-team, Inria Grenoble - Rhône-Alpes].

Since January 2013, the team is coordinating the C2S@Exa http://www-sop.inria.fr/c2s_at_exa Inria Project Lab (IPL). This national initiative aims at the development of numerical modeling methodologies that fully exploit the processing capabilities of modern massively parallel architectures in the context of a number of selected applications related to important scientific and technological challenges for the quality and the security of life in our society. At the current state of the art in technologies and methodologies, a multidisciplinary approach is required to overcome the challenges raised by the development of highly scalable numerical simulation software that can exploit computing platforms offering several hundreds of thousands of cores. Hence, the main objective of C2S@Exa is the establishment of a continuum of expertise in the computer science and numerical mathematics domains, by gathering researchers from Inria project-teams whose research and development activities are tightly linked to high performance computing issues in these domains. More precisely, this collaborative effort involves computer scientists that are experts of programming models, environments and tools for harnessing massively parallel systems, algorithmists that propose algorithms and contribute to generic libraries and core solvers in order to take benefit from all the parallelism levels with the main goal of optimal scaling on very large numbers of computing entities and, numerical mathematicians that are studying numerical schemes and scalable solvers for systems of partial differential equations in view of the simulation of very large-scale problems.

8.1.2. ANR project

8.1.2.1. TECSER

Participants: Emmanuel Agullo [HIEPACS project-team, Inria Bordeaux - Sud-Ouest], Xavier Antoine [CORIDA project-team, Inria Nancy - Grand-Est], Patrick Breuil [Nuclétudes, Les Ulis], Thomas Frachon, Luc Giraud [HIEPACS project-team, Inria Bordeaux - Sud-Ouest], Stéphane Lanteri, Ludovic Moya, Guillaume Sylvand [Airbus Group Innovations].

Type: ANR ASTRID

Duration: May 2014 - April 2017

Coordinator: Inria

Partner: Airbus Group Innovations, Inria, Nuclétudes

Inria contact: Stéphane Lanteri

Abstract: the objective of the TECSER project is to develop an innovative high performance numerical methodology for frequency-domain electromagnetics with applications to RCS (Radar Cross Section) calculation of complicated structures. This numerical methodology combines a high order hybridized DG method for the discretization of the frequency-domain Maxwell in heterogeneous media with a BEM (Boundary Element Method) discretization of an integral representation of Maxwell's equations in order to obtain the most accurate treatment of boundary truncation in the case of theoretically unbounded propagation domain. Beside, scalable hybrid iterative/direct domain decomposition based algorithms are used for the solution of the resulting algebraic system of equations.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. DEEP-ER

Title: Dynamic Exascale Entry Platform - Extended Reach

Program: FP7

Duration: October 2013 - September 2016

Coordinator: Forschungszentrum Juelich Gmbh (Germany)

Partner: Intel Gmbh (Germany), Bayerische Akademie der Wissenschaften (Germany), Ruprecht-Karls-Universitaet Heidelberg (Germany), Universitaet Regensburg (Germany), Fraunhofer-Gesellschaft zur Foerderung der Angewandten Forschung E.V (Germany), Eurotech Spa (Italy), Consorzio Interuniversitario Cineca (Italy), Barcelona Supercomputing Center - Centro Nacional de Supercomputacion (Spain), Xyratex Technology Limited (United Kingdom), Katholieke Universiteit Leuven (Belgium), Stichting Astronomisch Onderzoek in Nederland (The Netherlands) and Inria (France).

Inria contact: Stéphane Lanteri

Abstract: the DEEP-ER project aims at extending the Cluster-Booster Architecture that has been developed within the DEEP project with a highly scalable, efficient, easy-to-use parallel I/O system and resiliency mechanisms. A Prototype will be constructed leveraging advances in hardware components and integrate new storage technologies. They will be the basis to develop a highly scalable, efficient and user-friendly parallel I/O system tailored to HPC applications. Building on this I/O functionality a unified user-level checkpointing system with reduced overhead will be developed, exploiting multiple levels of storage. The DEEP programming model will be extended to introduce easy-to-use annotations to control checkpointing, and to combine automatic re-execution of failed tasks and recovery of long-running tasks from multi-level checkpoint. The requirements of HPC codes with regards to I/O and resiliency will guide the design of the DEEP-ER hardware and software components. Seven applications will be optimised for the DEEP-ER Prototype to demonstrate and validate the benefits of the DEEP-ER extensions to the Cluster-Booster Architecture.

8.2.1.2. HPC4E

Title: HPC for Energy

Programm: H2020

Duration: December 2015 - November 2017

Coordinator: Barcelona Supercomputing Center

Partner: Barcelona Supercomputing Center (Spain), Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas - CIEMAT (Spain), REPSOL SA (Spain), Iberdrola Renovables Energia SA (spain), Lancaster University (United Kingdom), COPPE/UFRJ - Universidade Federal do Rio de Janeiro (Brazil), LNCC (Brazil), INF/UFRGS - Universidade Federal do Rio Grande do Sul (Brazil), CER/UFPE - Universidade Federal de Pernambuco (Brazil), PETROBRAS (Brazil), TOTAL SA (France), and Inria (France).

Inria contact: Stéphane Lanteri

Abstract: This project aims to apply the new exascale HPC techniques to energy industry simulations, customizing them, and going beyond the state-of-the-art in the required HPC exascale simulations for different energy sources: wind energy production and design, efficient combustion systems for biomass-derived fuels (biogas), and exploration geophysics for hydrocarbon reservoirs. For wind energy industry HPC is a must. The competitiveness of wind farms can be guaranteed only with accurate wind resource assessment, farm design and short-term micro-scale wind simulations to forecast the daily power production. The use of CFD LES models to analyse atmospheric flow in a wind farm capturing turbine wakes and array effects requires exascale HPC systems. Biogas, i.e. biomass-derived fuels by anaerobic digestion of organic wastes, is attractive because of its wide availability, renewability and reduction of CO2 emissions, contribution to diversification of energy supply, rural development, and it does not compete with feed and food feedstock. However, its use in practical systems is still limited since the complex fuel composition might lead to unpredictable combustion performance and instabilities in industrial combustors. The next generation of exascale HPC systems will be able to run combustion simulations in parameter regimes relevant to industrial applications using alternative fuels, which is required to design efficient furnaces, engines, clean burning vehicles and power plants. One of the main HPC consumers is the oil & gas (O&G) industry. The computational requirements arising from full wave-form modelling and inversion of seismic and electromagnetic data is ensuring that the O&G industry will be an early adopter of exascale computing technologies. By taking into account the complete physics of waves in the subsurface, imaging tools are able to reveal information about the Earth's interior with unprecedented quality.

8.3. International Initiatives

8.3.1. Inria Associate Teams not involved in an Inria International Labs

8.3.1.1. HOMAR

Title: High performance Multiscale Algorithms for wave pRopagation problems

International Partner (Institution - Laboratory - Researcher):

> Laboratório Nacional de Computaçao Científica (Brazil) - Coordenaçao de Matemática Aplicada e Computaciona - Frédéric Valentin

Start year: 2015

See also: http://www-sop.inria.fr/nachos/index.php/Main/HOMAR

The general scientific context of the collaboration proposed in the HOMAR project is the study of time dependent wave propagation problems presenting multiscale features (in space and time). The general goal is the design, analysis and implementation of a family of innovative high performance numerical methods particularly well suited to the simulation of such multiscale wave propagation problems. Mathematical models based on partial differential equations (PDE) embedding multiscale features occur in a wide range of scientific and technological applications involving wave propagation in heterogeneous media. Electromagnetic wave propagation and seismic wave propagation are two relevant physical settings that will be considered in the project. Indeed, the present collaborative project will focus on two particular application contexts: the interaction of light (i.e. optical wave) with nanometer scale structure (i.e. nanophotonics) and, the interaction of seismic wave propagation with geological media for quantitative and non destructive evaluation of imperfect interfaces.

8.3.2. Inria International Partners

8.3.2.1. 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. Maciej Klemm, University of Bristol, Communication Systems & Networks Laboratory, Centre for Communications Research (United Kingdom)

Dr. Urs Aeberhard and Dr. Markus Ermes, Theory and Multiscale Simulation, IEK-5 Photovoltaik, Forschungszentrum Jülich, Germany

8.4. International Research Visitors

8.4.1. Visits of International Scientists

Prof. Liang Li, School of Mathematical Sciences, University of Electronic Science and Technology of China, Chengdu. From March 2016 to February 2017.

Dr. Antonio Tadeu Gomez and Dr. Frédéric Valentin, LNCC, Petropolis, Brazil. From December 15, 2016 to February 15, 2017.

Prof. Bin Li and Prof. Li Xu, School of Physical Electronics, University of Electronic Science and Technology of China, Chengdu. From August 1st to Agust 12, 2016.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific events organisation

9.1.1.1. Member of the Conference Program Committees

Stéphane Lanteri, Claire Scheid and Wilfried Blanc (LPMC, Université Nice Sophia Antipolis, Nice) have co-organized the meeting "CompNano2016: Modelling and simulation for nanophotonics" that took place at Inria Sophia Antipolis-Méditerranée, October 5-7, 2016.

Stéphane Lanteri and Frédéric Valentin (LNCC, Petropolis, Brazil) have co-organized a mini-symposium on "Hybridized and multiscale methods for waves" in the framework of the Icosahom 2016 conference that took place in Rio de Janeiro, Brazil, June 27-July 1st, 2016.

9.1.2. Invited Talks

Claire Scheid, "Numerical modelling of light-matter interaction at the nanoscale", BioComp seminar, Simula, Oslo, Norway, November 9, 2016.

Claire Scheid, "A structure preserving numerical discretization framework for the Maxwell Klein Gordon equation in 2D", Workshop on Structure and Scaling in Computational Field Theories, University of Oslo, Norway, October 26-28, 2016.

Claire Scheid, "A high order discretization framework for the numerical modelling in nanoplasmonics", Colloque Couplages Numériques, LJAD, Université Nice Sophia Antipolis, Nice, France, September 27-29, 2016.

Claire Scheid, "A discontinuous Galerkin framework for the numerical modelling in nanoplasmonics" Workshop on Recent Advances in Discontinuous Galerkin Methods, University of Reading, UK, June 13, 2016.

Claire Scheid, "A discontinuous Galerkin framework for the numerical modelling of light-matter interaction at the nanoscale", 28th CEA-GAMNI Seminar on CFD, IHP, Paris, January 25-26, 2016.

Stéphane Lanteri, "Recent advances on a finite element type simulation method for nanoscale light/matter interactions", 8èmes Journées Scientifiques du C'Nano PACA, Porquerolles, France, May 25-27, 2016.

Stéphane Lanteri, "Development of finite element type simulation methods for nanoscale light/matter interactions", ONERA Palaiseau, France, June 15, 2016.

Stéphane Lanteri, "High order HDG method for frequency-domain electromagnetics", Institut fuer Physik, Humboldt-Universitaet zu Berlin, Germany, February 9-11, 2016.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Stéphane Descombes, *Scientific computing*, M1, 36 h, Université Nice Sophia Antipolis.

Stéphane Descombes, *Principal components analysis*, M2, 30 h, Université Nice Sophia Antipolis.

Stéphane Lanteri, *Computational electromagnetics*, MAM5, 20 h, Polytech Nice Sophia.

Claire Scheid, *Lectures and practical works, Analysis*, *Agrégation*, 27 h, Université Nice Sophia Antipolis.

Claire Scheid, *Lectures and practical works, Numerical Analysis*, *Agrégation*, 34 h, Université Nice Sophia Antipolis.

9.2.2. Supervision

PhD in progress: Alexis Gobé, *Multiscale hybrid-mixed methods for time-domain nanophotonics*, November 2016, Stéphane Lanteri.

PhD in progress: Nikolai Schmitt, *Numerical modeling of electron beam interaction with nanostructures*, October 2015, Stéphane Lanteri and Claire Scheid.

PhD in progress: Hao Wang, *High order DGTD method for multiscale electromagnetic wave propagation problems*, September 2015, Bin Li and Li Xu (UESTC, Chengdu, China) and Stéphane Lanteri.

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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

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3.3.2. - Data mining
3.4.1. - Supervised learning
3.4.2. - Unsupervised learning
3.4.5. - Bayesian methods
3.4.6. - Neural networks
4.7. - Access control
5.1. - Human-Computer Interaction
5.3.2. - Sparse modeling and image representation
5.3.3. - Pattern recognition
5.4.1. - Object recognition
5.4.2. - Activity recognition
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7.1.1. - Pedestrian traffic and crowds
8.1. - Smart building/home
8.4. - Security and personal assistance

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2. Overall Objectives

2.1. Presentation

2.1.1. Research Themes

STARS (Spatio-Temporal Activity Recognition Systems) 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.

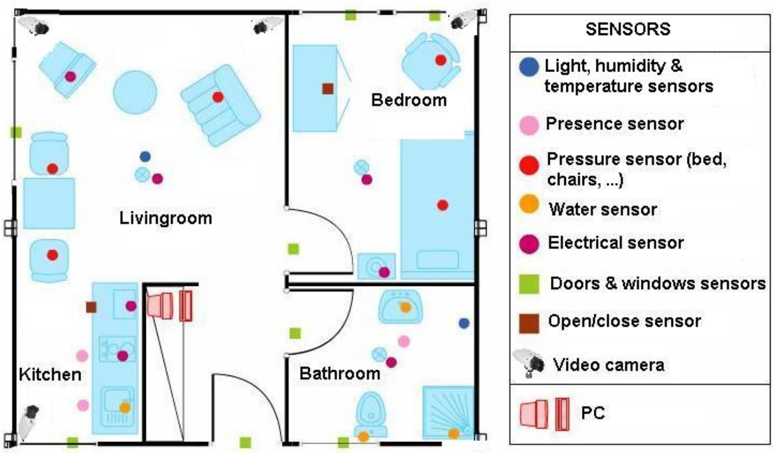

Figure 1. Homecare monitoring: the set of sensors embedded in an apartment

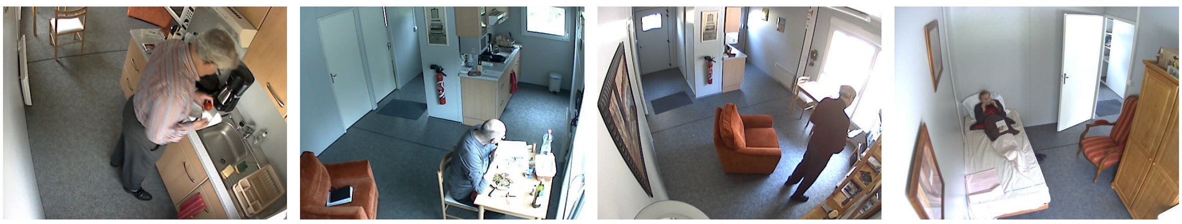

Figure 2. Homecare monitoring: the different views of the apartment captured by 4 video cameras

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.

Computer Vision; Cognitive Systems; Learning; Activity Recognition.

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

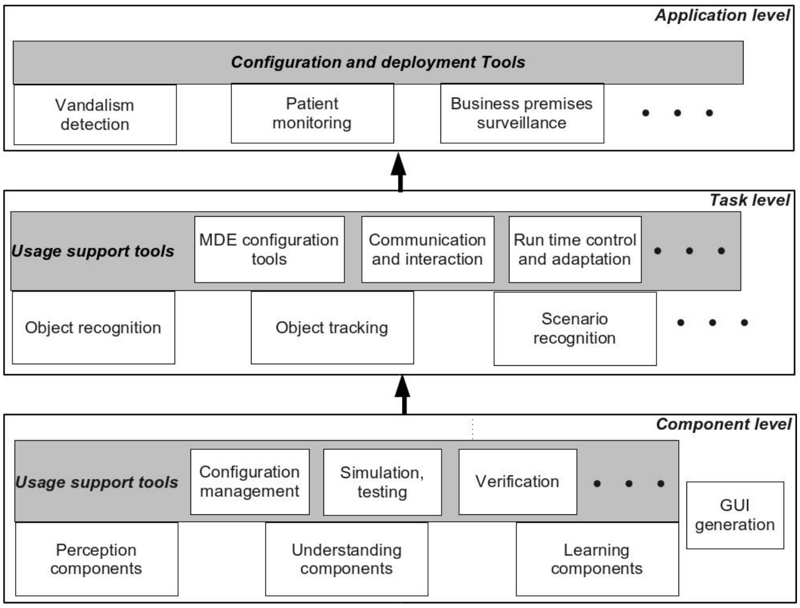

Figure 4. Global Architecture of an Activity Recognition The gray areas contain software engineering support modules whereas the other modules correspond to software components (at Task and Component levels) or to generated systems (at Application level).

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 [45]. 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 [77]. 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 [44], [89], [82].

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 [63], [91] (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 éthiques 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. New Software and Platforms

5.1. CLEM

FUNCTIONAL DESCRIPTION

The Clem Toolkit is a set of tools devoted to design, simulate, verify and generate code for LE programs. LE is a synchronous language supporting a modular compilation. It also supports automata possibly designed with a dedicated graphical editor and implicit Mealy machine definition.

- Participants: Daniel Gaffe and Annie Ressouche
- Contact: Annie Ressouche
- URL: http://www-sop.inria.fr/teams/pulsar/projects/Clem/

5.2. EGMM-BGS

FUNCTIONAL DESCRIPTION

This software implements a generic background subtraction algorithm for video and RGB-D cameras, which can take feedback from people detection and tracking processes. Embedded in a people detection framework, it does not classify foreground / background at pixel level but provides useful information for the framework to remove noise. Noise is only removed when the framework has all the information from background subtraction, classification and object tracking. In our experiment, our background subtraction algorithm outperforms GMM, a popular background subtraction algorithm, in detecting people and removing noise.

- Participants: Anh Tuan Nghiem, Francois Bremond and Vasanth Bathrinarayanan
- Contact: Francois Bremond

5.3. MTS

FUNCTIONAL DESCRIPTION

This software consists of a retrieval tool for a human operator to select a person of interest in a network of cameras. The multi-camera system can re-identify the person of interest, wherever and whenever (s)he has been observed in the camera network. This task is particularly hard due to camera variations, different lighting conditions, different color responses and different camera viewpoints. Moreover, we focus on non-rigid objects (i.e. humans) that change their pose and orientation contributing to the complexity of the problem. In this work we design two methods for appearance matching across non-overlapping cameras. One particular aspect is the choice of the image descriptor. A good descriptor should capture the most distinguishing characteristics of an appearance, while being invariant to camera changes. We chose to describe the object appearance by using the covariance descriptor as its performance is found to be superior to other methods. By averaging descriptors on a Riemannian manifold, we incorporate information from multiple images. This produces mean Riemannian covariance that yields a compact and robust representation. This new software has made digital video surveillance systems a product highly asked by security operators, especially the ones monitoring large critical infrastructures, such as public transportation (subways, airports, and harbours), industrials (gas plants), and supermarkets.

- Participants: Slawomir Bak and Francois Bremond
- Contact: Francois Bremond

5.4. Person Manual Tracking in a Static Camera Network (PMT-SCN)

FUNCTIONAL DESCRIPTION

This software allows tracking a person in a heterogeneous camera network. The tracking is done manually. The advantage of this software is to give the opportunity to operators in video-surveillance to focus on tracking the activity of a person without knowing the positions of the cameras in a considered area. When the tracked person leaves the field-of–view (FOV) of a first camera, and enters the FOV of a second one, the second camera is automatically showed to the operator. This software was developed conjointly by Inria and Neosensys.

- Participants: Bernard Boulay, Anais Ducoffe, Sofia Zaidenberg, Annunziato Polimeni and Julien Gueytat
- Partner: Neosensys
- Contact: Anais Ducoffe

5.5. PrintFoot Tracker

FUNCTIONAL DESCRIPTION

This software implements a new algorithm for tracking multiple persons in a single camera. This algorithm computes many different appearance-based descriptors to characterize the visual appearance of an object and to track it over time. Object tracking quality usually depends on video scene conditions (e.g. illumination, density of objects, object occlusion level). In order to overcome this limitation, this algorithm presents a new control approach to adapt the object tracking process to the scene condition variations. More precisely, this approach learns how to tune the tracker parameters to cope with the tracking context variations. The tracking context, or video context, of a video sequence is defined as a set of six features: density of mobile objects, their occlusion level, their contrast with regard to the surrounding background, their contrast variance, their 2D area and their 2D area variance. The software has been experimented with three different tracking algorithms and on long, complex video datasets.

- Participants: Duc Phu Chau and Francois Bremond
- Contact: Francois Bremond

5.6. Proof Of Concept Néosensys (Poc-NS)

FUNCTIONAL DESCRIPTION

This is a demonstration software which gathers different technologies from Inria and Neosensys: PMT-SCN, re-identification and auto-side switch. This software is used to approach potential clients of Neosensys.

- Participants: Bernard Boulay, Sofia Zaidenberg, Julien Gueytat, Slawomir Bak, Francois Bremond, Annunziato Polimeni and Yves Pichon
- Partner: Neosensys
- Contact: Francois Bremond

5.7. 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: François Brémond, Carlos Fernando Crispim Junior and Etienne Corvée
- Partners: CEA - CHU Nice - I2R - Université de Hamburg - USC Californie
- Contact: Francois Bremond
- URL: https://team.inria.fr/stars/software

5.8. 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 Francois Bremond
- Contact: Francois Bremond
- URL: http://www-sop.inria.fr/teams/pulsar/EvaluationTool/ViSEvAl_Description.html

5.9. py_ad

py action detection
FUNCTIONAL DESCRIPTION

Action Detection framework Allows user to detect action in video stream. It uses model trained in py_ar.

- Participants: Michal Koperski and Francois Bremond
- Contact: Michal Koperski

5.10. py_ar

py action recognition
FUNCTIONAL DESCRIPTION

Action Recognition training/evaluation framework. It allows user do define action recognition experiment (on clipped videos). Train, test model, save the results and print the statistics.

- Participants: Michal Koperski and Francois Bremond
- Contact: Michal Koperski

5.11. py_sup_reader

FUNCTIONAL DESCRIPTION

This is a library which allows to read video saved in SUP format in Python.

- Participant: Michal Koperski
- Contact: Michal Koperski

5.12. py_tra3d

py trajectories 3d
SCIENTIFIC DESCRIPTION

New video descriptor which fuse trajectory information with 3D information from depth sensor.
FUNCTIONAL DESCRIPTION

3D Trajectories descriptor Compute 3D trajectories descriptor proposed in (http://hal.inria.fr/docs/01/05/49/49/PDF/koperski-icip.pdf)

- Participants: Michal Koperski and Francois Bremond
- Contact: Michal Koperski

5.13. sup_ad

sup action detection
SCIENTIFIC DESCRIPTION

This software introduces the framework for online/real-time action recognition using state-of-the-art features and sliding window technique.
FUNCTIONAL DESCRIPTION

SUP Action Detection Plugin Plugin for SUP platform which performs action detection using sliding window and Bag of Words. It uses an input data model trained in py_ar project.

- Participants: Michal Koperski and Francois Bremond
- Contact: Michal Koperski

6. New Results

6.1. 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.

6.1.1. Perception for Activity Recognition

Participants: Piotr Bilinski, François Brémond, Etienne Corvée, Antitza Dancheva, Furqan Muhammad Khan, Michal Koperski, Thi Lan Anh Nguyen, Javier Ortiz, Remi Trichet, Jana Trojanova, Ujjwal Ujjval.

The new results for perception for activity recognition are:

- Exploring Depth Information for Head Detection with Depth Images (see 6.2)
- Modeling Spatial Layout of Features for Real World Scenario RGB-D Action Recognition (see 6.3)
- Multi-Object Tracking of Pedestrian Driven by Context (see 6.4)
- Pedestrian detection: Training set optimization (see 6.5)
- Pedestrian Detection on Crossroads (see 6.6)
- Automated Healthcare: Facial-expression-analysis for Alzheimer's patients in Musical Mnemotherapy (see 6.7)
- Hybrid Approaches for Gender estimation (see 6.8)
- Unsupervised Metric Learning for Multi-shot Person Re-identification (see 6.9)

6.1.2. Semantic Activity Recognition

Participants: François Brémond, Carlos Fernando Crispim Junior, Michal Koperski, Farhood Negin, Thanh Hung Nguyen, Philippe Robert.

For this research axis, the contributions are :

- Semi-supervised Understanding of Complex Activities in Large-scale Datasets (see 6.10)
- On the Study of the Visual Behavioral Roots of Alzheimer's disease (see 6.11)
- Uncertainty Modeling with Ontological Models and Probabilistic Logic Programming (see 6.12)
- A Hybrid Framework for Online Recognition of Activities of Daily Living In Real-World Settings (see 6.13)
- Praxis and Gesture Recognition (see 6.14)

6.1.3. Software Engineering for Activity Recognition

Participants: Sabine Moisan, Annie Ressouche, Jean-Paul Rigault, Ines Sarray, Daniel Gaffé, Rachid Guerchouche, Matias Marin, Etienne Corvée, Julien Badie, Manikandan Bakthavatchalam, Vasanth Bathrinarayanan, Ghada Balhoul, Anais Ducoffe, Jean Yves Tigli, François Brémond.

The contributions for this research axis are:

- Scenario Recognition (see 6.15)
- The CLEM Workflow (see 6.16)
- Safe Composition in Middleware for Internet of Things (see 6.17)
- Verification of Temporal Properties of Neuronal Archetype (see 6.18)
- Dynamic Reconfiguration of Feature Models (see 6.19)
- Setup and management of SafEE devices (see 6.20)
- Brick & Mortar Cookies (see 6.21)

6.2. Exploring Depth Information for Head Detection with Depth Images

Participants: Thanh Hung Nguyen, Siyuan Chen.

Head detection may be more demanding than face recognition and pedestrian detection in the scenarios where a face turns away or body parts are occluded in the view of a sensor, but when locating people is needed. This year [29], we introduce an efficient head detection approach for single depth images at low computational expense. First, a novel head descriptor was developed and used to classify pixels as head or non-head. We used depth values to guide each window size, to eliminate false positives of head centers, and to cluster head pixels, which significantly reduce the computation costs of searching for appropriate parameters. High head detection performance was achieved in experiments with 90% accuracy for our dataset containing heads with different body postures, head poses, and distances to a Kinect2 sensor, and above 70% precision on a public dataset composed of a few daily activities, which is better than using a head-shoulder detector with HOG feature for depth images (see Figure 5)

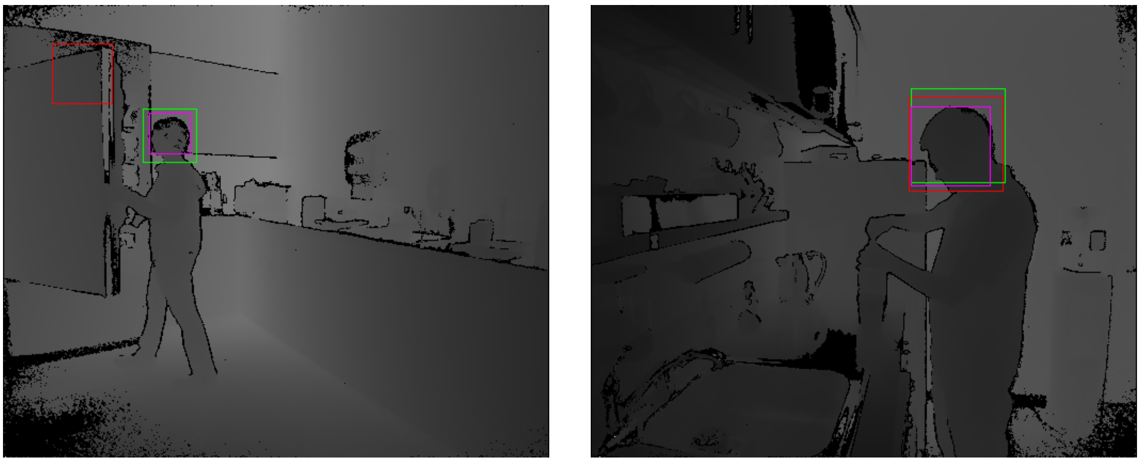

Figure 5. Examples of head detection where our algorithm successfully detects head. Pink square represents the ground truth, green rectangle represents our algorithm.

6.3. Modeling Spatial Layout of Features for Real World Scenario RGB-D Action Recognition

Participants: Michal Koperski, François Brémond.

keywords: computer vision, action recognition

Challenges in action representation in real-world scenario using RGB-D sensor

With RGB-D sensor it is easy to take advantage of real-time skeleton detection. Using skeleton information we can model not only dynamics of action, but also static features like pose. Skeleton-based methods have been proposed by many authors, and have reported superior accuracy on various daily activity data-sets. But the main drawback of skeleton-based methods is that they cannot make the decision when skeleton is missing.

We claim that in real world scenario of daily living monitoring, skeleton is very often not available or is very noisy. This makes skeleton based methods unpractical. There are several reasons why skeleton detection fails in real-world scenario. Firstly, the sensor has to work outside of it's working range. Since daily living monitoring is quite an unconstrained environment, the monitored person is very often too far from sensor, or is captured from non-optimal viewpoint angle. In Figure 6 we show two examples where skeleton detection fails. In the first example, the person on the picture wears black jeans which interferes with sensor. In such a case depth information from lower body parts is missing, making skeleton detection inaccurate. In the second example (see Figure 7) the person is too far from sensor and basically disappears in the background. In this case depth information is too noisy, thus skeleton detection fails. All disadvantages mentioned above will affect skeleton-based action recognition methods, because they strictly require skeleton detection.

On the other hand, local points-of-interest methods do not require skeleton detection, nor segmentation. That is why they received great amount of interest in RGB based action recognition where segmentation is much more difficult than with RGB-D. Those methods rely mostly on detection of points-of-interest usually based on some motion features (eg optical flow). The features are either based on trajectory of points-of-interest or descriptors are computed around the points-of-interest. One of the main disadvantage of those methods is fact that they fail when they cannot "harvest" enough points-of-interest. It happens when action has low dynamics eg "reading a book" or "writing on paper". Such actions contain very low amount of motion coming from hand when writing or turning the pages. In addition local points-of-interest methods very often ignore the spatial layout of detected features.

Proposed method

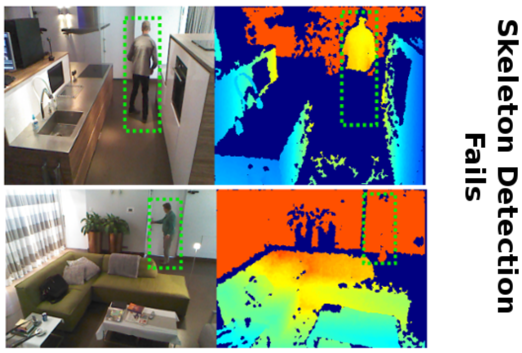

Figure 6. We show two examples where skeleton detection methods fail. Pictures on the left show RGB frame, pictures on the right show depth map (dark blue indicates missing depth information).

To address those problems we propose to replace skeleton detection by RGB-D based people detector. Note that person detection is much easier than skeleton detection. In addition we propose to use two people detectors: RGB and depth based - to take advantage of two information streams.

We propose to model spatial layout of motion features obtained from a local points-of-interest based method. We use Dense Trajectories [99] as a point of interest detector and MBH (Motion Boundary Histogram [62]) as a descriptor. To improve the discriminating power of MBH descriptor we propose to model spatial-layout of visual words computed based on MBH (Figure 7). We divide a person bounding box into Spatial Grid (SG) and we compute Fisher Vector representation in each cell. In addition, we show that other spatial-layout encoding methods also improve recognition accuracy. We propose 2 alternative spatial-layout encoding methods an we compare them with Spatial Grid.

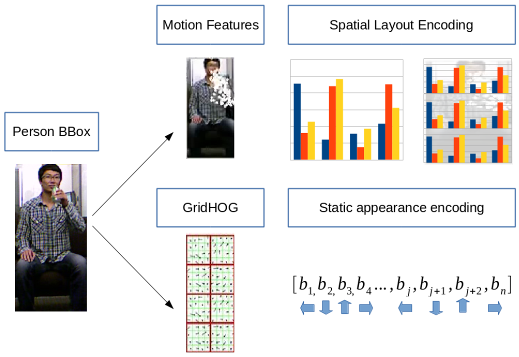

Figure 7. We show proposed method where we use people detection in place of skeleton. Next we propose to encode spatial-layout of visual words computed from motion features. In addition we propose GridHOG descriptor which encodes static appearance information.

To improve recognition of actions with low amount of motion we propose a descriptor which encodes rough static appearance (Figure 7). This can be interpreted as rough pose information. We divide the detected person bounding box into grid cells. Then we compute HOG [61] descriptor inside each cell to form the GHOG (GridHog) descriptor.

Further details can be find in the paper [37]. The contributions of this paper can be listed as follows:

- We propose to use two people detectors (RGB and depth based) to obtain person bounding box instead of skeleton.
- We propose to use Spatial Grid (SG) inside person bounding box. To model spatial-layout of MBH features.
- We propose to encode static information by using novel GHOG descriptor.
- We propose two other methods which model spatial-layout of MBH features and we compare them with Spatial Grid.

Experiments

We evaluate our approach on three daily activity data-sets: MSRDailyActivity3D, CAD-60 and CAD-120. The experiments show that we outperform most of the skeleton-based methods without requiring difficult in real-world scenario skeleton detection and thus being more robust (see Table1, Table2 and Table3).

6.4. Multi-Object Tracking of Pedestrian Driven by Context

Participants: Thi Lan Anh Nguyen, François Brémond, Jana Trojanova.

Keywords: Tracklet fusion, Multi-object tracking

Multi-object tracking (MOT) is essential to many applications in computer vision. As so many trackers have been proposed in the past, one would expect the tracking task as solved. It is true for scenarios containing solid background with a low number of objects and few interactions. However, scenarios with appearance changes due to pose variation, abrupt motion changes, and occlusion still represent a big challenge.

Table 1. Recognition Accuracy Comparison for MSRDailyActivity3D data-set. corresponds to methods which require skeleton detection.

Method	Accuracy [%]
NBNN [94]	*70.00*
HON4D [87]	*80.00*
STIP + skeleton [106]	*80.00*
SSFF [95]	*81.90*
DSCF [102]	*83.60*
Actionlet Ensemble [101]	*85.80*
RGGP + fusion [79]	*85.60*
Super Normal [80]	*86.26*
BHIM [74]	86.88
DCSF + joint [102]	*88.20*
Our Approach	**85.95**

Table 2. Recognition Accuracy Comparison for CAD-60 data-set. corresponds to methods which require skeleton detection.

Method	Accuracy [%]
STIP [106]	62.50
Order Sparse Coding [86]	*65.30*
Object Affordance [75]	*71.40*
HON4D [87]	*72.70*
Actionlet Ensemble [101]	*74.70*
JOULE-SVM [72]	*84.10*
Our Approach	**80.36**

Table 3. Recognition Accuracy Comparison for CAD-120 data-set. corresponds to methods which require skeleton detection.

Method	Accuracy [%]
Salient Proto-Objects [92]	78.20
Object Affordance [75]	*84.70*
STS [76]	*93.50*
Our Approach	**85.48**

In the state of the art, some sets of efficient methods are proposed to face this challenge: data association (local and global) and tracking parameter adaptation. A very popular method for local data association is the bipartite matching. The exact solution can be found via Hungarian algorithm [85]. These methods are computationally inexpensive, but can deal only with short term occlusion. An example of global method is the extension of the bipartite matching into network flow [104]. Given the objects detections at each frame, the direct acyclic graph is formed and the solution is found through minimum-cost flow algorithm. The algorithms reduce trajectory fragments and improve trajectory consistency but lack robustness to identity switches of close or intersecting trajectories.

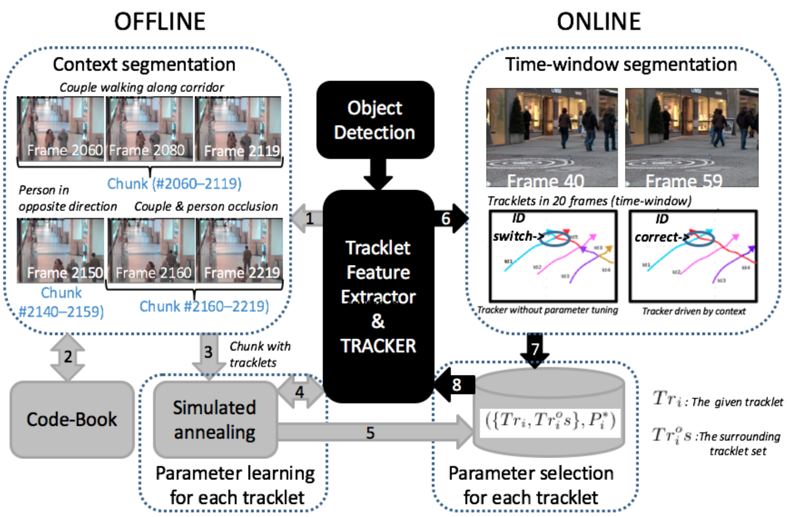

Figure 8. Our proposed framework.

Another set of methods for MOT is online parameter adaptation [56]. They tune automatically the tracking parameters based on the context information, while methods mentioned above use one appearance and/or one motion feature for the whole video. In [56], the authors learn the parameters for the scene context offline. In online phase the tracking parameters are selected from database based on the current context of the scene. These parameters are applied to all objects in the scene. Such a concept assumes discriminative appearance and trajectories among individuals, which is not always the case in real scenarios.

In order to overcome these limitations, we propose a new long term tracking framework. This framework has several dominant contributions:

- We introduce new long term tracking framework which combines short data association and the online parameter tuning for individual tracklets. In contrast to previous methods that used the same setting for all tracklets.
- We show that large number of parameters can be efficiently tuned via multiple simulated annealing, whereas previous method could tune only a limited number of parameters and fix the rest to be able to do exhaustive search.
- We define the surrounding context around each tracklet and similarity metric among tracklets allowing us to match learned context with unseen video set.

The proposed framework was trained on 9 public video sequences and tested on 3 unseen sets. It outperforms the state-of-art pedestrian trackers in scenarios of motion changes, appearance changes and occlusion of objects as shown in Table 4. The paper is accepted in conference AVSS-2016 [39].

Table 4. Tracking performance. The best values are printed in red.

Dataset	Method	MOTA	MOTP	GT	MT	PT	ML
PETS2009	Shitrit et al. [52]	0.81	0.58	21	–	–	–
	***Bae et al.**-global association* [50]	0.73	0.69	23	*100*	0	*0.0*
	Chau et al. [57]	0.62	0.63	21	–	–	–
	Chau [58]([57] + parameter tuning for whole video context)	0.85	0.71	21	–	–	–
	Ours ([57] + Proposed approach)	*0.86*	*0.73*	21	76.2	14.3	9.5
TUD-Stadtmitte	Andriyenko et al. [47]	0.62	0.63	9	60.0	20.0	10.0
	Milan et al. [81]	*0.71*	*0.65*	9	*70.0*	20.0	*0.0*
	Chau et al. [57]	0.45	0.62	10	60.0	40.0	*0.0*
	Chau [58]([57] + parameter tuning for whole video context)	–	–	10	*70.0*	10.0	20.0
	Ours ([57] + Proposed approach)	0.47	*0.65*	10	*70.0*	30.0	*0.0*
TUD-Crossing	Tang et al. [96]	–	–	11	*53.8*	38.4	7.8
	Chau et al. [57]	0.69	0.65	11	46.2	53.8	*0.0*
	Ours ([57] + Proposed approach)	*0.72*	*0.67*	11	*53.8*	46.2	*0.0*

6.5. Pedestrian detection: Training set optimization

Participants: Remi Trichet, Javier Ortiz.

keywords: computer vision, pedestrian detection, classifier training, data selection, data generation, data weighting

The emphasis of our work is on data selection. Training for pedestrian detection is, indeed, a peculiar task. It aims to differentiate a few positive samples with relatively low intra-class variation and a swarm of negative samples picturing everything else present in the dataset. Consequently, the training set lacks discrimination and is highly imbalanced. Due to the possible creation of noisy data while oversampling, and the likely loss of information when undersampling, balancing positive and negative instances is a rarely addressed issue in the literature.

Bearing these data selection principles in mind, we introduce a new training methodology, grounded on a two-component contribution. First, it harnesses an expectation-maximization scheme to weight important training data for classification. Second, it improves the cascade-of-rejectors [105][54] classification by enforcing balanced train and validation sets every step of the way, and optimizing separately for recall and precision. A new data generation technique was developped for this purpose.

The training procedure unfolds as follows. After the initial data selection, we balance the negative and positive sample cardinalities. Then, a set of n negative data rejectors are trained and identified negative data are discarded. The validation set negative samples are iteratively oversampled after each training to ensure a balanced set. The final classifier is learned after careful data selection. Figure 9 illustrates the process.

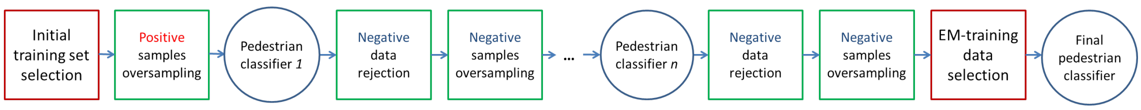

Figure 9. Training pipeline.

Experiments carried out on the Inria [61] and PETS2009 [69] datasets, demonstrate the effectiveness of the approach, leading to a simple HoG-based detector to outperform most of its near real-time competitors.

Table 5. Comparison with the state-of-the-art on the Inria dataset. Our approach is in italic. Computation time are calculated according to 640×480 resolution frames. The used metric is the log-average miss rate (the lower the better).

Method	Inria	Speed
HoG [61]	46%	21fps
DPM-v1 [68]	44%	< 1fps
HoG-LBP [98]	39%	Not provided
MultiFeatures [100]	36%	< 1fps
FeatSynth [51]	31%	< 1fps
MultiFeatures+CSS [97]	25%	No
FairTrain - HoG + Luv	*25%*	*11fps*
FairTrain - HoG	*25%*	*16fps*
Channel Features [65]	21%	0.5fps
FPDW [64]	21%	2-5fps
DPM-v2 [67]	20%	< 1fps
VeryFast [53]	18%	8fps(CPU)
VeryFast [53]	18%	135fps(GPU)
WordChannels [60]	17%	8fps(GPU)

Table 6. Comparison with the state-of-the-art on the PETS2009 S2.L1 sequence. Our approach is in italic. The used metric is the MODA (the higher the better).

Method	PETS2009	Speed
Arsic [48]	44%	n.a.
Alahi [46]	73%	n.a.
Conte [59]	85%	n.a.
FairTrain - HoG	*85.38%*	*29fps*
FairTrain - HoG + Luv	*85.49%*	*18fps*
Breitenstein [55]	89%	n.a.
Yang [103]	96%	n.a.

6.6. Pedestrian Detection on Crossroads

Participants: Ujwal Ujwal, François Brémond.

Pedestrian detection has a specific relevance in the space of object detection problems in computer vision. Due to increasing role of automated surveillance systems in increasing areas, demands for a highly robust and accurate pedestrian detection system is increasing day after day. Recently, deep learning has emerged as an important paradigm to tackle complex object detection problems. This year, we performed our initial studies on pedestrian detection using deep learning techniques. These studies form an important basis for us to extend our work in the future.

Evaluation Metrics

The relative comparison of different pedestrian detection systems was done using evaluation metrics. In the area of pedestrian detection, the most widely used evaluation metric is that of *miss rate*(MR). *Miss rate* is related to the concept of *recall*, which is another very commonly used metric in computer vision, especially in problems related to retrieval of images and concepts. *Miss Rate* is defined as follows:

$$Miss\ Rate = \frac{False\ Negatives}{True\ Positives + False\ Negatives} \tag{9}$$

		Pedestrian Detector	
		Pedestrian	Other
Ground Truth	Pedestrian	True Positive (TP)	False Negative (FN)
	Other	False Positive (FP)	True Negative (TN)

Figure 10. True and False Positives in pedestrian detection

In equation 1, *True Positives*(TP) and *False Negatives*(FN) can be understood from figure 10. A good pedestrian detector should not miss many people in a scene and this aspect is reflected in the definition of equation 1. A good pedestrian detector is required to detect as few *False Positives*(FP) as possible. This is expressed in the literature usually in the form of False Positives Per Image(FPPI). FPPI is basically a per-image average of total number of FP detections.

Pedestrian detection systems usually work with a number of parameters. Different values of these parameters may tune a system to different MR and FPPI value. This is usually expressed in the form of a *Precision-recall*(PR) curve. This curve is created by varying a control parameter of a system and plotting MR and FPPI values. In literature it is customary to report MR value at 0.1 FPPI.

Experiments

We considered deep learning based models for our initial set of experiments. This is primarily owing to their popularity and the promise which they have demonstrated in the area of object detection over the past several years.
There are many deep learning based models which have been used for object detection. The purpose of these experiments was to gain a deeper insight into the performance of deep neural networks for pedestrian detection. We experimented with Faster-RCNN [88] and SSD detector [78]. These were chosen owing to the fact that they are recent models (2015 for Faster-RCNN and 2016 for SSD Detector), and have displayed state-of-art performance in terms of detection speeds and accuracy across many object categories.

The results shown in table7 were obtained by fine-tuning VGG-16 with imagenet and MS-COCO datasets which did not involve any public dataset specific to pedestrian detection. Hence, we took the fine-tuned model and further fine-tuned it with different pedestrian datasets to study the effectiveness of fine-tuning with pedestrian-specific datasets.

Each row in the first column of table8, reflects the dataset(s) which were used to fine-tune the model. For each row, the model was fine-tuned using the dataset indicated in its first column, as well as the datasets indicated in the first column of all rows preceding it. The model was then evaluated against the test set of each dataset and the miss-rates are indicated in the table.

Table 7. Performance of fine-tuned Faster RCNN on pedestrian detection datasets.Numbers indicate the miss-rate.

Performance of fine-tuned Faster RCNN		
Dataset	**Faster RCNN Performance**	**State of Art**
Inria	13.47%	13%
Daimler	37.7%	29%
ETH-Zurich	32.1%	
Caltech	26.7%	19%
TUD-Brussels	52.2%	45%

-

Table 8. Faster-RCNN performance after fine-tuning with pedestrian datasets. Numbers indicate the miss-rate.

	Image datasets				
Trained Model	**Inria**	**Daimler**	**TUD-Brussels**	**ETH-Zurich**	**Caltech**
+Inria	13.4%	36.9%	52%	32.1%	28.2%
+Daimler	13.6%	33.7%	51.1%	32.7%	29.1%
+ETH-Zurich	13.8%	34.6%	49.3%	32%	26%
+Caltech	16%	35.4%	48%	33.2%	25.2%

While the initial results as seen from table 7 are encouraging, they still need a lot of improvement especially with complex datasets such as TUD-Brussels and Caltech. We also see from table8, that fine-tuning with pedestrian datasets tends to improve the performance but the magnitude of improvement varies depending upon the dataset(s) being fine-tuned with and the dataset(s) being tested upon. These observations indicate some important research directions. Data in computer vision applications are highly varied and it is not very easy to capture its complexity and variations with sufficient ease. It is important to proceed to work on better

dataset usage by clustering the datasets together based on traits such as viewpoint, resolution etc. Resolution is another important element which significantly affects deep learning based approaches. This is because deep learning involves automated feature extractions from the pixel level and low resolution appearance often makes that problem difficult.
We intend to work upon and cover these issues in subsequent efforts towards solving the pedestrian detection problem.

6.7. Automated Healthcare: Facial-expression-analysis for Alzheimer's patients in Musical Mnemotherapy

Participants: Antitza Dantcheva, Piotr Bilinski, Philippe Robert, François Brémond.

keywords: automated healthcare, healthcare monitoring, expression recognition

The elderly population has been growing dramatically and future predictions and estimations showcase that by 2050 the number of people over 65 years old will increase by 70%, the number of people over 80 years old will increase by 170%, outnumbering younger generations from 0-14 years. Other studies indicate that around half of the current population of over 75 year old suffer from physical and / or mental impairments and as a result are in need of high level of care. The loss of autonomy can be delayed by maintaining an active life style, which also would lead to reduced healthcare financial costs. With the expected increase of the world elderly population, and on the other hand limited available human resources for care a question arises as "How can we improve health care in an efficient and cost effective manner?".

Motivated by the above, we propose an approach for detecting facial expressions in Alzheimer's disease (AD) patients that can be a pertinent unit in an automated assisted living system for elderly subjects. Specifically, we have collected video-data of AD patients in musical therapy at the AD center Fondation G.S.F J. L. Noisiez in Biot, France from multiple therapy-sessions for validating our method. We note that in such sessions even AD patients suffering from apathy exhibit a number of emotions and expressions. We propose a spatio-temporal algorithm for facial expression recognition based on dense trajectories, Fisher Vectors and support vector machine classification. We compared the proposed algorithm to a facial-landmark-based algorithm concerning signal displacement of tracked points within the face.

Our algorithm differentiates between four different facial expressions: (i) neutral, (ii) smile, (iii) talking, and (iv) singing with an accuracy of 56%, outperforming the facial-landmark-based algorithm. Challenging for both algorithms has been the unconstrained setting involving different poses, changes in illumination and camera movement. One expected benefit for AD patients is that positive expressions and their cause could be determined and replicated in order to increase life standard for such patients, which also brings to the fore a delay in the development of AD (see figure 11).

This work is published in the Gerontolgy Journal.

6.8. Hybrid Approaches for Gender Estimation

Participants: Antitza Dantcheva, Piotr Bilinski.

keywords: gender estimation, soft biometrics, biometrics, visual attributes

Automated gender estimation has numerous applications including video surveillance, human computer-interaction, anonymous customized advertisement, and image retrieval. Most commonly, the underlying algorithms analyze facial appearance for clues of gender.
Can a smile reveal your gender? [28], [35]

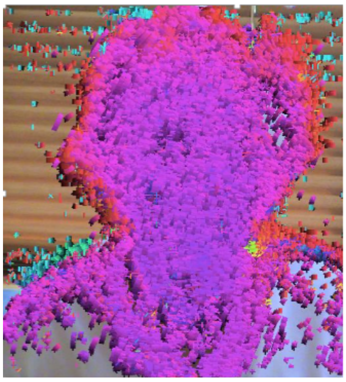

Figure 11. Expression recognition in AD patients based on dense trajectories and Fisher vectors. Dense trajectories visualization.

Deviating from such algorithms in [28] we proposed a novel method for gender estimation, exploiting dynamic features gleaned from smiles and show that (a) facial dynamics incorporate gender clues, and (b) that while for adults appearance features are more accurate than dynamic features, for subjects under 18, facial dynamics outperform appearance features. While it is known that sexual dimorphism concerning facial appearance is not pronounced in infants and teenagers, it is interesting to see that facial dynamics provide already related clues. The obtained results (see Table 9) show that smile-dynamic include pertinent and complementary to appearance gender information. Such an approach is instrumental in cases of (a) omitted appearance-information (*e.g.* low resolution due to poor acquisition), (b) gender spoofing (*e.g.* makeup-based face alteration), as well as can be utilized to (c) improve the performance of appearance-based algorithms, since it provides complementary information.

Table 9. True gender classification rates. Age given in years.

Age	< 20	> 19
Subj. amount	143	214
OpenBR	52.45%	78.04%
Dynamics (SVM+PCA) [28]	60.1%	69.2%
Dynamics (AdaBoost) [28]	59.4%	61.7%
OpenBR + Dynamics (Bagged Trees) [28]	60.8%	80.8%
Motion-based descriptors [35]	77.7%	80.11%
Improved dynamics [35]	$\mathbf{86.3}\%$	$\mathbf{91.01}\%$

We improve upon the above work by proposing a spatio-temporal features based on dense trajectories, represented by a set of descriptors encoded by Fisher Vectors [35]. Our results suggest that smile-based features include significant gender-clues. The designed algorithm obtains true gender classification rates of 86.3% for adolescents, significantly outperforming two state-of-the-art appearance-based algorithms (*OpenBR* and *how-old.net*), while for adults we obtain true gender classification rates of 91.01%, which is comparably discriminative to the better of these appearance-based algorithms (see Table 9).

Distance-based gender prediction: What works in different surveillance scenarios?

In this work [36] we studied gender estimation based on information deduced jointly from face and body, extracted from single-shot images. The approach addressed challenging settings such as low-resolution-images, as well as settings when faces were occluded. Specifically the face-based features included local binary patterns (LBP) and scale-invariant feature transform (SIFT) features, projected into a PCA space. The features of the novel body-based algorithm proposed in this work included continuous shape information extracted from body silhouettes and texture information retained by HOG descriptors. Support Vector Machines (SVMs) were used for classification for body and face features. We conduct experiments on images extracted from video-sequences of the Multi-Biometric Tunnel database, emphasizing on three distance-settings: close, medium and far, ranging from full body exposure (far setting) to head and shoulders exposure (close setting). The experiments suggested that while face-based gender estimation performs best in the close-distance-setting, body-based gender estimation performs best when a large part of the body is visible. Finally we presented two score-level-fusion schemes of face and body-based features, outperforming the two individual modalities in most cases (see Table10 and Table 11).

Table 10. Performance (%) of the Face Gender Estimation algorithm (FGE) and the Body Gender Estimation algorithm (BGE).

Distance	FGE			BGE		
Scenario	Male TPR	Fem. TPR	Acc.	Male TPR	Fem. TPR	Acc.
Far	94.28	20	57.14	87.14	88.57	87.85
Medium	71.42	90	80.71	85.71	87.14	86.42
Close	88.57	90	89.28	78.57	80	79.28

Table 11. Performance (%) of the Sum fusion and Smarter Sum Fusion of FGE and BGE in terms of True Positive Rate (TPR) for Male and Female (Fem.), overall Accuracy (Acc.). Best performance (in terms of Acc.) of each distance-setting is bolded.

Distance	Sum Fusion			Prop. Sum Fusion		
Scenario	Male TPR	Fem TPR	Acc.	Male TPR	Fem TPR	Acc.
Far	87.14	88.57	**87.85**	87.14	88.57	**87.85**
Medium	88.57	90	**89.28**	88.57	90	**89.28**
Close	87.14	88.57	87.85	92.85	94.28	**93.57**

6.9. Unsupervised Metric Learning for Multi-shot Person Re-identification

Participants: Furqan Khan, François Brémond.

keywords: re-identification, long term visual tracking, metric learning, unsupervised labeling

Automatic label generation for metric learning

Appearance based person re-identification is a challenging task, specially due to difficulty in capturing high intra-person appearance variance across cameras when inter-person similarity is also high. Metric learning is often used to address deficiency of low-level features by learning view specific re-identification models. The models are often acquired using a supervised algorithm. This is not practical for real-world surveillance systems because annotation effort is view dependent. Therefore, everytime a camera is replaced or added, a significant amount of data has to be annotated again. We propose a strategy to automatically generate labels for person tracks to learn similarity metric for multi-shot person re-identification task. Specifically, we use the fact that non-matching (negative) pairs far out-number matching (positive) pairs in any training set. Therefore, the true class conditional probability of distance given negative class can be estimated using the empirical marginal distribution of distance. This distribution can be used to sample non-matching person pairs for metric learning. A brief overview of the approach is presented below, please refer to [33] for details.

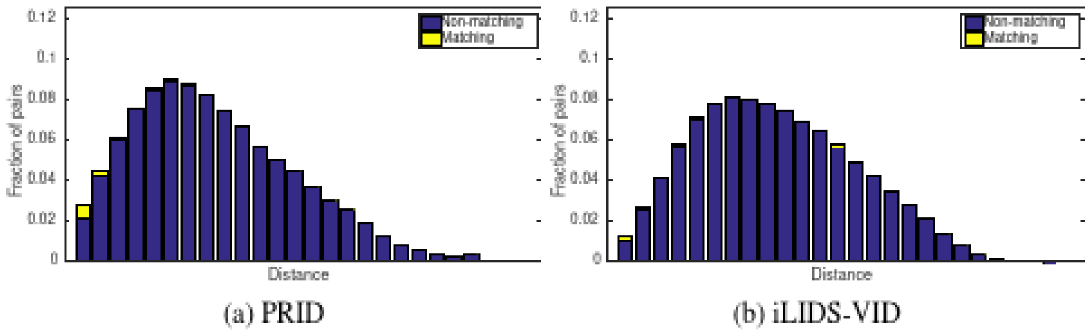

Figure 12. Distributions of distances between pairs of signature of randomly selected half of a) PRID, and b) iLIDS-VID datasets for MCM representation using Euclidean distance. The distributions are averaged for 10 trials.

In figure 12, empirical distribution of Euclidean distance (using MCM [43] representation) is plotted for two publicly available datasets. It can be noted that the positive samples lie on one side of distribution mode. Therefore, negative pairs can be sampled according to the probability proportional to the signed distance from the mode. Practically, we only select sample pairs that are farthest away in the distribution as negative pairs. For positive pairs, we use the fact that each track has more than one image for a person. Thus we generate positive pairs using the persons selected for negative pairs. We evaluated our approach on three publicly available datasets in multi-shot settings: iLIDS-VID, PRID and iLIDS-AA. Performance comparison of different representations using recognition rates at rank r are detailed in table 12, table 13 and table 14. Our results validate the effectiveness of our approach by considerably reducing the performance gap between fully-supervised models using KISSME algorithm and Euclidean distance.

Table 12. PRID

Method	r=1	r=5	r=10	r=20
MCM+MPD	53.6	83.1	91.0	96.9
MCM+UnKISSME	59.2	81.7	90.6	96.1
MCM+KISSME	64.3	86.1	94.5	98.0

Table 13. iLIDA-VID

Method	r=1	r=5	r=10	r=20
MCM+MPD	34.3	61.5	74.4	83.3
MCM+UnKISSME	38.2	65.7	75.9	84.1
MCM+KISSME	40.3	69.9	79.0	87.5

6.10. Semi-supervised Understanding of Complex Activities in Large-scale Datasets

Participants: Carlos F. Crispim-Junior, Michal Koperski, Serhan Cosar, François Brémond.

keywords: Semi-supervised methods, activity understanding, probabilistic models, pairwise graphs

Table 14. iLIDS-AA

Method	r=1	r=5	r=10	r=20
MCM+MPD	56.5	79.7	90.9	95.2
MCM+UnKISSME	61.2	85.1	92.8	96.0
MCM+KISSME	62.9	84.7	93.4	97.0

Informations

Methods for action recognition have evolved considerably over the past years and can now automatically learn and recognize short term actions with satisfactory accuracy. Nonetheless, the recognition of complex activities - compositions of actions and scene objects - is still an open problem due to the complex temporal and composite structure of this category of events. Existing methods focus either on simple activities or oversimplify the modeling of complex activities by targeting only whole-part relations between its sub-parts (*e.g.*, actions). We study a semi-supervised approach (Fig. 13) that can learn complex activities from the temporal patterns of concept compositions in different arities (*e.g.*, "slicing-tomato" before "pouring_into-pan"). So far, our semi-supervised, probabilistic model using pairwise relations both in compositional and temporal axis outperforms prior work by 6 % (59% against 53%, mean Average precision, Fig. 14). Our method also stands out from the competition by its capability to handle relation learning in a setting with large number of video sequences (*e.g.*, 256) and distinct concept classes (Cooking Composite dataset, 218 classes, [90]), an ability that current state-of-the-art methods lack. Our initial achievements in this line of research has been published in [31]. Further work will focus on learning relations of higher arity.

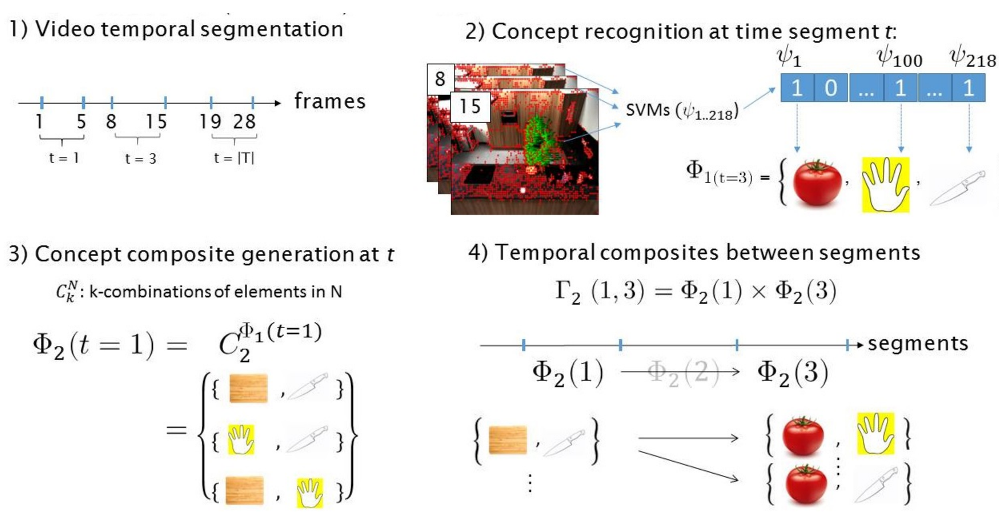

Figure 13. Semi-supervised learning of a video representation: 1) video temporal segmentation, 2) concept recognition 3) composite concept generation per time segment, 4) Temporal composite generation between segments.

6.11. On the Study of the Visual Behavioral Roots of Alzheimer's disease

Participants: Carlos F. Crispim-Junior, François Brémond.

Keywords: Activities of Daily Living, Dementia prediction, RGBD sensors, Activity Recognition, Cognitive Health

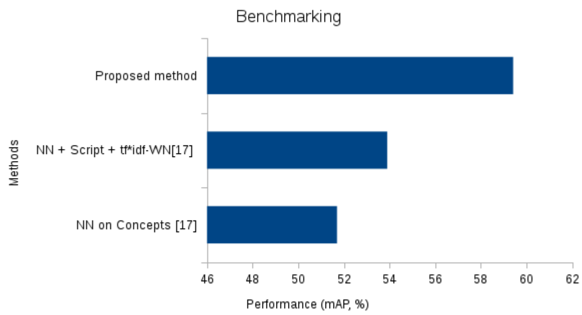

*Figure 14. Performance benchmarking of our approach against data set baselines: a) Nearest Neighbor classifier (NN) on concepts, script data, and tf*idf-WN, and b) NN only on concepts.*

Existing computer vision studies for the diagnosis of Dementia have focused on extracting discriminative patterns between healthy and people with dementia from neuroimagery exams, like functional MRI and PET scans. Nonetheless, the effects of dementia over human behaviors are a discriminative component that is barely explored by automatic vision-based methods. We studied a framework to automatically recognize the cognitive health of seniors from the visual observation of their activities of daily living (Fig.16). We employ a lightweight activity recognition system based on RGBD sensors to recognize the set of target activities (*e.g.*, prepare drink, prepare medication, make a payment transaction) performed by a person in a continuous video stream. Then, we summarize the absolute and relative activity patterns present in the video sequence using a novel probabilistic representation of activity patterns. Finally, this representation serves as input to Random Forest classifiers to predict the class of cognitive health that the person in question belongs to. We demonstrate that with the current framework can recognized the cognitive health status of seniors (*e.g.*, healthy, Mild Cognitive Impairment and Alzheimer's disease) with an average F_1-score of 69 % in real life scenarios.

6.12. Uncertainty Modeling with Ontological Models and Probabilistic Logic Programming

Participants: Carlos F. Crispim-Junior, François Brémond.

keywords: probabilistic logic programming, activities of daily living, senior monitoring, ontological models,

We have been investigating novel probabilistic, knowledge-driven formalisms that can join the representation expressiveness of an ontology-based language with the probabilistic reasoning of probabilistic graphical models, like probabilistic graphical models and probabilistic programming languages. The goal is to support the representation of events (entities, sub-events and constraints) and hierarchical structures (event, sub-events) and at the same time be capable of handling uncertainty related to both entity/sub-event detection and soft constraints. Prior work in probabilistic logic provides support to reasoning either about uncertainty related to entity recognition (probability of entity x in the scene defined in ProbLog2) or to soft-constraint (relevance of violation of constraint i to model y as defined in Markov Logic). In our current work in partnership with KU university of Leuven, we have extended the ontological models of our vision pipeline (Fig.17) with probabilistic logic formalism proposed by ProbLog (Fig.18), a probabilistic logic programming language. Current results on the recognition of daily activities of seniors are promising as they improved the precision of our prior method by 1%. Further work will focus on extending our uncertainty models to be robust to constraint violations.

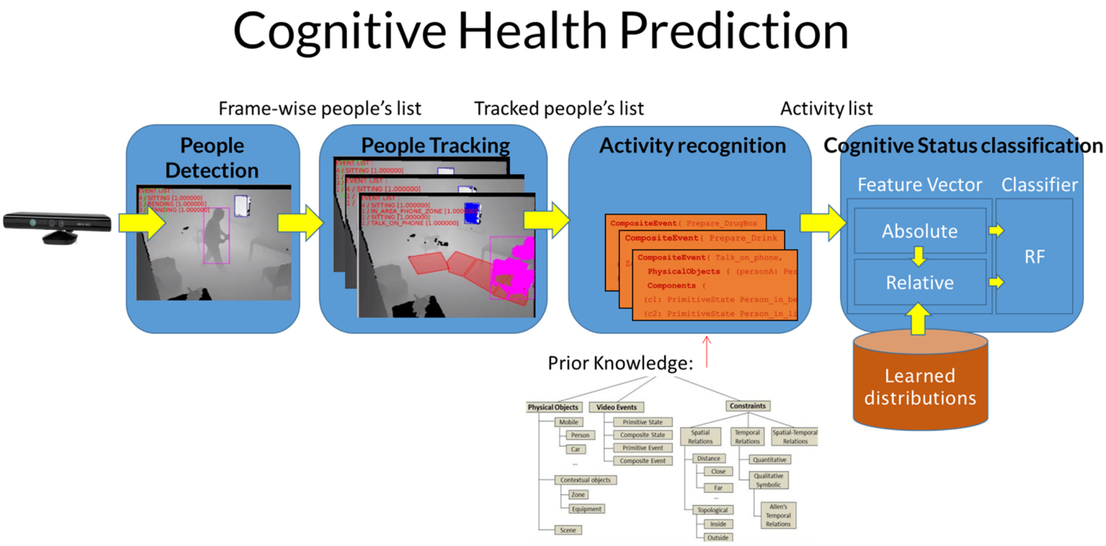

Figure 15. Automatic framework for visual recognition of cognitive health status: visual event recognition is responsible to detect and track people in the scene and recognize their events based on spatio-temporal relations with scene objects. Cognitive health classification represents absolute and relative information about the target classes.

Figure 16. Monitoring a senior performing at a gait-related event

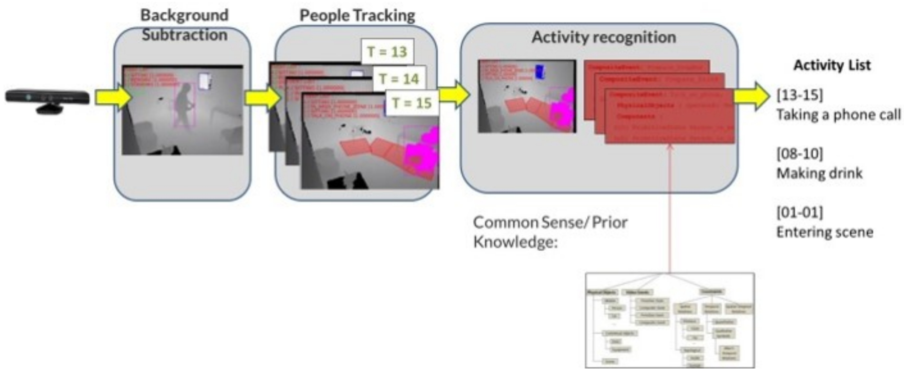

Figure 17. Pipeline for online activity recognition: given an acquisition camera (e.g. a Kinect), it firstly detects people using background subtraction algorithm, then it looks for appearance correspondence between people detected in the current frame with respect to past detections (past-present approach), and thirdly it recognizes the activities performed by each of the tracked people.

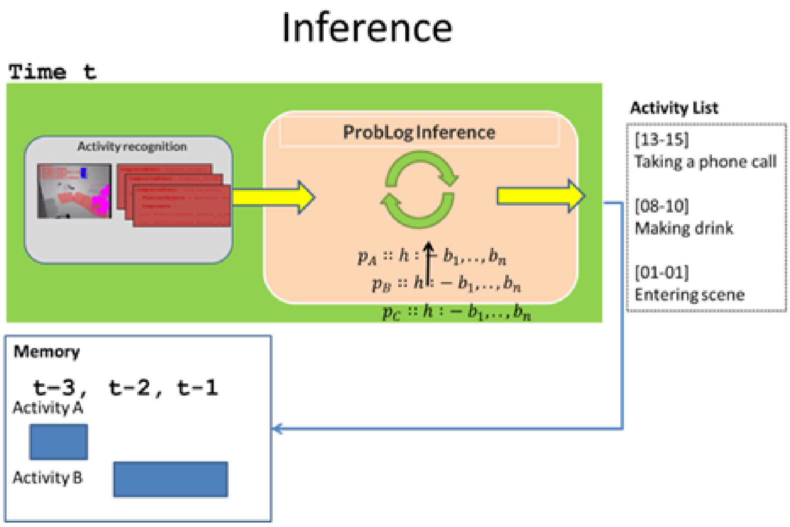

Figure 18. Temporal Inference using ProbLog engine. It takes as input deterministic observations and frame-wisely it recognizes the target events. Frame-events are aggregated into time intervals to create the time intervals of complex activities.

6.13. A Hybrid Framework for Online Recognition of Activities of Daily Living In Real-World Settings

Participants: Farhood Negin, Serhan Cosar, Michal Koperski, Carlos Crispim, Konstantinos Avgerinakis, François Brémond.

keywords: Supervised and Unsupervised Learning, Activity Recognition

State-of-the-art and Current Challenges

Recognizing human actions from videos has been an active research area for the last two decades. With many application areas, such as surveillance, smart environments and video games, human activity recognition is an important task involving computer vision and machine learning. Not only the problems related to image acquisition, e.g., camera view, lighting conditions, but also the complex structure of human activities makes activity recognition a very challenging problem. Traditionally, there are two variants of approach to cope with these challenges: supervised and unsupervised methods. Supervised approaches are suitable for recognizing short-term actions. For training, these approaches require a huge amount of user interaction to obtain well-clipped videos that only include a single action. However, Activities of Daily Living (ADL) consists of many simple actions which form a complex activity. Therefore, the representation in supervised approaches are insufficient to model these activities and a training set of clipped videos for ADL cannot cover all the variations. In addition, since these methods require manually clipped videos, they can only follow an offline recognition scheme. On the other hand, unsupervised approaches are strong in finding spatio-temporal patterns of motion. However, the global motion patterns are not enough to obtain a precise classification of ADL. For long-term activities, there are many unsupervised approaches that model global motion patterns and detect abnormal events by finding the trajectories that do not fit in the pattern [70], [83]. Many methods have been applied on traffic surveillance videos to learn the regular traffic dynamics (e.g. cars passing a cross road) and detect abnormal patterns (e.g. a pedestrian crossing the road) [71].

Proposed Method

We propose a hybrid method to exploit the benefits of both approaches. With limited user interaction our framework recognizes more precise activities compared to available approaches. We use the term precise to indicate that, unlike most of trajectory-based approaches which cannot distinguish between activities under same region, our approach can be more sensitive in the detection of activities thanks to local motion patterns. We can summarize the contributions of this work as following: i) online recognition of activities by automatic clipping of long-term videos and ii) obtaining a comprehensive representation of human activities with high discriminative power and localization capability.

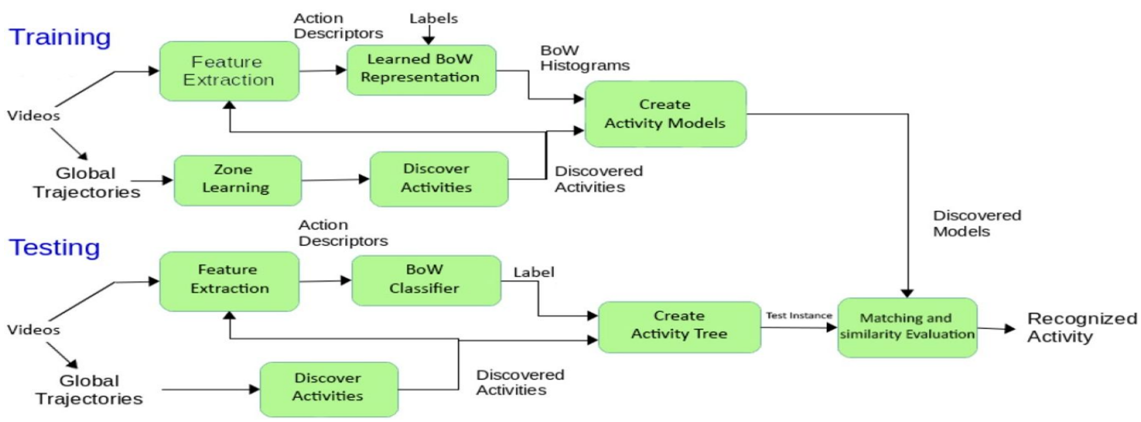

Figure 19. Architecture of the framework: Training and Testing phases

Figure 19 illustrates the flow of the training and testing phases in the proposed framework. For the training phase, the algorithm learns relevant zones in the scene and generates activity models for each zone by complementing the models with information such as duration distribution and BoW representations of discovered activities. At testing, the algorithm compares the test instances with the generated activity models and infers the most similar model.

The performance of the proposed approach has been tested on the public GAADRD dataset [73] and CHU dataset. Our approach always performs equally or better than online supervised approach in [99] (see Table15 and Table16). And even most of the time it outperforms totally supervised approach (manually clipped) of [99]. This reveals the effectiveness of our hybrid technique where combining information coming from both constituents could contribute to enhance recognition. The paper of this work was accepted in AVSS 2016 conference [30].

Table 15. The activity recognition results for CHU dataset. Bold values represent the best sensitivity and precision results for each class.

	Supervised (Manually Clipped) of [99]		Online Version of [99]		Unsupervised Using Global Motion [66]		Proposed Approach	
ADLs	Recall (%)	Prec. (%)	Recall (%)	Prec. (%)	Recall (%)	Prec. (%)	Recall (%)	Prec. (%)
Answering Phone	57	78	**100**	**86**	**100**	60	**100**	81.82
P. Tea + W. Plant	89	**86.5**	76	38	84.21	80	**94.73**	81.81
Using Phar. Basket	**100**	83	**100**	43	90	**100**	**100**	**100**
Reading	35	**100**	92	36	81.82	**100**	**100**	91.67
Using Bus Map	90	**90**	**100**	50	**100**	54.54	**100**	83.34
AVERAGE	74.2	87.5	93.6	50.6	91.2	78.9	**98.94**	**87.72**

6.14. Praxis and Gesture Recognition

Participants: Farhood Negin, Jeremy Bourgeois, Emmanuelle Chapoulie, Philippe Robert, François Brémond.

keywords: Gesture Recognition, Dynamic and Static Gesture, Alzheimer Disease, Reaction Time, Motion Descriptors

Challenges and Proposed Method

Most of the developed societies are experiencing an aging trend of their population. Aging is correlated with cognitive impairment such as dementia and its most common type: Alzheimer's disease. So, there is an urgent need to develop technological tools to help doctors to do early and precise diagnoses of cognitive decline. Inability to correctly perform purposeful skilled movements with hands and other forelimbs most commonly is associated with Alzheimerâs disease [84]. These patients have difficulty to correctly imitate hand gestures and mime tool use, e.g. pretend to brush one's hair. They make spatial and temporal errors. We propose a gesture recognition and evaluation framework as a complementary tool to help doctors to spot symptoms of cognitive impairment at its early stages. It is also useful to assess one's cognitive status. First, the algorithm classifies the defined gestures in the gestures set and then it evaluates gestures of the same category to see how well they perform compared to correct gesture templates. Methods Shape and motion descriptors such as HOG (histogram of oriented gradient) [61] and HOF (histogram of optical flow) [62] are an efficient clue to characterize different gestures (Figure 20 Left). Extracted descriptors are utilized as input to train the

Table 16. The activity recognition results for GAADRD dataset. Bold values represent the best sensitivity and precision results for each class.

ADLs	Supervised (Manually Clipped) Approach [99]		Online Version of [99]		Classification by detection using SSBD [49]		Unsupervised Using Global Motion [66]		Proposed Approach	
	Recall (%)	Prec. (%)	Recall (%)	Prec. (%)	Recall (%)	Prec. (%)	Recall (%)	Prec. (%)	Recall (%)	Prec. (%)
Answering Phone	**100**	88	**100**	70	96	34.29	**100**	**100**	**100**	88
Establish Acc. Bal.	67	**100**	**100**	29	41.67	41.67	**100**	86	67	**100**
Preparing Drink	**100**	69	**100**	69	96	80	78	**100**	**100**	82
Prepare Drug Box	58.33	**100**	11	20	**86.96**	51.28	33.34	**100**	22.0	**100**
Watering Plant	54.54	**100**	0	0	**86.36**	86.36	44.45	57	44.45	**80**
Reading	**100**	**100**	88	37	**100**	31.88	**100**	**100**	**100**	**100**
Turn On Radio	60	86	**100**	75	96.55	19.86	89	89	89	89
AVERAGE	77.12	**91.85**	71.29	42.86	**86.22**	49.33	77.71	90.29	74.57	91.29

classifiers. We use bag-of-visual-words approach to characterize gestures with descriptors. The classification happens in two steps: first we train a classifier to distinguish different gestures and after, we train another classifier with correct and incorrect samples of the same class. This way, we could recognize which gesture is performed and whether it is performed accurately or not.

Experiments and Results

The framework is fed by input data which come from a depth sensor (Kinect, Microsoft). At first phase, the correct samples of gestures performed by clinicians, are recorded. We train the framework using correct instances of each gesture class. In the second phase, participants were asked to perform the gestures. We use virtual reality as modality to interact with subjects to make the experiments more immersive and realistic experience. First an avatar performs a specific gesture and then she asks the subject to repeat the same gesture (Figure 20 Right). In this work, we analyze two categories of gestures. First category is dynamic gestures where the whole motion of the hands is considered as a complete gesture. Second category of gestures is static gestures where only a static pose of hands is the desired gesture. For static gestures, we also need to detect this key frame. Moreover, reaction time which starts after avatar asked the subject to do the gesture, until subject really starts to perform the gesture, could be an important diagnostic factor. Our algorithm uses motion descriptors to detect key frames and reaction time. In the preliminary tests, our framework successfully recognized more than 80% of the dynamic gestures. It also detects key frames and reaction time with a high precision. Thus the proposed gesture recognition framework helps doctors by providing a complete assessment of gestures performed by subject.

This work is published in [30] and will appear in the Gerontechnology Journal.

6.15. Scenario Recognition

Participants: Inès Sarray, Sabine Moisan, Annie Ressouche, Jean-Paul Rigault.

Keywords: Synchronous Modeling, Model checking, Mealy machine, Cognitive systems.

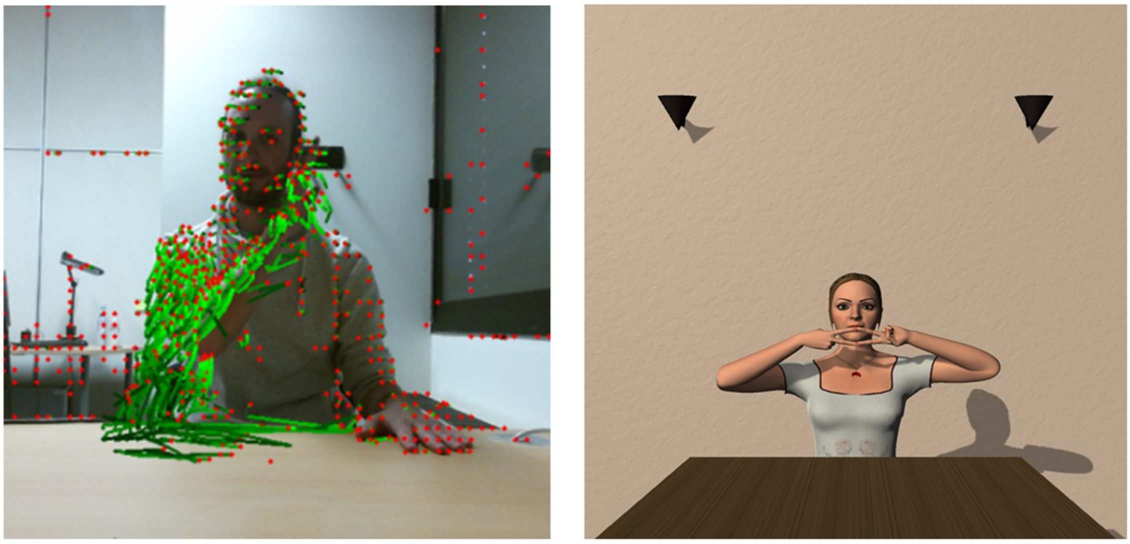

Figure 20. Left: Extracted motion descriptors while performing a gesture Right: virtual avatar guides patients in a virtual reality environment

Activity recognition systems aim at recognizing the intentions and activities of one or more persons in real life, by analyzing their actions and the evolution of the environment. This is done thanks to a pattern matching and clustering algorithms, combined with adequate knowledge representation (e.g scene topology, temporal constraints) at different abstraction levels (from raw signal to semantics).Stars has been working to ameliorate and facilitate the generation of these activity recognition systems. As we can use these systems in a big range of important fields, we propose a generic approach to design activity recognition engine. These engines should continuously and repeatedly interact with their environment and react to its stimuli. On the other hand, we should take into consideration the dependability of these engines which is very important to avoid possible safety issue, that's why we need also to rely on formal methods that allow us to verify these engines behavior. Synchronous modeling is a solution that allows us to create formal models that describe clearly the system behavior and its reactions when it detects different stimuli. Using these formal models, we can build effective recognition engines for each formal model and validate them easily using model checking. This year, we adapted this approach to create a new simple scenario language to express the scenario behaviors and to automatically generate its recognition automata at compile time. This automata will be embedded into the recognition engine at runtime.

Scenario description Language

As we work with non-computer-science end-users, we need a friendly description language that helps them to express easily their scenarios. To this aim, we collaborated with Ludotic ergonomists to define the easiest way for a simple user to deal with the new language. Using AxureRP tool, we defined two types of language:

1- Textual language:

For the textual language, we decided to use a simple language. Using 9 operators, and after the definition of the types, roles, and sub-scenarios, the user can describe a scenario in a simple way, such as in figure21.

This year, we implemented this textual language and it is under testing.

2)- Graphical language:

```
Type Personne, Equipement,Zone;

Scenario coupTel :

role
        Patient:Personne;
        Tel: Equipement;
        table: Equipement;
        sejour: Zone;

Subscenarios
        entend(Personne, Equipement);
        decroche(Personne, Equipement);
        commence_a_parler(Personne);
        finit_de_parler(Personne);
        raccroche(Personne,Equipement);

EtatInitial : dans_Zone(Patient, sejour);

debut

  pres_de(Patient, table) parallele entend(Patient, Tel)
puis
  decroche(Patient, Tel)
puis
  commence_a_parler(Patient)
puis
  finit_de_parler(Patient)
puis
  raccroche(Patient, Tel)
puis
     Alert (fin_de_scenario)

fin
```

Figure 21. Example of the textual language

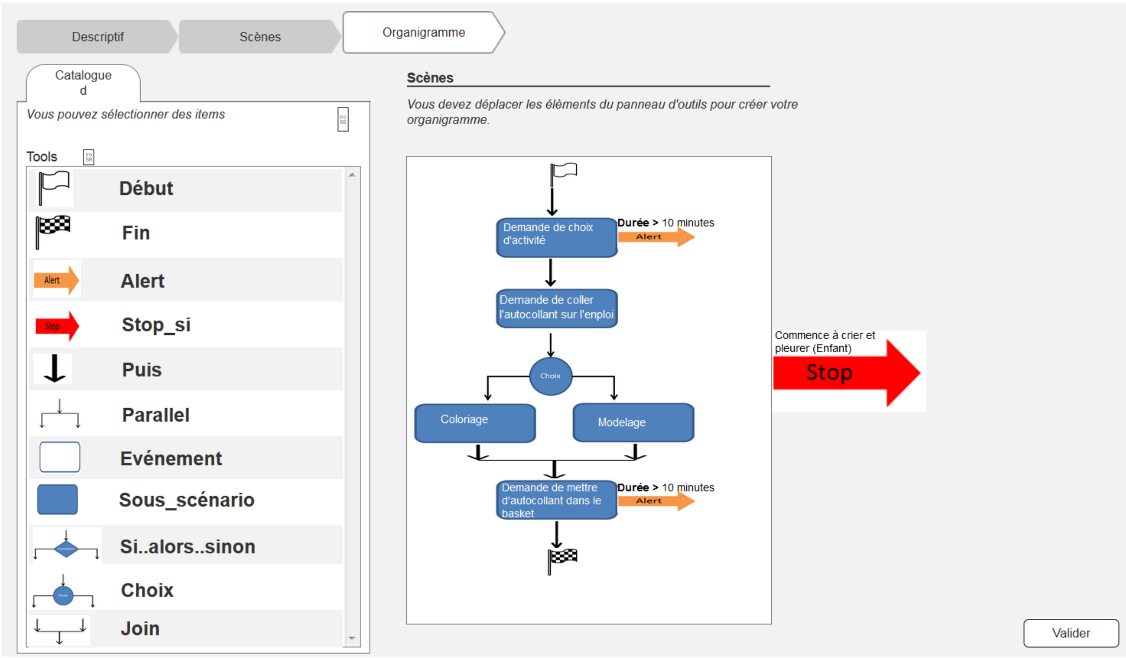

Figure 22. Generic flowchart

The graphical language model has 3 basic interfaces: The first interface allows the user to define the types, roles, and the initial state of the scenario. The second one is dedicated to describe the sub-scenarios and to express simple scenarios using a timeline. In case of complicated scenarios, the third interface offers users a tool panel that allows them to describe their scenarios in a hierarchical way using a flowchart-like representation (see figure 22).

Recognition Automata

This year, we worked also on recognition automata generation. We used the synchronous modeling and semantics to define these engines. The semantics consists in a set of formal rules that describe the behavior of a program. We specified first the language operators: we rely on a 4-valued algebra with a bilattice structure to define two semantics for the recognition engine: a behavioral and equational one. A behavioral semantics defines the behavior of a program and its operators and gives it a clear interpretation. Equational semantics allows us to make a modular compilation of our programs using rules that translate each program into an equation system. After defining these two semantics, we verified their equivalence for all operators, by proving that these semantics agree on both the set of emitted signals and the termination value for a program P. We implemented these semantics and we are now working on the automatic generation of the recognition automata.

6.16. The Clem Workflow

Participants: Annie Ressouche, Daniel Gaffé.

Keywords: Synchronous languages, Synchronous Modeling, Model checking, Mealy machine.

This research axis concerns the theoretical study of a synchronous language LE with modular compilation and the development of a toolkit around the language (see Figure 23) to design, simulate, verify, and generate code for programs. The novelty of the approach is the ability to manage both modularity and causality.

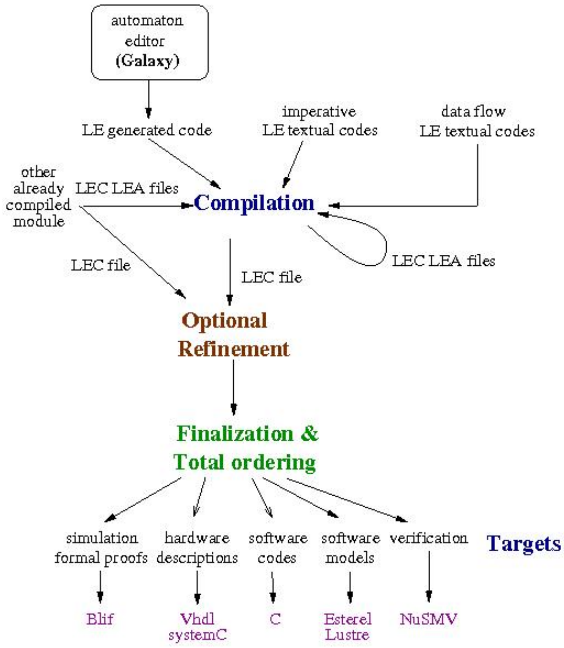

Figure 23. The Clem Toolkit

This year, we continued to focus on the improvement of both LE language and compiler concerning data handling and the generation of back-ends, required by other research axis of the team. We also designed a large application: a mechatronics system in CLEM and we have proved that its main safety properties hold in our modeling. Now, to complete the improvement done these two last years concerning data handling, we want to extend the verification side of CLEM. To this aim, this year we began to replace the fundamental representation of Boolean values as BDD (Binary Decision Diagrams) with LDD (Logical Decision Diagrams), which allow to encode integer values in a very efficient way. It turns out that the validation mechanism of CLEM could take into account properties over integer data. However, this is a first test and the integration of a model checking technique in CLEM remains a challenge.

6.17. Safe Composition in Middleware for Internet of Things

Participants: Annie Ressouche, Daniel Gaffé, Jean-Yves Tigli.

Keywords: Synchronous Modeling, Ubiquitous Computing, middleware, internet of things

The main concern of this research axis is the dependability of a component-based adaptive middleware which dynamically adapt and recompose assemblies of web components. Such a middleware plays an important role in the generation of event recognition engines we are currently building in Stars team (see section 6.15). One of the main challenge is how to guarantee and validate some safety and integrity properties throughout the system's evolution. These two last years, we have proposed to rely on synchronous models to represent component behavior and their composition and to verify that these compositions verify some constraints during the dynamic adaptation to appearance and disappearance of components. We defined a generic way to express these constraints and we proposed the Description Constraint Language (DCL) to express these constraints. Hence, we compile them into LE programs (see 6.16) and we benefit from CLEM model checking facilities to ensure that they are respected [93]. This year, we improved the DCL language in order to take into account both the dynamic variation of components and also applications which use these components and we are currently testing the efficiency of our method to add and remove components. Moreover, genericity is expressed by the notion of type and we aim at extending this notion to a thinner representation of knowledge about components.

6.18. Verification of Temporal Properties of Neuronal Archetypes

Participants: Annie Ressouche, Daniel Gaffé.

Keywords: Synchronous Modeling, model-checking, lustre, temporal logic, biologic archetypes

This year, we began a collaboration with with the I3S CNRS laboratory and Jean Dieudonné CNRS laboratory to verify temporal properties of neuronal archetypes. There exist many ways to connect two, three or more neurons together to form different graphs. We call archetypes only the graphs whose properties can be associated to specific classes of biologically relevant structures and behaviors. These archetypes are supposed to be the basis of typical instances of neuronal information processing. To model different representative archetypes and express their temporal properties, we use a synchronous programming language dedicated to reactive systems (Lustre). Then, we generate several back ends to interface different model checkers supporting data types and automatically validate these properties. We compare the respective results. They mainly depend on the underlying abstraction methods used in model checkers.

These results are published in [32]

6.19. Dynamic Reconfiguration of Feature Models

Participants: Sabine Moisan, Jean-Paul Rigault.

Keywords: feature models, model at run time, self-adaptive systems

In video understanding systems, context changes (detected by system sensors) are often unexpected and can combine in unpredictable ways, making it difficult to determine in advance (off line) the running configuration suitable for each context combination. To address this issue, we keep, at run time, a model of the system and its context together with its current running configuration. We adopted an enriched Feature Model approach to express the variability of the architecture as well as of the context. A context change is transformed into a set of feature modifications (selection/deselection of features) to be processed on the fly. This year we proposed a fully automatic mechanism to compute at run time the impact of the current selection/deselection requests. First, the modifications are checked for consistency; second, they are applied as a single atomic “transaction” to the current configuration to obtain a new configuration compliant with the model; finally, the running system architecture is updated accordingly. This year we implemented the reconfiguration step and its algorithms and heuristics and we evaluated its run time efficiency.

Our ultimate goal is to control the system through a feed back loop from video components and sensor events to feature model manipulation and back to video components modifications.

The fully automatic adaptation that we propose is similar to a Feature Model editor. That is the reason why our previous attempt was to embed a general purpose feature model editor at run time. This revealed two major differences between our mechanism and an editor. First, in a fully automatic process there is no human being to drive a series of edits, hence heuristics are required. Second, the editor operations are often elementary while we need a global “transaction-like” application of all the selections/deselections to avoid temporary unconsistencies.

In order to evaluate our algorithm performance, we randomly generated feature models (from 60 to 1400 features). We also randomly generated context changes. The results are shown on figure 24: no processing time explosion is noticeable; in fact the time seems to grow rather linearly. Moreover, the computation time of a new initial partial configuration does not exceed 3ms for a rather big model. The algorithm and its evaluation are detailed in [41].

6.20. Setup and management of SafEE devices

Participants: Matias Marin, Etienne Corvée, François Brémond.

The aim of the SafEE project (see section 8.1.1.2) is to provide assistance for the safety, autonomy and quality of life of elderly people at risk or already presenting Alzheimer’s disease or related pathology.

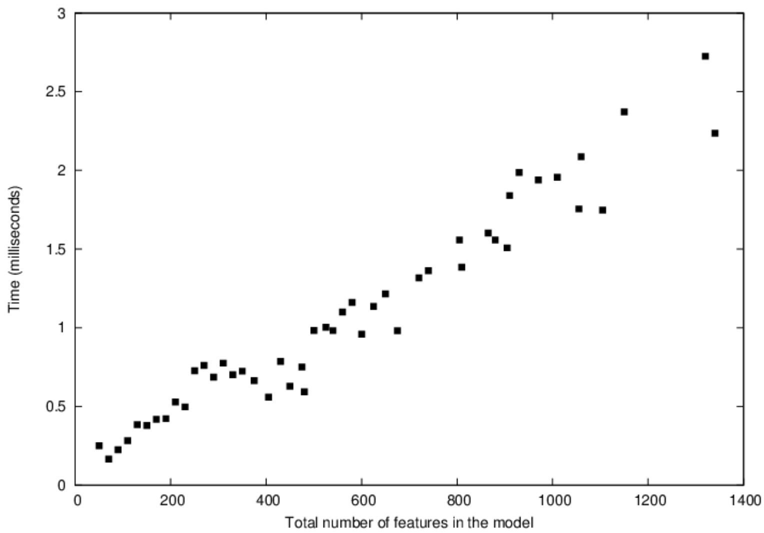

Figure 24. Computation time of initial models

Within EHPAD building (in Nice), 4 patients participated to our experiment and we plan to include more patients in the project throughout next years. Besides, 2 other patients have participated in the project at their own home.

More precisely, the SafEE project focuses on specific clinical targets: behavior, motricity, cognitive capabilities For this, the SafEE project includes:

- srvsafee(web server): a behavior analysis platform has been created to allow identification of certain daytime behavior disturbances (agitation, for example) and nocturnal disturbances (sleep disorders), locomotor capacities (walking and posture). It centralizes data saved in each local PC with Kinect2 sensor on the one hand, and postgresql database, on the other hand. About 30 Gb data are recorded for each patient in a day, which represents a huge amount to manage in the long run.
- Aroma diffuser (AromaCare): for sleep disturbances, using in particular an automated device for diffusing fragrances (aromatherapy) adapted to the perturbations detected by the analysis platform.
- Tablet (Serious game, MusicCare): for disturbances in spatial orientation, improved procedural memory and a sense of control and confidence in technological tools, using multimedia interfaces using an application for Android OS.
- Kinect2: motion detection for analysis linked to a PC, with a database to store recorded events.
- Bed sensor: able to track the sleep by analyzing the movements of the body, the breathing, and the beating of the heart.

Fig. 25 shows the Safee project environment.

6.21. Brick & Mortar Cookies

Participants: Julien Badie, Manikandan Bakthavatchalam, Vasanth Bathrinarayanan, Ghada Balhoul, Anais Ducoffe.

The objective of the BMC project is to create a software that aims to present attendance and attractiveness of the customer in stores, based on automatic video analysis. The final system should be designed to be used

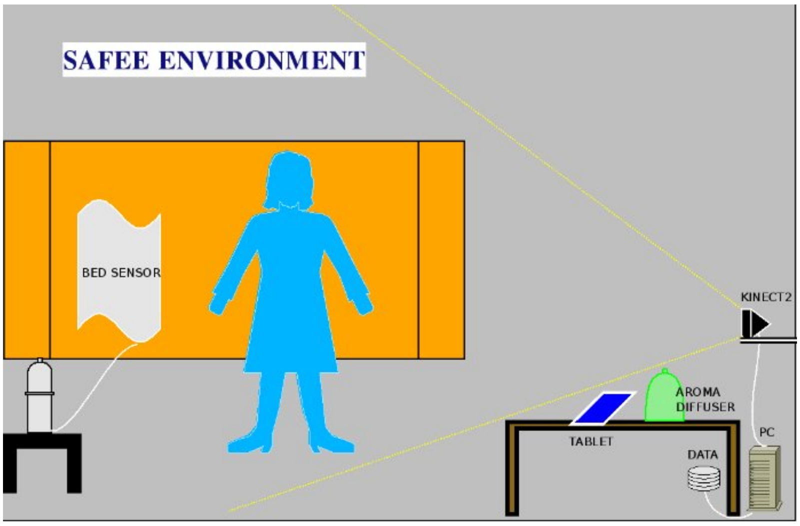

Figure 25. The Safee environment

without changing the current camera network of the customer store, dedicated to security purpose. Analysis should be given at different time and space resolutions. For instance, attendance of one particular day can be as interesting as attendance of the entire year. Moreover, shop owners want to be able to compare two given years or months, etc... As space resolution is concerned, the software should be able to give information about the global attractiveness of the store but should also analyze some specific zones.

IVA embedded on Bosch cameras

Intelligence Video Analysis (IVA) is embedded in some models of Bosch cameras. The algorithms are composed of human detection and tracking. They can be configured directly on the camera interface via *tasks*. We are using a live connection to get metadata directly from the camera stream using a RTSP connection. Thie year we improved the results of last year using calibration tool embedded in the camera : shape of people detected was better, feet were followed with more precision as bounding boxes were more stable. We also tested the new IVA developed by BOSCH which was built to better manage changes in scene brightness and crossing of people. In the former version people close to each other were often detected as one person. Our first tests in shop revealed that it reduces the number of false detection but people were detected later than in the previous version. The case of people crossing doesn't seem to be better managed than before.

Inria algorithms : people detection and tracking

The previously enumerated tasks use algorithms to detect people and get their trajectories. Stars team has developed similar algorithms and has adapted their parameters values to the specific needs of this software. To improve results after some tests made during summer, the people detection is now using a deep learning method. People are detected earlier than before with this new algorithm and people crossing and occlusions are far better managed. The performances and the reliability of those algorithms were tested using an annotation tool developed in Stars Team.

Annotation tool

Manual annotation of videos requires major human effort. It can take hours and hours of fastidious work to annotate a tiny set of data. That's why we propose a semi-automatic tool which reduces the time of the annotation. This new semi automatic annotation tool uses a simple input data format, XML file or XGTF file to describe the video contents and algorithms output. Users only have to correct false or missing detection and to fix some wrong object id of the algorithms results using the annotation tool interface.

Tests in real conditions

We tested our video acquisition tool and our people detection and people tracking algorithms during summer in a partner supermarket in Nice. We successfully acquire 2 weeks of the desired metadata. By the end of summer, our results were highly improved by using a deep learning method to detect people. Moreover we can get results in quasi real-time. Except for the video stream acquisition tool, which needs to be connected to the camera network, our system is now running on an independent and local network. In case there is a crash of our system, the supermarket network will not be affected. Moreover, sensitive data are protected. A test is starting soon in SuperU to run and evaluate this new prototype.

Metadata storage in database

Last year metadata outputs of our analysis were first stored in XML files. Now to manage the quasi real-time solution, metadata are stored directly in the database we designed last year. We improve architecture of this database to manage simultaneously several connections as the final solution is supposed to be composed of several servers which will manage several video streams at the same time.

Web interface (HIM)

The web graphic interface is in progress. User interactions were added and improved so that the interface should be more user-friendly. We also changed some charts and tables so that statistical results should be better understood by users.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- **Toyota Europ**: this project with Toyota runs from the 1st of August 2013 up to 2017 (4 years). It aims at detecting critical situations in the daily life of older adults living home alone. We believe that a system that is able to detect potentially dangerous situations will give peace of mind to frail older people as well as to their caregivers. This will require not only recognition of ADLs but also an evaluation of the way and timing in which they are being carried out. The system we want to develop is intended to help them and their relatives to feel more comfortable because they know potentially dangerous situations will be detected and reported to caregivers if necessary. The system is intended to work with a Partner Robot (to send real-time information to the robot) to better interact with older adults.
- **LinkCareServices**: this project with Link Care Services runs from 2010 upto 2015. It aims at designing a novel system for Fall Detection. This study consists in evaluating the performance of video-based systems for Fall Detection in a large variety of situations. Another goal is to design a novel approach based on RGBD sensors with very low rate of false alarms.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

8.1.1.1. MOVEMENT

Program: ANR CSOSG

Project acronym: MOVEMENT

Project title: AutoMatic BiOmetric Verification and PersonnEl Tracking for SeaMless Airport ArEas Security MaNagemenT

Duration: January 2014-June 2017

Coordinator: MORPHO (FR)

Other partners: SAGEM (FR), Inria Sophia-Antipolis (FR), EGIDIUM (FR), EVITECH (FR) and CERAPS (FR)

Abstract: MOVEMENT is focusing on the management of security zones in the non public airport areas. These areas, with a restricted access, are dedicated to service activities such as maintenance, aircraft ground handling, airfreight activities, etc. In these areas, personnel movements tracking and traceability have to be improved in order to facilitate their passage through the different areas, while insuring a high level of security to prevent any unauthorized access. MOVEMENT aims at proposing a new concept for the airport's non public security zones (e.g. customs control rooms or luggage loading/unloading areas) management along with the development of an innovative supervision system prototype.

8.1.1.2. SafEE

Program: ANR TESCAN

Project acronym: SafEE

Project title: Safe & Easy Environment for Alzheimer Disease and related disorders

Duration: December 2013-May 2017

Coordinator: CHU Nice

Other partners: Nice Hospital(FR), Nice University (CobTeck FR), Inria Sophia-Antipolis (FR), Aromatherapeutics (FR), SolarGames(FR), Taichung Veterans General Hospital TVGH (TW), NCKU Hospital(TW), SMILE Lab at National Cheng Kung University NCKU (TW), BDE (TW)

Abstract: SafEE project aims at investigating technologies for stimulation and intervention for Alzheimer patients. More precisely, the main goals are: (1) to focus on specific clinical targets in three domains behavior, motricity and cognition (2) to merge assessment and non pharmacological help/intervention and (3) to propose easy ICT device solutions for the end users. In this project, experimental studies will be conducted both in France (at Hospital and Nursery Home) and in Taiwan.

8.1.2. FUI

8.1.2.1. 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 Hospitaliere Sainte-Marie.

Abstract: This French project from Industry Minister aims at designing a platform to re-educate at home people with visual impairment.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. CENTAUR

Title: Crowded ENvironments moniToring for Activity Understanding and Recognition

Programm: FP7

Duration: January 2013 - December 2016

Coordinator: Honeywell

Partners:

Ecole Polytechnique Federale de Lausanne (Switzerland)

"honeywell, Spol. S.R.O" (Czech Republic)

Neovision Sro (Czech Republic)

Queen Mary University of London (United Kingdom)

Inria contact: François Bremond

'We aim to develop a network of scientific excellence addressing research topics in computer vision and advancing the state of the art in video surveillance. The cross fertilization of ideas and technology between academia, research institutions and industry will lay the foundations to new methodologies and commercial solutions for monitoring crowded scenes. Research activities will be driven by specific sets of scenarios, requirements and datasets that reflect security operators' needs for guaranteeing the safety of EU citizens. CENTAUR gives a unique opportunity to academia to be exposed to real life dataset, while enabling the validation of state-of-the-art video surveillance methodology developed at academia on data that illustrate real operational scenarios. The research agenda is motivated by ongoing advanced research activities in the participating entities. With Honeywell as a multi-industry partner, with security technologies developed and deployed in both its Automation and Control Solutions and Aerospace businesses, we have multiple global channels to exploit the developed technologies. With Neovison as a SME, we address small fast paced local markets, where the quick assimilation of new technologies is crucial. Three thrusts identified will enable the monitoring of crowded scenes, each led by an academic partner in collaboration with scientists from Honeywell: a) multi camera, multicoverage tracking of objects of interest, b) Anomaly detection and fusion of multimodal sensors, c) activity recognition and behavior analysis in crowded environments. We expect a long term impact on the field of video surveillance by: contributions to the state-of-the-art in the field, dissemination of results within the scientific and practitioners community, and establishing long term scientific exchanges between academia and industry, for a forum of scientific and industrial partners to collaborate on addressing technical challenges faced by scientists and the industry.'

8.3. International Initiatives

8.3.1. Inria International Labs

8.3.1.1. Informal International Partners

- **Collaborations with Asia:** Stars has been cooperating with the Multimedia Research Center in Hanoi MICA on semantics extraction from multimedia data. Stars also collaborates with the National Cheng Kung University in Taiwan and I2R in Singapore.
- **Collaboration with U.S.A.:** Stars collaborates with the University of Southern California.
- **Collaboration with Europe:** Stars collaborates with Multitel in Belgium, the University of Kingston upon Thames UK, and the University of Bergen in Norway.

8.3.1.2. Other IIL projects

The ANR SafEE (see section 8.1.1.2) collaborates with international partners such as Taichung Veterans General Hospital TVGH (TW), NCKU Hospital(TW), SMILE Lab at National Cheng Kung University NCKU (TW) and BDE (TW).

8.4. International Research Visitors

8.4.1. Visits of International Scientists

This year, Stars has been visited by the following international scientists:

- Salwa Baabou, Ecole Nationale d'Ingénieurs de Gabès, Tunisia;
- Siyuan Chen, University of New South Wales, Australia;
- Adlen Kerboua, University of Skikda, Algeria;
- Karel Krehnac, Neovision, Praha, Czech Republic;
- Jana Trojnova, Honeywell, Praha, Czech Republic;
- Luis Emiliano Sanchez, Rosario University, Argentina.

8.4.1.1. Internships

Seongro Yoon

Date: Apr 2016-Dec 2016
Institution: Korea Advanced Institute of Science and Technology, Daejeon, Korea
Supervisor: François Brémond

Yashas Annadani

Date: May2016-June 2016
Institution: National Institute Of Technology Karnataka, India
Supervisor: Carlos Fernando Crispim Junior

Chandraja Dharmana

Date: May 2016-June 2016
Institution: Birla Institute of Technology and Science, Pilani, Hyderbrad
Supervisor: Carlos Fernando Crispim Junior

Shanu Vashistha

Date: May 2016-June 2016
Institution: Indian Institute of Technology, Kanpur, India
Supervisor: Carlos Fernando Crispim Junior

Nairouz Mrabah

Date: Apr 2016-Sep 2016
Institution: National School of Computer Science (ENSI), Tunisia
Supervisor: Inès Sarray

Isabel Rayas

Date: June 2016-Dec 2016
Institution: Massachusetts Institute of Technology, USA
Supervisor: Farhood Negin

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific events organisation

9.1.1.1. General chair, scientific chair

François Brémond was organizer of the ISG 2016, 10th World Conference of Gerontechnology, Nice,28th to 30th September 2016.

François Brémond was editor of the Crowd Understanding workshop, part of ECCV, Amsterdam, October 2016.

9.1.1.2. Member of the organizing committee

François Brémond was a member of the Management Committee and COST Action IC1307 in 2016.

9.1.2. Scientific events selection

9.1.2.1. Member of the conference program committees

François Brémond was program committee member of the conferences and workshops: KSE 2016, PETS2016, MMM2017.

François Brémond was ACM Multimedia Area Chair for Multimedia and Vision, Amsterdam, 2016.

François Brémond was session chair of AVSS-16, Colorado Springs, USA, 2016.

Jean-Paul Rigault is a member of the *Association Internationale pour les Technologies à Objets* (AITO) which organizes international conferences such as ECOOP.

Antitza Dantcheva was program committee member of the conference International Conference on Biometrics (ICB 2016), the CVPR Workshop ChaLearn Looking at People 2016 and the Healthcare Conference Workshop within the EAIInternational Conference on Pervasive Computing Technologies.

9.1.2.2. Reviewer

François Brémond was reviewer for the conferences : CVPR2016-7, ECCV2016, VOT2016, MARMI2016, WACV 2017.

Carlos Fernando Crispim Junior was reviewer for the conferences: International Conference on Intelligent Robot and Systems, IEEE International Conference on Robotics and Automaton, Brazilian Conference in Biomadical Engineering, AMBIANT Conference, Computer on the Beach.

9.1.3. Journal

9.1.3.1. Member of the editorial boards

François Brémond was handling editor of the international journal "SDECLAREMachine Vision and Application".

9.1.3.2. Reviewer - Reviewing activities

François Brémond was reviewer for the journal revue Retraite et sociétéänd Medical Engineering & Physics.

Carlos Fernando Crispim Junior was reviewer for the journals: Pattern Recognition, Neurocomputing, Computer Vision and Image Understanding Journal, Computers in Biology and Medecine Journal, PLOS One Journal, Frontiers in Neuroscience, Sensors.

Antitza Dantcheva reviewed for the journals: IEEE Transactions on Information Forensics and Security (TIFS), Information Processing Letters, The Computer Journal, IET Biometrics, Multimedia Systems, International Journal for Information Management, Information Fusion (INFFUS), Sensors, Pattern Recognition.

9.1.4. Invited talks

François Brémond was invited by Prof. Ram Nevatia to give a talk on research initiatives and new directions in Video Understanding, USC, LA, USA 17 August 2016.

François Brémond was invited by Prof. Jonathan Ventura to give a talk on People detection, at the SLDP 2016 workshop of AVSS, Colorado Springs, USA,23 August 2016.

François Brémond was invited by Prof. William Robson Schwartz,Department of Computer Science, Federal University of Minas Gerais to give a talk on Video Analytic, at Video Surveillance workshop in Belo Horizonte-Brazil, 03 October 2016.

François Brémond was invited by Prof. William Robson Schwartz to give a talk on People Tracking, at SIBGRAPI 2016, Sao Paulo-Brazil, 05 October 2016.

François Brémond was invited by Prof. Cosimo Distante, Consiglio Nazionale delle Ricerche to give a talk on Activity Recognition, at ACIVS 2016, Lecce, Italy, 26 October 2016.

François Brémond was invited by Sebastien Ambellouis (IFSTTAR) to give a talk on Activity Monitoring, at IEEE IPAS 2016,Hammamet, Tunisia,5-7 November 2016.

Carlos Fernando Crispim Junior was invited to give a talk at the 1st Inter-lalex seminar "Smart Systems", Besançon, France, November 23rd 2016.

Carlos Fernando Crispim Junior was invited to make a presentation at PSI-VISICS seminar at ESAT department in KU Leuven University,October 24th 2016.

Carlos Fernando Crispim Junior was invited to make a presentation at Machine Learning seminar at Computer Science department of KU Leuven University, October 17th 2016.

Carlos Fernando Crispim Junior was invited to give a talk at ISG 2016 - Seminar European FP7 project Dem@care: Automatic Video Analysis for Diagnosis and Care, Nice, France, October 29th 2016.

Carlos Fernando Crispim Junior was invited speaker at the internal seminar of LAAS-CNRS, Toulouse, France, July3rd-4th.

Carlos Fernando Crispim Junior was invited speaker at CPUEX seminar, LABRI-CNRS, Bordeaux, France, February 2016.

9.1.5. Scientific expertise

François Brémond was expert for EU European Reference Network for Critical Infrastructure Protection (ERNCIP) - Video Anlaytics and surveillance Group, at European Commission's Joint Research Centre in Brussels in July 2016.

François Brémond was expert for the Foundation Médéric Alzheimer, for the doctoral fellowship selection, September 2016.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master : Annie Ressouche, Safety in Middleware for Internet of Things, 10h, niveau (M2), Polytech Nice School of Nice University.

Jean-Paul Rigault is Full Professor of Computer Science at Polytech'Nice (University of Nice): courses on C++ (beginners and advanced), C, System Programming, Software Modeling.

9.2.2. Supervision

PhD in progress : Auriane Gros, Evaluation and Specific Management of Emotionnal Disturbances with Activity Recognition Systems for Alzheimer patient, Sept 2014, François Brémond.

PhD in progress : Minh Khue Phan Tran, Man-machine interaction for older adults with dementia, May 2013, François Brémond.

PhD in progress : Michal Koperski, Detecting critical human activities using RGB/RGBD cameras in home environment, François Brémond.

PhD in progress : Thi Lan Anh Nguyen, Complex Activity Recognition from 3D sensors, Dec 2014, François Brémond.

PhD in progress : Ines Sarray, Activity Recognition System Design, Oct 2015, Sabine Moisan.

PhD in progress : Farhood Negin, People Detection for Activity Recognition using RGB-Depth Sensors, Jan 2015, François Brémond.

PhD in progress : Ujjwal Ujjwal, Pedestrian Detection to Dynamically Populate the Map of a Crossroad, Sep 2016, François Brémond.

9.2.3. Juries

François Brémond was jury member of the following PhD theses:

PhD, Andrei Stoian, CNAM, Paris, 15 January 2016.

PhD, Romain Endelin, University of Montpellier, 2nd June 2016.

PhD, Jean-Charles Bricola, CMM, Mines ParisTech, Fontainebleau, 19 October 2016.

PhD, Salma Moujtahid, LIRIS-Equipe IMAGINE-INSA Lyon, 3 November 2016.

PhD, Marion Chevalier, Laboratoire d'Informatique de Paris 6, Thales Optronique S.A.S., Paris,2 December 2016.

9.3. Popularization

François Brémond was invited to give a talk at Conférence des métiers at International Lycée (CIV) in Sophia, January 2016.

François Brémond was interviewed by the agence Citizen Press February 2016.

François Brémond was invited to give a talk at the Artificial Intelligence Workshop Meeting Amadeus - Inria, June 2016.

François Brémond was invited to give a talk at la rencontre Inria Industrie Ed-Tech, 1 December 2016.

François Brémond has published an article in ERCIM news, December 2016.

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Project-Team TITANE

Geometric Modeling of 3D Environments

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Interaction and visualization

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Project-Team TITANE

Creation of the Team: 2013 January 01, updated into Project-Team: 2014 January 01

Keywords:

Computer Science and Digital Science:

5.3. - Image processing and analysis
5.4.4. - 3D and spatio-temporal reconstruction
5.5.1. - Geometrical modeling
7.5. - Geometry, Topology

Other Research Topics and Application Domains:

3.3. - Geosciences
5. - Industry of the future
8. - Smart Cities and Territories

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Visiting Scientists

Jingjing Shen [Fitzwilliam College, from May to Jun 2016]
David Bommes [RWTH Aachen, Research professor, Sep 2016]
Martin Heistermann [RWTH Aachen, PhD student, Sep 2016]

Administrative Assistant

Florence Barbara [Inria]

Others

Mathieu Desbrun [Inria, International Chair from Aug. to Nov. 2016 - Associate Researcher from Caltech]
Chunlin Xiao [Inria, Master intern from UNS, from Mar to Sep 2016, funded by CNES]

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. 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

5.1.1. Awards

We obtained a Proof of Concept grant from the European Research Council, entitled TITANIUM (Software Components for Robust Geometry Processing). The TITANIUM project aims to develop a software demonstrator for geometry processing and 3D urban modeling, in order to facilitate the pre-commercialization of novel software components for the Computational Geometry Algorithms Library. The demonstrator will include novel approaches resulting from the ERC-funded IRON project.

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BEST PAPERS AWARDS :

[] **Computer Graphics Forum**. Z. SHI, P. ALLIEZ, M. DESBRUN, H. BAO, J. HUANG.

6. New Software and Platforms

6.1. CGAL Barycentric_coordinates_2

This CGAL software component offers an efficient and robust implementation of two-dimensional closed-form generalized barycentric coordinates defined for simple two-dimensional polygons.

- Participants: Pierre Alliez
- Contact: Pierre Alliez
- URL: http://doc.cgal.org/latest/Barycentric_coordinates_2/index.html#Chapter_2D_Generalized_Barycentric_Coordinates

6.2. MeshMantics

This software component implements an approach that reconstructs 3D urban scenes in the form of levels of detail (LODs). Starting from raw data sets such as surface meshes generated by multi-view stereo systems, the algorithm proceeds in three main steps: classification, abstraction and reconstruction. From geometric attributes and a set of semantic rules combined with a Markov random field, we classify the scene into four meaningful classes. The abstraction step detects and regularizes planar structures on buildings, fits icons on trees, roofs and facades, and performs filtering and simplification for LOD generation. The abstracted data are then provided as input to the reconstruction step which generates watertight buildings through a min-cut formulation on a set of 3D arrangements.

- Participants: Florent Lafarge and Pierre Alliez
- Contact: Pierre Alliez
- URL: https://bil.inria.fr

6.3. Module CGAL : Point Set Processing

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: Pierre Alliez and Clément Jamin
- Contact: Pierre Alliez
- URL: http://doc.cgal.org/latest/Point_set_processing_3/index.html#Chapter_Point_Set_Processing

6.4. Module CGAL : Scale space surface reconstruction

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
- Contact: Pierre Alliez
- URL: http://doc.cgal.org/latest/Scale_space_reconstruction_3/index.html#Chapter_Scale_space_reconstruction

6.5. Skeleton-Blockers

Skeleton-Blockers is a compact, efficient and generic data-structure that can represent any simplicial complex. The implementation is in C++11.

- Participant: David Salinas
- Contact: David Salinas
- URL: https://project.inria.fr/gudhi/software/

6.6. APP Deposits

WALLEMME is a software for classifying large-scale urban areas from dense textured 3D meshes in a supervised manner.

- Participants: Mohammad Rouhani, Florent Lafarge and Pierre Alliez.

DIMUVIC is a software for reconstructing in 3D a polyline-sketch using contextual knowledge contained in multiview stereo images.

- Participants: Jean-Dominique Favreau, Florent Lafarge and Adrien Bousseau.

ROOFEXTRACTOR is a software for reconstructing roofs from dense defect-laden meshes as compact piecewise-planar surface representations.

- Participants: Sven Oesau and Florent Lafarge.

7. New Results

7.1. Analysis

7.1.1. Object Classification via Planar Abstraction

Participants: Sven Oesau, Florent Lafarge, Pierre Alliez.

In collaboration with EADS ASTRIUM

We contributed a supervised machine learning approach for classification of objects from sampled point data. The main idea consists in first abstracting the input object into planar parts at several scales, then discriminate between the different classes of objects solely through features derived from these planar shapes. Abstracting into planar shapes provides a means to both reduce the computational complexity and improve robustness to defects inherent to the acquisition process. Measuring statistical properties and relationships between planar shapes offers invariance to scale and orientation. A random forest is then used for solving the multiclass classification problem. We demonstrate the potential of our approach on a set of indoor objects from the Princeton shape benchmark and on objects acquired from indoor scenes and compare the performance of our method with other point-based shape descriptors [9]. This work was published in the proceedings of ISPRS.

7.1.2. *Fidelity vs. Simplicity: a Global Approach to Line Drawing Vectorization*

Participants: Jean-Dominique Favreau, Florent Lafarge.

In collaboration with Adrien Bousseau (GraphDeco Inria team)

Vector drawing is a popular representation in graphic design because of the precision, compactness and editability offered by parametric curves. However, prior work on line drawing vectorization focused solely on faithfully capturing input bitmaps, and largely overlooked the problem of producing a compact and editable curve network. As a result, existing algorithms tend to produce overly-complex drawings composed of many short curves and control points, especially in the presence of thick or sketchy lines that yield spurious curves at junctions. We propose the first vectorization algorithm that explicitly balances fidelity to the input bitmap with simplicity of the output, as measured by the number of curves and their degree. By casting this trade-off as a global optimization, our algorithm generates few yet accurate curves, and also disambiguates curve topology at junctions by favoring the simplest interpretations overall. We demonstrate the robustness of our algorithm on a variety of drawings, sketchy cartoons and rough design sketches (See Figure 1). This work was published at ACM SIGGRAPH 2016 [4].

7.1.3. *High-Resolution Semantic Labeling with Convolutional Neural Networks*

Participants: Emmanuel Maggiori, Yuliya Tarabalka, Pierre Alliez.

In collaboration with Guillaume Charpiat (Inria TAO team)

Convolutional neural networks (CNNs) were initially conceived for image categorization, i.e., the problem of assigning a semantic label to an entire input image. We have address the problem of dense semantic labeling, which consists in assigning a semantic label to *every* pixel in an image. Since this requires a high spatial accuracy to determine *where* labels are assigned, categorization CNNs, intended to be highly robust to local deformations, are not directly applicable. By adapting categorization networks, many semantic labeling CNNs have been recently proposed. Our first contribution is an in-depth analysis of these architectures. We establish the desired properties of an ideal semantic labeling CNN, and assess how those methods stand with regard to these properties. We observe that even though they provide competitive results, these CNNs often do not leverage properties of semantic labeling that could lead to more effective and efficient architectures. Out of these observations, we then derive a CNN framework specifically adapted to the semantic labeling problem [12]. In addition to learning features at different resolutions, it learns how to combine these features. By integrating local and global information in an efficient and flexible manner, it outperforms previous techniques. We evaluate the proposed framework and compare it with state-of-the-art architectures on public benchmarks of high-resolution aerial image labeling.

7.1.4. *Learning Iterative Processes with Recurrent Neural Networks to Correct Satellite Image Classification Maps*

Participants: Emmanuel Maggiori, Yuliya Tarabalka, Pierre Alliez.

In collaboration with Guillaume Charpiat (Inria TAO team)

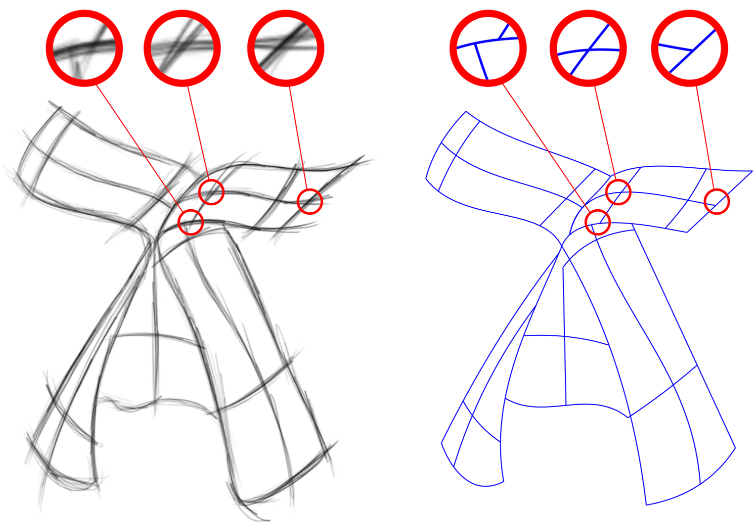


Figure 1. Line Drawing Vectorization. Rough sketches often contain overlapping strokes (left). Since existing algorithms analyze junctions locally, they cannot recover the proper topology of these seemingly similar line configurations. By adopting a global formulation that optimizes for both fidelity to the input sketch and simplicity of the output curve network, our algorithm recovers proper topology while significantly reducing the overall number of curves and control points (right). Design sketch after Sori Yanagi Butterfly stool.

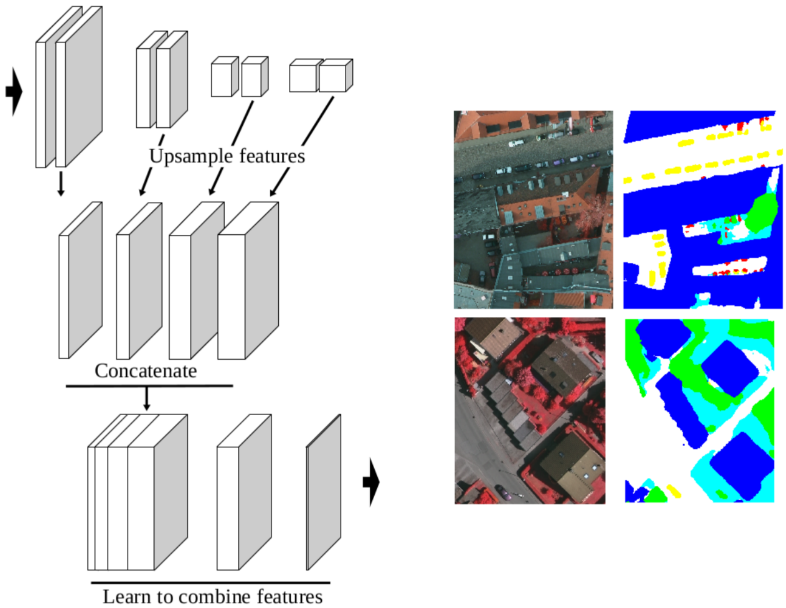


Figure 2. Our MLP network architecture (left) learns features at different resolutions and also learns how to combine those features. The technique was evaluated on the ISPRS 2D Semantic Segmentation Contest (right), providing competitive results.

While initially devised for image categorization, convolutional neural networks (CNNs) are being increasingly used for the pixelwise semantic labeling of images. However, the proper nature of the most common CNN architectures makes them good at recognizing but poor at localizing objects precisely. This problem is magnified in the context of aerial and satellite image labeling, where a spatially fine object outlining is of paramount importance.

Different iterative enhancement algorithms have been presented in the literature to progressively improve the coarse CNN outputs, seeking to sharpen object boundaries around real image edges. However, one must carefully design, choose and tune such algorithms. Instead, our goal is to directly learn the iterative process itself. For this, we formulate a generic iterative enhancement process inspired from partial differential equations, and observe that it can be expressed as a recurrent neural network (RNN). Consequently, we train such a network from manually labeled data for our enhancement task. In a series of experiments we show that our RNN effectively learns an iterative process that significantly improves the quality of satellite image classification maps [11].

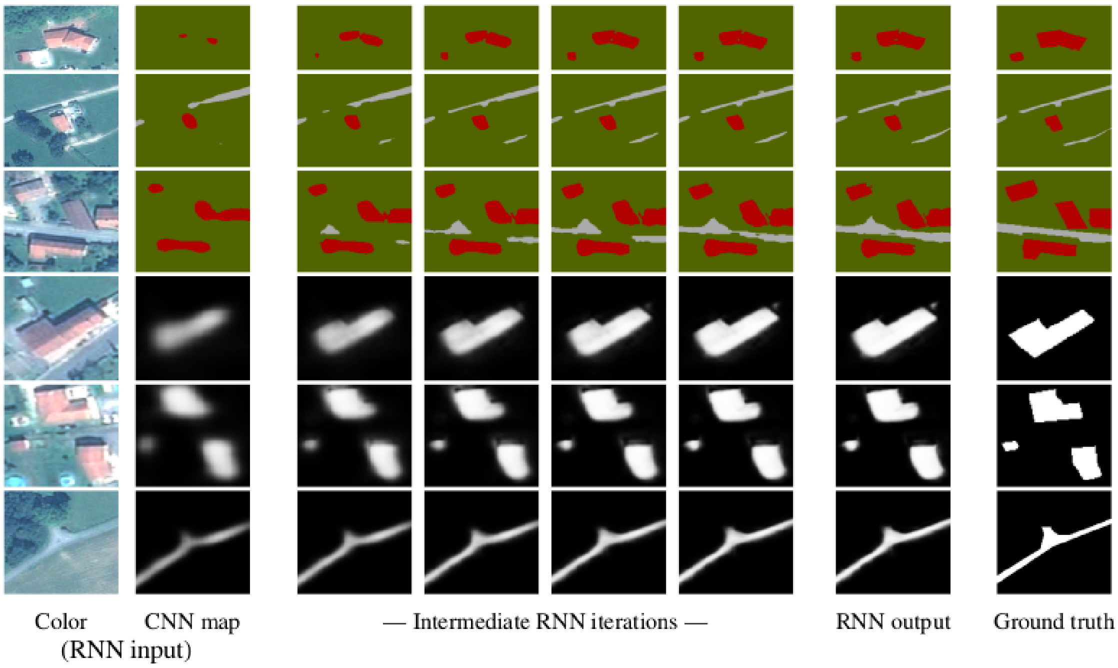


Figure 3. A recurrent neural network (RNN) learns an algorithm to iteratively correct the output of a coarse classification map. As a result, the satellite image classification maps become finer and better aligned to the real objects.

7.1.5. Convolutional Neural Networks for Large-Scale Remote-Sensing Image Classification

Participants: Emmanuel Maggiori, Yuliya Tarabalka, Pierre Alliez.

In collaboration with Guillaume Charpiat (Inria TAO team)

We propose an end-to-end framework for the dense, pixelwise classification of satellite imagery with convolutional neural networks (CNNs). In our framework, CNNs are directly trained to produce classification maps out of the input images. We first devise a *fully convolutional* architecture and demonstrate its relevance to the dense classification problem. We then address the issue of imperfect training data through a two-step training approach: CNNs are first initialized by using a large amount of possibly inaccurate reference data, then refined on a small amount of accurately labeled data. To complete our framework we design a multi-scale neuron module that alleviates the common trade-off between recognition and precise localization. A series of experiments show that our networks take into account a large amount of context to provide fine-grained classification maps. This work was published in IEEE Transactions on Geoscience and Remote Sensing (TGRS) [5].

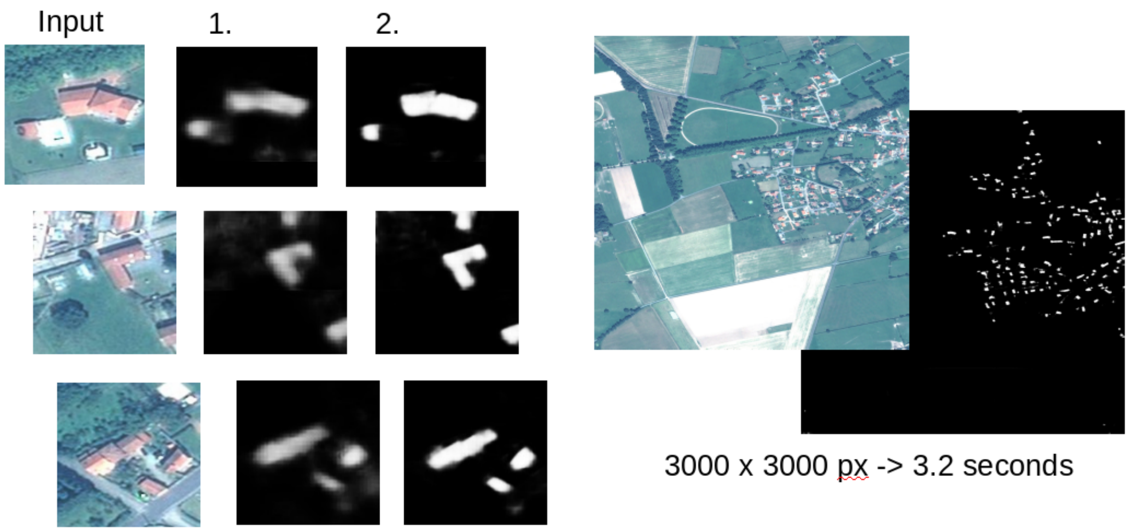


Figure 4. We train in a two-step scheme: first we train a fully convolutional network on large amounts of imperfect training data, to capture the generalities of the problem, which leads to coarse classification maps (1). In a second stage we fine-tune the network for few iterations on a precise manually labeled dataset, outputting fine classification maps as a results (2). The overall system is efficient and scalable.

7.1.6. Fully Convolutional Neural Networks for Remote Sensing Image Classification

Participants: Emmanuel Maggiori, Yuliya Tarabalka, Pierre Alliez.

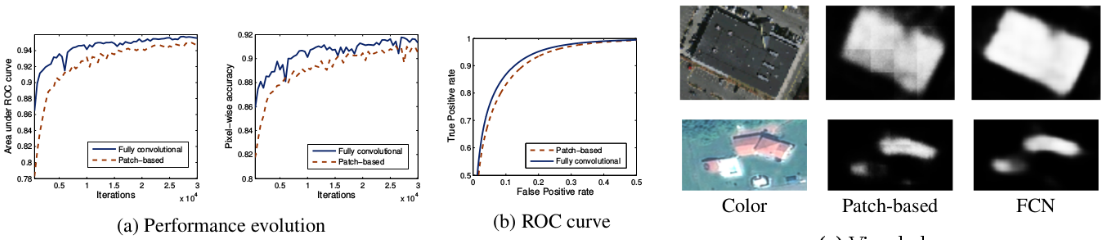
In collaboration with Guillaume Charpiat (Inria TAO team)

We propose a convolutional neural network (CNN) model for remote sensing image classification, i.e. the assignment of a class to every pixel in an image. Using CNNs provides us with a means of learning contextual features for large-scale image labeling. Our network consists of four stacked convolutional layers that downsample the image and extract relevant features. On top of these, a deconvolutional layer upsamples the data back to the initial resolution, producing a final dense image labeling. Contrary to previous frameworks, our architecture is a fully convolutional network (FCN), contains only convolution and deconvolution operations and no fully connected layers as in previous work. The fact of being fully convolutional removes the artifacts present in previous work by construction and is considerably more efficient. Experiments on aerial images show that our network produces more accurate classifications in lower computational time. This work was published in the proceedings of the IEEE International Geoscience and Remote Sensing Symposium (IGARSS) [8].

7.1.7. Large-scale Remote Sensing Image Segmentation and Classification

Participants: Chunlin Xiao, Emmanuel Maggiori, Yuliya Tarabalka.

In collaboration with Guillaume Charpiat (Inria TAO team)



(a) Performance evolution (b) ROC curve (c) Visual closeups

Figure 5. Our fully convolutional network (FCN) provides a better accuracy compared to a previous method (the "patch-based" network), as observed by the evolution of the accuracy through the training iterations (a) and the final precision/recall curve (b). We can also observe, visually, that our FCN network removes the artifacts at the border of patches (c). Besides the improved performance, the architecture drastically reduces the number of trainable parameters, being 10 times faster to run compared to the patch-based counterpart.

The representation of images with binary partition trees (BPTs) has proven to be very efficient for multiscale analysis, object detection and classification of high-resolution images. We propose a new framework for multi-class image segmentation using a binary partition tree. The region model is composed of three components : color component, probability component and shape component, some of which can be used or omitted depending on the information available and the application itself. The problem to extract a segmentation is formulated as the minimization of an energy function which can be solved with dynamical programming efficiently. However, BPT represents a hierarchy of the image regions at different scales. For large-scale images such representation can be demanding in terms of both memory and computation resources. We propose a tile-based scheme to extend the framework for processing arbitrarily large images. Experiments (see Fig. 6) prove that the algorithm can segment large images efficiently while ensuring quite similar results with respect to processing the whole image at once. This work has not been published yet.

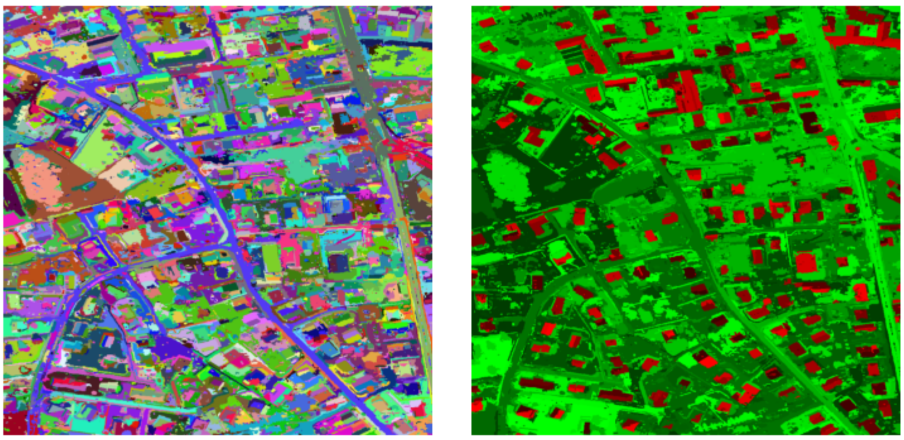


Figure 6. Results of (left) unsupervised segmentation and (right) supervised segmentation of the image into building (red) and non-building (green) regions, using 4×4 tiling scheme.

7.2. Reconstruction

7.2.1. Towards Large-scale City Reconstruction from Satellites

Participants: Liuyun Duan, Florent Lafarge.

In collaboration with Geoimage.

Automatic city modeling from satellite imagery is one of the biggest challenges in urban reconstruction. Existing methods produce at best rough and dense Digital Surface Models. Inspired by recent works on semantic 3D reconstruction and region-based stereovision, we propose a method for producing compact, semantic-aware and geometrically accurate 3D city models from stereo pair of satellite images [7]. Our approach relies on two key ingredients. First, geometry and semantics are retrieved simultaneously bringing robustness to occlusions and to low image quality. Second, we operate at the scale of geometric atomic region which allows the shape of urban objects to be well preserved, and a gain in scalability and efficiency. We demonstrate the potential of our algorithm by reconstructing different cities around the world in a few minutes (See Figure 7). This work has been published in the proceedings of the European Conference on Computer Vision (ECCV).

Figure 7. City reconstruction from satellites. Starting from a stereo pair of satellite images (left), our algorithm produces a compact and semantic-aware 3D model (right) in a few minutes.

7.2.2. A Survey of Surface Reconstruction from Point Clouds

Participant: Pierre Alliez.

In collaboration with Matthew Berger, Andrea Tagliasacchi, Lee Seversky, Gael Guennebaud (Inria MANAO), Joshua Levine, Andrei Sharf and Claudio Silva.

The area of surface reconstruction has seen substantial progress in the past two decades. The traditional problem addressed by surface reconstruction is to recover the digital representation of a physical shape that has been scanned, where the scanned data contains a wide variety of defects. While much of the earlier work has been focused on reconstructing a piece-wise smooth representation of the original shape, recent work has taken on more specialized priors to address significantly challenging data imperfections, where the reconstruction can take on different representations – not necessarily the explicit geometry. We survey the field of surface reconstruction, and provide a categorization with respect to priors, data imperfections, and reconstruction output. By considering a holistic view of surface reconstruction, we show a detailed characterization of the field, highlight similarities between diverse reconstruction techniques, and provide directions for future work in surface reconstruction. This survey was published in Computer Graphics Forum [2].

7.3. Approximation

7.3.1. A Line/Trimmed NURBS Surface Intersection Algorithm Using Matrix Representations

Participant: Pierre Alliez.

In collaboration with Laurent Busé from Inria AROMATH, and Jingjing Shen and Neil Dodgson from Cambridge University (UK).

We contribute a reliable line/surface intersection method for trimmed NURBS surfaces, based on a novel matrix-based implicit representation and numerical methods in linear algebra such as singular value decomposition and the computation of generalized eigenvalues and eigenvectors. A careful treatment of degenerate cases makes our approach robust to intersection points with multiple pre-images. We then apply our intersection algorithm to seamlessly mesh NURBS surfaces through Delaunay refinement (see Figure 8). We demonstrate the added value of our approach in terms of accuracy and treatment of degenerate cases, by providing comparisons with other intersection approaches as well as a variety of meshing experiments. This work was published in Computer Aided Geometric Design [6].

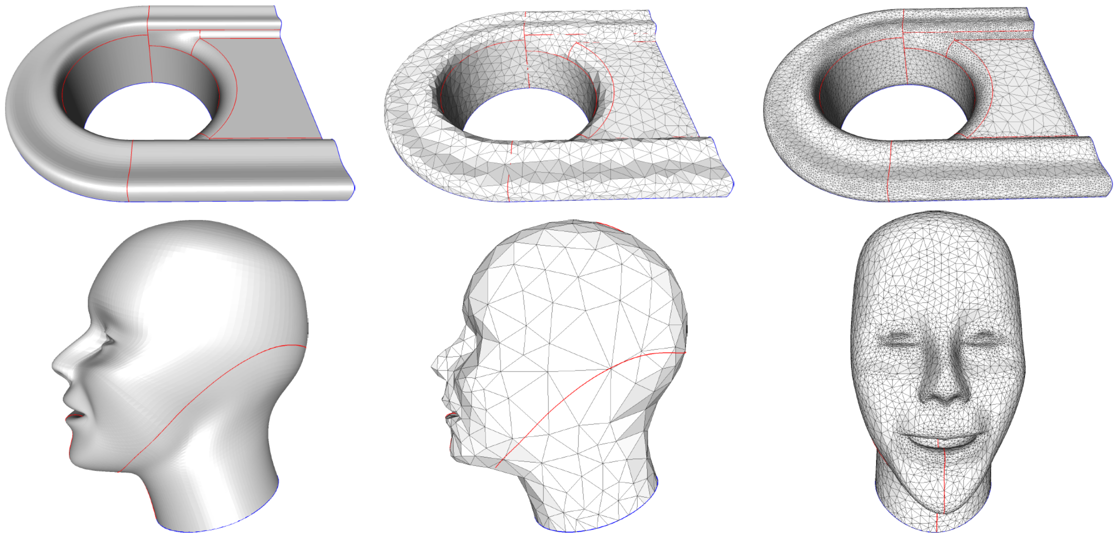


Figure 8. Seamless meshing. Top: meshing with two mesh sizing values. The initial point set is generated by sampling along the open boundary. Bottom: meshing across smooth edges (red). The initial point set is generated by sampling along the boundary edge (blue). Meshes generated with two sizing values (side and front view).

7.3.2. Optimal Voronoi Tessellations with Hessian-based Anisotropy

Participants: Pierre Alliez, Mathieu Desbrun.

In collaboration with Max Budninskiy and Beibei Liu from Caltech, Fernando de Goes from Pixar and Yiying Tong from Michigan State University.

We contribute a variational method to generate cell complexes with local anisotropy conforming to the Hessian of any given convex function and for any given local mesh density. Our formulation builds upon approximation theory to offer an anisotropic extension of Centroidal Voronoi Tessellations which can be seen as a dual form of Optimal Delaunay Triangulation. We thus refer to the resulting anisotropic polytopal meshes as Optimal Voronoi Tessellations. Our approach sharply contrasts with previous anisotropic versions of Voronoi diagrams as it employs first-type Bregman diagrams, a generalization of power diagrams where sites are augmented with not only a scalar-valued weight but also a vector-valued shift. As such, our OVT meshes contain only convex cells with straight edges (Figure 9), and admit an embedded dual triangulation that is combinatorially-regular. We show the effectiveness of our technique using off-the-shelf computational geometry libraries. This work was published at ACM SIGGRAPH Asia [3].

7.3.3. Symmetry and Orbit Detection via Lie-Algebra Voting

Participants: Pierre Alliez, Mathieu Desbrun.

In collaboration with Zeyun Shi, Hujun Bao and Jin Huang from Zhejiang University.

We formulate an automatic approach to the detection of partial, local, and global symmetries and orbits in arbitrary 3D datasets. We improve upon existing voting-based symmetry detection techniques by leveraging the Lie group structure of geometric transformations. In particular, we introduce a logarithmic mapping that ensures that orbits are mapped to linear subspaces, hence unifying and extending many existing mappings in a single Lie-algebra voting formulation (Figure 10). Compared to previous work, our resulting method offers significantly improved robustness as it guarantees that our symmetry detection of an input model is frame, scale, and reflection invariant. As a consequence, we demonstrate that our approach efficiently and reliably discovers symmetries and orbits of geometric datasets without requiring heavy parameter tuning. This work was published in the proceedings of the EUROGRAPHICS Symposium on Geometry Processing [].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Geoimage

Participants: Liuyun Duan, Florent Lafarge.

The aim of this collaboration is to devise a new type of 2.5D representation from satellite multi-view stereo images which is more accurate, compact and meaningful than the conventional digital elevation models (DEMs). A key direction consists in incorporating semantic information directly during the image matching process. This semantic is related to the type of components of the scene, such as vegetation, roofs, building edges, roads and land.

- Starting date: November 2013 - Duration: 4 years

8.1.2. CSTB 1

Participants: Sven Oesau, Florent Lafarge.

The goal of this collaboration was to consolidate and integrate research codes developed in Titane on urban semantization and reconstruction into the CSTB reconstruction platform.

- Starting date: September 2015 - Duration: 6 months

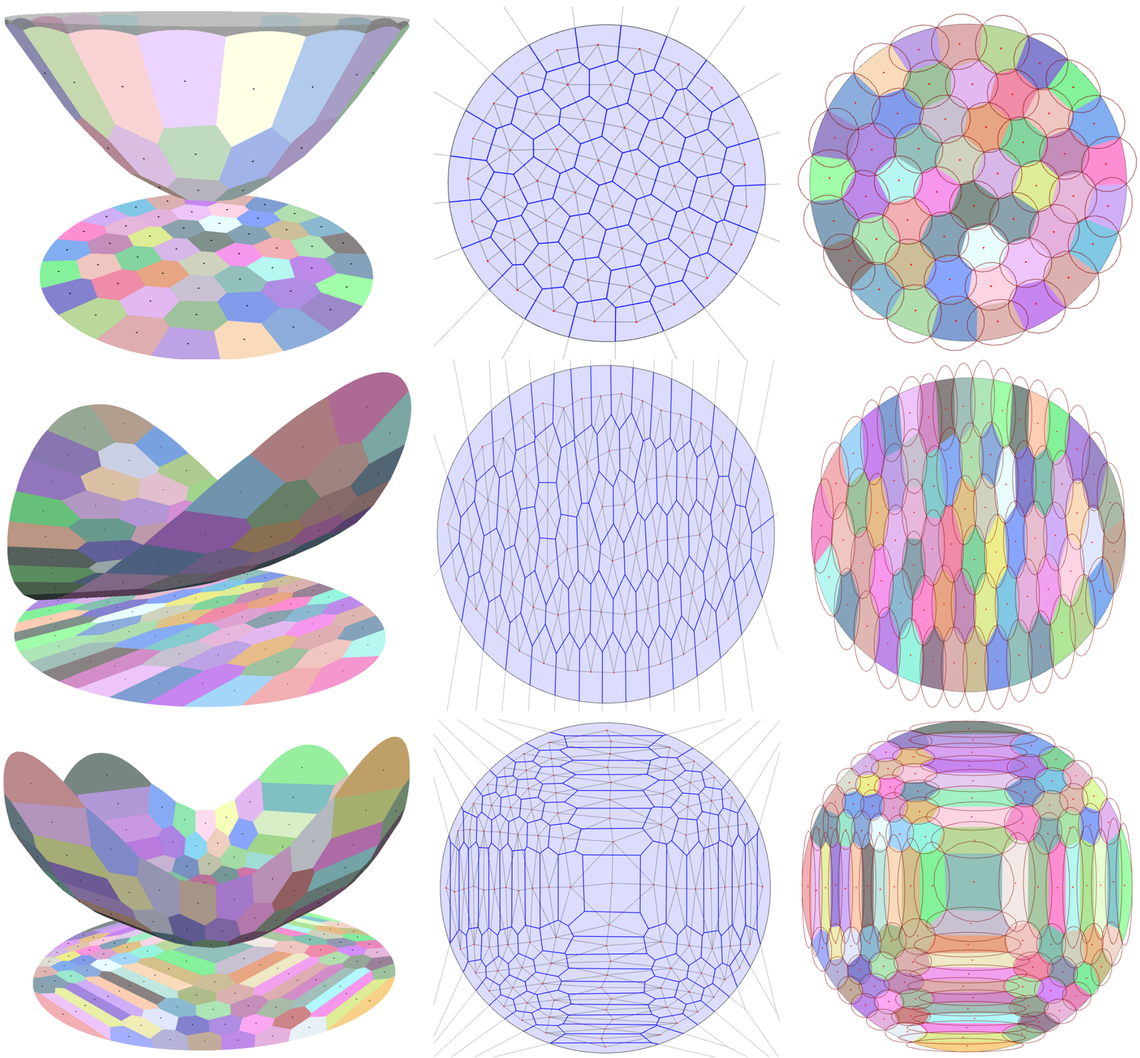
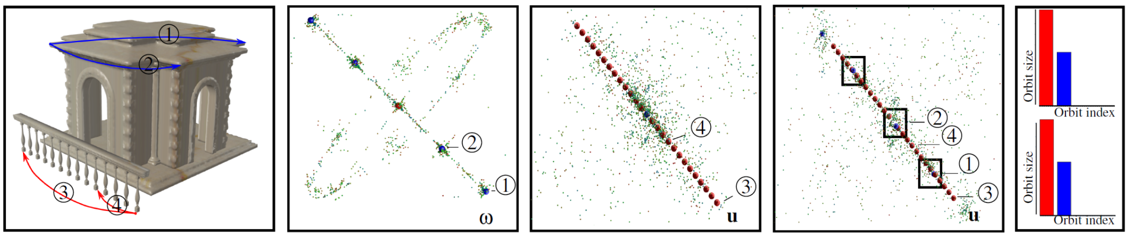


Figure 9. Optimal Voronoi Tessellations with Hessian-based Anisotropy. We show that the construction of an optimal piecewise-linear approximation of a function over a cell complex (left) extends the isotropic notion of Centroidal Voronoi Tessellations (CVT, top) to an anisotropic variant (middle and bottom) we call Optimal Voronoi Tessellation (OVT), to stress its duality to Optimal Delaunay Triangulation (ODT). Cell anisotropy (indicated by tightest ellipses) and density are independently controlled, and the dual triangulation based on cell barycenters is embedded and combinatorially-regular.



(a) (b) (c) (d) (e)

Figure 10. Our Lie algebra voting approach to symmetry and orbit detection maps SE(3) transformations into points in a logarithmic space composed of a rotation part and a translation part. The rotational orbit of the church and the translational orbit of the side railing (a) are mapped into collinear blue and red spheres respectively (a few transformations within these two orbits are marked with circled numbers to enhance comprehension). When the scene is centered, the two lines are orthogonal to each other and easy to distinguish (b). However, after a rigid translation of the scene, the rotational orbit now has translation-values near the translation orbit points, making it impossible to automatically distinguish these two orbits using a Euclidean distance (d), while our adjoint invariant distance for orbit shows no discernible difference in results as evidenced by a binning of detected orbit sizes for both situations (e).

8.1.3. CSTB 2

Participants: Hao Fang, Florent Lafarge.

The goal of this recent collaboration is to develop methods for analyzing and exploring scale-spaces into urban 3D data.

- Starting date: March 2016 - Duration: 3 years

8.1.4. Luxcarta

Participants: Jean-Philippe Bauchet, Florent Lafarge.

The goal of this recent collaboration is to design automatics approaches for producing LOD2 city models from the last generation of satellites.

- Starting date: October 2016 - Duration: 3 years

8.2. Bilateral Grants with Industry

8.2.1. CNES Toulouse

Participants: Emmanuel Maggiori, Yuliya Tarabalka [PI].

Hierarchical approaches for object-oriented classification of multi-source images. Contract 150490/00.

- Starting date: November 2015
- Duration: 2 years

9. Partnerships and Cooperations

9.1. European Initiatives

9.1.1. FP7 & H2020 Projects

9.1.1.1. TITANIUM - Software Components for Robust Geometry Processing

Type: IDEAS

Instrument: ERC Proof of concept

Duration: 18 months

Coordinator: Pierre Alliez

Inria contact: Pierre Alliez

Abstract: The TITANIUM project aims to develop a software demonstrator for geometry processing and 3D urban modeling, in order to facilitate the pre-commercialization of novel software components for the Computational Geometry Algorithms Library. The demonstrator will include novel approaches resulting from the ERC-funded IRON project (Robust Geometry Processing, StG-2010-257474), which are illustrated by publications presented at premier conferences in our field and a patent submitted in 2015. The expected outcomes of TITANIUM will be versatile methods for 3D reconstruction and simplification of data gathered from geometric measurements, as well as related methods specifically tailored to urban modeling. These methods represent a significant step forward by offering unrivaled levels of robustness, and automated generation of levels of detail that are semantically meaningful. The acronym TITANIUM, a robust and lightweight material, conveys our wish to streamline the geometric modeling pipeline through robust algorithms and lightweight representations. This Proof of Concept project will also implement the steps required for pre-commercialization. In view of this goal, we have included an industrial partner, GeometryFactory, a spinoff from Inria. We have already established preliminary contacts in the fields of metrology and geographic information systems. These contacts will provide real-world industrial case studies.

9.2. International Initiatives

9.2.1. Inria International Partners

9.2.1.1. Declared Inria International Partners

We have a long standing collaboration with Prof. Mathieu Desbrun from Caltech.

9.2.1.2. Informal International Partners

We collaborate with researchers from RWTH Aachen.

9.3. International Research Visitors

9.3.1. Visits of International Scientists

Prof. Mathieu Desbrun visited us for 3 months between August and November, within the framework of the Inria international chair.

9.3.1.1. Internships

Chunlin Xiao (University of Nice Sophia-Antipolis and University of L'Aquila): large-scale remote sensing image segmentation and classification.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

Florent Lafarge was co-chair of the ISPRS working group on point cloud processing.

10.1.1.2. Member of the Organizing Committees

Pierre Alliez is a member of the Steering Board of the EUROGRAPHICS Workshop on Graphics and Cultural Heritage.

Yuliya Tarabalka chaired a session “Classification of Hyperspectral Image” at IEEE IGARSS 2016.

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

Pierre Alliez was a program committee member of ACM SIGGRAPH, EUROGRAPHICS annual conference, EUROGRAPHICS Symposium on Geometry Processing, Geometric Modeling and Processing, Shape Modeling International and EUROGRAPHICS Workshop on Graphics and Cultural Heritage.
Florent Lafarge was a program committee member for the ISPRS congress in 2016.
Yuliya Tarabalka was a program committee member for ACIVS 2016, Lecce, Italy.

10.1.2.2. Reviewer

Pierre Alliez was a reviewer for the conferences listed above, and for around 25 additional papers in several journals ranging from geometric modeling to computer vision. Florent Lafarge was a reviewer for JPRS.
Yuliya Tarabalka was a reviewer for the conferences IEEE IGARSS (student competition selection committee) and ACIVS 2016.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

Pierre Alliez is an associate editor of ACM Transactions on Graphics, Elsevier Graphical Models, Computer Aided Geometric Design and Visual Informatics (since 2016). He is also a member of the editorial board of the CGAL open source project.

Florent Lafarge is an associate editor of The Visual Computer since 2015.

Yuliya Tarabalka was a co-editor of the special issue “Hyperspectral Imaging and Image Processing” of the Springer journal Sensing and Imaging.

10.1.3.2. Reviewer - Reviewing Activities

Florent Lafarge was a reviewer for CVPR, ECCV, and SIGGRAPH.
Yuliya Tarabalka was a reviewer for the journals IEEE TGRS and IEEE JSTARS.

10.1.4. Invited Talks

Pierre Alliez gave an invited talk at the CVPR Workshop on Large Scale 3D Data: Acquisition, Modelling and Analysis. The talk was entitled: *Shape Reconstruction and Approximation: Robustness and Guarantees*. See http://www.multimediauts.org/3DWorkshop_CVPR2016/Program.html.
He also gave a keynote at STAG 2016: Smart Tools and Apps in computer Graphics, organized October 3-4, in Genova, Italy. The talk was entitled: *Low Distortion Inter-surface Mapping via Optimal Mass Transport*.
He also gave a course at ACM SIGGRAPH on the CGAL library, in collaboration with Andreas Fabri from GeometryFactory.

10.1.5. Scientific Expertise

Pierre Alliez was an evaluator and reviewer for the H2020, EuroSTARS and ERC programmes from the European commission. He participated to the Scientific Commissions of Belgium FNRS (Fund for Scientific Research). He was a member of the panel GEV 01 (mathematics and computer science) of ANVUR (Italian research evaluation agency). We evaluated the period 2011-2014 through bibliometry and peer-review. He was also a reviewer for PRIN projects (fundamental research projects) for the MIUR (the Italian Ministry for Education, University and Research).

Yuliya Tarabalka was an expert evaluator for an ANR project submission in May 2016. She is since November 2016 a member of the expert panel SBWT (signal processing) of the FWO (Belgian research funding foundation).

10.1.6. Research Administration

Pierre Alliez: member of the BCP (bureau du CP) since 2015, comité MASTIC (popularization), and comité espace immersif.

Florent Lafarge was an elected member of the Comité de Centre from 2013 to 2016, and a member of the CSD (Commission de Suivi Doctorale) from 2011 to 2016.

Yuliya Tarabalka is an elected member of the Comité de Centre since 2016.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master: Pierre Alliez and Florent Lafarge, Ingeniérie 3D, 21h, M2, university Nice Sophia Antipolis, France.

Master: Pierre Alliez and Florent Lafarge, 3D Meshes and Applications, 32h, M2, Ecole des Ponts ParisTech, France.

Master: Pierre Alliez, Mathématiques pour la géométrie, 24h, M2, EFREI, France.

Master: Florent Lafarge, Traitement d'images numériques, 9h, M2, university Nice Sophia Antipolis, France.

Master: Yuliya Tarabalka, Mathematical methods, 25h, MSc in data sciences and business analytics ESSEC-CS, CentraleSupelec, France.

L2: Yuliya Tarabalka, Advanced algorithms, 28.5h, L2 Networks and Telecoms, IUT Nice Cote d'Azur, Sophia-Antipolis, France.

10.2.2. Supervision

PhD defended November 29th: Manish Mandad, Shape approximation with guarantees, since October 2012, Pierre Alliez.

PhD in progress: Dorothy Duan, Semantized Elevation Maps, since October 2013, Florent Lafarge.

PhD in progress: Jean-Dominique Favreau, Sketch-based modeling in multi-view context, since October 2014, Florent Lafarge and Adrien Bousseau.

PhD in progress: Hao Fang, Scale-space understanding in urban scenes, since March 2016, Florent Lafarge.

PhD in progress: Jean-Philippe Bauchet, City modelling from high resolution satellite images, since October 2016, Florent Lafarge.

PhD in progress: Emmanuel Maggiori, Representation and Analysis of Multisensor Remote Sensing Images with Partition Trees, University of Nice-Sophia Antipolis, since January 2015, Yuliya Tarabalka and Pierre Alliez.

10.2.3. Juries

Pierre Alliez:

- Thesis reviewer: Ludovic Blache (CReSTIC-SIC Reims).
- Thesis reviewer: Ruqi Huang (Inria Saclay).
- Thesis examiner: Mael Rouxel-Labbé (Inria Sophia Antipolis)

Florent Lafarge:

- Thesis examiner: Remi Cura (University Paris Est).

Yuliya Tarabalka:

- Monitoring committee for the thesis of Amine Bohi, Southern University of Toulon-Var in October 2016.

10.3. Popularization

Pierre Alliez participated to the "Fête de la science" in Juan-les-Pins, October 22 and 23. He also gave two talks in high schools: April 28 in Celony, and February 25th in Aix Valabre, and organized a workshop for MathC2+ in June.

11. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] M. MANDAD.*Robust Shape Approximation and Mapping between Surfaces*, Université de Nice-Sophia Antipolis, November 2016, https://hal.inria.fr/tel-01396443.

Articles in International Peer-Reviewed Journal

[2] M. BERGER, A. TAGLIASACCHI, L. SEVERSKY, P. ALLIEZ, G. GUENNEBAUD, J. LEVINE, A. SHARF, C. SILVA.*A Survey of Surface Reconstruction from Point Clouds*, in "Computer Graphics Forum", 2016, 27 [*DOI :* 10.1111/CGF.12802], https://hal.inria.fr/hal-01348404.

[3] M. BUDNINSKIY, B. LIU, F. DE GOES, Y. TONG, P. ALLIEZ, M. DESBRUN.*Optimal Voronoi Tessellations with Hessian-based Anisotropy*, in "ACM Transactions on Graphics", December 2016, 12, https://hal.inria.fr/hal-01376243.

[4] J.-D. FAVREAU, F. LAFARGE, A. BOUSSEAU.*Fidelity vs. Simplicity: a Global Approach to Line Drawing Vectorization*, in "ACM Transactions on Graphics", 2016 [*DOI :* 10.1145/2897824.2925946], https://hal.inria.fr/hal-01309271.

[5] E. MAGGIORI, Y. TARABALKA, G. CHARPIAT, P. ALLIEZ.*Convolutional Neural Networks for Large-Scale Remote Sensing Image Classification*, in "IEEE Transactions on Geoscience and Remote Sensing", September 2016, https://hal.inria.fr/hal-01369906.

[6] J. SHEN, L. BUSÉ, P. ALLIEZ, N. DODGSON.*A Line/Trimmed NURBS Surface Intersection Algorithm Using Matrix Representations*, in "Computer Aided Geometric Design", 2016, vol. 48, p. 1-16 [*DOI :* 10.1016/J.CAGD.2016.07.002], https://hal.inria.fr/hal-01268109.

International Conferences with Proceedings

[7] 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.

[8] E. MAGGIORI, Y. TARABALKA, G. CHARPIAT, P. ALLIEZ.*Fully Convolutional Neural Networks For Remote Sensing Image Classification*, in "IEEE International Geoscience and Remote Sensing Symposium", Beijing, China, Proc. IEEE International Geoscience and Remote Sensing Symposium (IGARSS), IEEE, July 2016, p. 5071-5074, https://hal.inria.fr/hal-01350706.

[9] S. OESAU, F. LAFARGE, P. ALLIEZ.*Object classification via planar abstraction*, in "ISPRS congress", Prague, Czech Republic, July 2016, https://hal.inria.fr/hal-01318637.

Other Publications

[10] S.-G. JEONG, Y. TARABALKA, N. NISSE, J. ZERUBIA.*Progressive Tree-like Curvilinear Structure Reconstruction with Structured Ranking Learning and Graph Algorithm*, December 2016, working paper or preprint, https://hal.inria.fr/hal-01414864.

[11] E. MAGGIORI, G. CHARPIAT, Y. TARABALKA, P. ALLIEZ.*Learning Iterative Processes with Recurrent Neural Networks to Correct Satellite Image Classification Maps*, October 2016, working paper or preprint, https://hal.inria.fr/hal-01388551.

[12] E. MAGGIORI, Y. TARABALKA, G. CHARPIAT, P. ALLIEZ.*High-Resolution Semantic Labeling with Convolutional Neural Networks*, November 2016, working paper or preprint, https://hal.inria.fr/hal-01393279.

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

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Project-Team TOSCA

Creation of the Project-Team: 2007 January 01

Keywords:

Computer Science and Digital Science:

6.1.2. - Stochastic Modeling (SPDE, SDE)
6.1.3. - Discrete Modeling (multi-agent, people centered)
6.1.4. - Multiscale modeling
6.2.2. - Numerical probability
6.2.3. - Probabilistic methods
6.2.4. - Statistical methods
6.4.2. - Stochastic control

Other Research Topics and Application Domains:

1.1.8. - Evolutionnary biology
1.1.10. - Mathematical biology
1.2. - Ecology
1.3.1. - Understanding and simulation of the brain and the nervous system
3.2. - Climate and meteorology
3.3.4. - Atmosphere
4.3.2. - Hydro-energy
4.3.3. - Wind energy
9.4.2. - Mathematics
9.9.1. - Environmental risks
9.9.2. - Financial risks

1. Members

Research Scientists

Denis Talay [Team leader, Inria, Senior Researcher, HDR]
Madalina Deaconu [Deputy leader, Inria, Researcher, HDR]
Mireille Bossy [Inria, Senior Researcher, HDR]
Nicolas Champagnat [Inria, Researcher, HDR]
Olivier Faugeras [Inria, Emeritus Senior Researcher, also member of the team MATHNEURO, HDR]
Antoine Lejay [Inria, Senior Researcher, HDR]
Etienne Tanré [Inria, Researcher]

Faculty Member

Denis Villemonais [Univ. Lorraine, Associate Professor]

PhD Students

Maxime Bonelli [Koris International, CIFRE, until Sep. 2016]
Pascal Helson [Univ. Nice, from Oct. 2016, internship April-August 2016]
Benoit Henry [Univ. Lorraine, until Nov. 2016]
Kouadio Jean Claude Kouaho [Cotutelle Univ. Lorraine and Univ. F. Houphouët Boigny (Abidjan), from Mar. 2016]
Radu Maftei [Univ. Nice]

Khaled Salhi [Univ. Lorraine, until Dec. 2016]
Milica Tomasevic [Inria]

Post-Doctoral Fellows

Coralie Fritsch [Ecole Polytechnique]
Paolo Pigato [Inria]
Alexandre Richard [Inria, until January 2016]

Visiting Scientists

Roberto Amaru Cortez Milan [Inria, Sep 2016]
Samuel Herrmann [Univ. Bourgogne, Professor, HDR]
Jean-Francois Jabir [University of Valparaíso, until March and in September and December]
Sylvain Maire [Univ. Toulon, Associate Professor]
Nadia Maïzi [ENSM Paris]
Philip Protter [Columbia University, June 2016]

Administrative Assistants

Laurence Benini [Inria, until July 2016]
Isabelle Blanchard [Inria, from Aug. 2016]
Christine Faber [Inria]

Others

Dai Taguchi [Ritsumeikan University, Japan, Ph.D. student, Mar. 2016]
Areski Cousin [Univ. Lyon I, Maître de Conférences, from Sep 2016, HDR]
Hamid Oudghiri-Idrissi [Inria, internship, from Jul 2016 until Aug 2016]

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

TOSCA is interested in developing stochastic models and probabilistic numerical methods. Our present motivations come from models with singular coefficients, with applications in Geophysics, Molecular Dynamics and Neurosciences; Lagrangian modeling in Fluid Dynamics and Meteorology; Population Dynamics, Evolution and Genetics; Neurosciences; and Financial Mathematics.

4.1.1. Stochastic models with singular coefficients: Analysis and simulation

Stochastic differential equations with discontinuous coefficients arise in Geophysics, Chemistry, Molecular Dynamics, Neurosciences, Oceanography, etc. In particular, they model changes of diffusion of fluids, or diffractions of particles, along interfaces.

For practioners in these fields, Monte Carlo methods are popular as they are easy to interpret — one follows particles — and are in general easy to set up. However, dealing with discontinuities presents many numerical and theoretical challenges. Despite its important applications, ranging from brain imaging to reservoir simulation, very few teams in mathematics worldwide are currently working in this area. The Tosca project-team has tackled related problems for several years providing rigorous approach. Based on stochastic analysis as well as interacting with researchers in other fields, we developed new theoretical and numerical approaches for extreme cases such as Markov processes whose generators are of divergence form with discontinuous diffusion coefficient.

The numerical approximation of singular stochastic processes can be combined with backward stochastic differential equations (BSDEs) or branching diffusions to obtain Monte Carlo methods for quasi-linear PDEs with discontinuous coefficients. The theory of BSDEs has been extensively developed since the 1980s, but the general assumptions for their existence can be quite restrictive. Although the probabilistic interpretation of quasi-linear PDEs with branching diffusions has been known for a long time, there have been only a few works on the related numerical methods.

Another motivation to consider stochastic dynamics in a discontinuous setting came to us from time evolution of fragmentation and coagulation phenomena, with the objective to elaborate stochastic models for the avalanche formation of soils, snow, granular materials or other geomaterials. Most of the models and numerical methods for avalanches are deterministic and involve a wide variety of physical parameters such as the density of the snow, the yield, the friction coefficient, the pressure, the basal topography, etc. One of these methods consists in studying the safety factor (or limit load) problem, related to the shallow flow of a visco-plastic fluid/solid with heterogeneous thickness over complex basal topography. The resulting nonlinear partial differential equation of this last theory involves many singularities, which motivates us to develop an alternative stochastic approach based on our past works on coagulation and fragmentation. Our approach consists in studying the evolution of the size of a typical particle in a particle system which fragments in time.

4.1.2. Stochastic Lagrangian modeling in Computational Fluid Dynamics

Stochastic Lagrangian models were introduced in the eighties to simulate complex turbulent flows, particularly two-phase flows. In Computational Fluid Dynamics (CFD), they are intensively used in the so-called Probability Density Functions (PDF) methods in order to model and compute the reaction-phase terms in the fundamental equations of fluid motions. The PDF methods are currently developed in various laboratories by specialists in scientific computation and physicists. However, to our knowledge, we are innovating in two ways:

- our theoretical studies are the pioneering mathematical analysis of Lagrangian stochastic models in CFD;
- our work on the Stochastic Downscaling Method (SDM) for wind simulation is the first attempt to solve the fundamental equations themselves by a fully 3D stochastic particle method.

We emphasize that our numerical analysis is essential to the SDM development which takes benefits from our deep expertise on numerical schemes for McKean-Vlasov-non-linear SDEs.

4.1.3. Population Dynamics, Evolution and Genetics

The activity of the team on stochastic modeling in population dynamics and genetics mainly concerns application in adaptive dynamics, a branch of evolutionary biology studying the interplay between ecology and evolution, ecological modeling, population genetics in growing populations, and stochastic control of population dynamics, with applications to cancer growth modeling. Stochastic modeling in these areas mainly considers individual-based models, where the birth and death of each individual is described. This class of model is well-developed in Biology, but their mathematical analysis is still fragmentary. Another important topic in population dynamics is the study of populations conditioned to non-extinction, and of the corresponding stationary distributions, called quasi-stationary distributions (QSD). This domain has been the object of a lot of studies since the 1960's, but we made recently significant progresses on the questions of existence, convergence and numerical approximation of QSDs using probabilistic tools rather than the usual spectral tools.

Our activity in population dynamics also involves a fully new research project on cancer modeling at the cellular level by means of branching processes. In 2010 the International Society for Protons Dynamics in Cancer was launched in order to create a critical mass of scientists engaged in research activities on Proton Dynamics in Cancer, leading to the facilitation of international collaboration and translation of research to clinical development. Actually, a new branch of research on cancer evolution is developing intensively; it aims in particular to understand the role of proteins acting on cancerous cells' acidity, their effects on glycolysis and hypoxia, and the benefits one can expect from controlling pH regulators in view of proposing new therapies.

4.1.4. Stochastic modeling in Neuroscience

It is generally accepted that many different neural processes that take place in the brain involve noise. Indeed, one typically observes experimentally underlying variability in the spiking times of an individual neuron in response to an unchanging stimulus, while a predictable overall picture emerges if one instead looks at the average spiking time over a whole group of neurons. Sources of noise that are of interest include ionic currents crossing the neural membrane, synaptic noise, and the global effect of the external environment (such as other parts of the brain).

It is likely that these stochastic components play an important role in the function of both the neurons and the networks they form. The characterization of the noise in the brain, its consequences at a functional level and its role at both a microscopic (individual neuron) level and macroscopic level (network of thousands of neurons) is therefore an important step towards understanding the nervous system.

To this end, a large amount of current research in the neuroscientific literature has involved the addition of noise to classical purely deterministic equations resulting in new phenomena being observed. The aim of the project is thus to rigorously study these new equations in order to be able to shed more light on the systems they describe.

4.1.5. Stochastic modeling in Financial Mathematics

4.1.5.1. Technical Analysis

In the financial industry, there are three main approaches to investment: the fundamental approach, where strategies are based on fundamental economic principles; the technical analysis approach, where strategies are based on past price behavior; and the mathematical approach where strategies are based on mathematical models and studies. The main advantage of technical analysis is that it avoids model specification, and thus calibration problems, misspecification risks, etc. On the other hand, technical analysis techniques have limited theoretical justifications, and therefore no one can assert that they are risk-less, or even efficient.

4.1.5.2. Financial Risks Estimation and Hedging

Popular models in financial mathematics usually assume that markets are perfectly liquid. In particular, each trader can buy or sell the amount of assets he/she wants at the same price (the “market price”). They moreover assume that the decision taken by the trader does not affect the price of the asset (the small investor assumption). In practice, the assumption of perfect liquidity is never satisfied but the error due to liquidity is generally negligible with respect to other sources of error such as model error or calibration error, etc.

Derivatives of interest rates are singular for at least two reasons: firstly the underlying (interest rate) is not directly exchangeable, and secondly the liquidity costs usually used to hedge interest rate derivatives have large variation in times.

Due to recurrent crises, the problem of risk estimation is now a crucial issue in finance. Regulations have been enforced (Basel Committee II). Most asset management software products on the markets merely provide basic measures (VaR, Tracking error, volatility) and basic risk explanation features (e.g., “top contributors” to risk, sector analysis, etc).

4.1.5.3. Energy and Carbon Markets

With the rise of renewable energy generation (from solar, wind, waves...), engineers face new challenges which heavily rely on stochastic and statistical problems.

Besides, in the context of the beginning of the second phase (the Kyoto phase) in 2008 of the European carbon market, together with the fact that French carbon tax was scheduled to come into law on Jan. 1, 2010, the year 2009 was a key year for the carbon price modeling. Our research approach adopts the point of view of the legislator and energy producers. We used both financial mathematical tools and a game theory approach. Today, with the third phase of the EU-ETS, that didn’t yet start, and the report form the Cour des Comptes (October 2013) that pointed out (among many others point) the lack of mathematical modeling on such carbon market design, we continue our research in this direction.

4.1.5.4. Optimal Stopping Problems

The theory of optimal stopping is concerned with the problem of taking a decision at the best time, in order to maximise an expected reward (or minimise an expected cost). We work on the general problem of optimal stopping with random discounting and additional cost of observation.

4.1.5.5. First hitting times distributions

Diffusion hitting times are of great interest in finance (a typical example is the study of barrier options) and also in Geophysics and Neurosciences. On the one hand, analytic expressions for hitting time densities are well known and studied only in some very particular situations (essentially in Brownian contexts). On the other hand, the study of the approximation of the hitting times for stochastic differential equtions is an active area of research since very few results still are available in the literature.

5. New Software and Platforms

5.1. AGH

FUNCTIONAL DESCRIPTION

AGH (for Analysis of Galton-Watson Harris paths) is a Matlab toolbox providing methods for statistical analysis of ordered trees from their Harris paths in a user-friendly environment. More precisely it allows to easily compute estimators of the relative scale of trees which share the same shape. These estimators have been introduced for Galton-Watson trees conditioned on their number of nodes but may be computed for any ordered tree.

- Participants: Romain Azaïs, Alexandre Genadot, Benoît Henry
- Contact: Benoît Henry
- URL: http://agh.gforge.inria.fr/

5.2. ExitBM

FUNCTIONAL DESCRIPTION

The exitbm library provides methods to simulate random variables related to the first exit time and position of the Brownian motion from simple domains, namely intervals, squares and rectangles.

- Participants: Madalina Deaconu and Antoine Lejay
- Contact: Antoine Lejay
- URL: http://exitbm.gforge.inria.fr/

5.3. SDM-WindPoS

Stochastic Downscaling Method and Wind Power Simulation
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, we have developed a computer code belonging to the family of codes of atmospheric flow calculation, in the atmospheric boundary layer. SDM-windpos especially concerns the simulation of wind at small space scales (meaning that the horizontal resolution is one kilometer or less), based on the combination of an existing Numerical Weather Prediction model providing a coarse prediction, and a Lagrangian Stochastic Model for turbulent flows.

The ability of SDM-WindPoS to regamma the wind computation in the horizontal scale but also in the vertical scale is of particular interest for wind farm power production assessment. WindPoS couples direct actuator disk approach and SDM Atmospheric Boundary Layer (ABL) model for wind farm simulation.

This year we start to introduce more accurate ABL convection models in SDM. Moreover, we start to add the possibility to introduce more accurate topography when SDM is running with some coarse scale atmospheric input data. Our dedicated GUI was also improved (better rendering for the 2D and 3D views).

- Participants: Mireille Bossy
- Contact: Mireille Bossy
- URL: http://windpos.inria.fr

6. New Results

6.1. Probabilistic numerical methods, stochastic modelling and applications

Participants: Mireille Bossy, Nicolas Champagnat, Madalina Deaconu, Coralie Fritsch, Pascal Helson, Benoît Henry, Kouadio Jean Claude Kouaho, Antoine Lejay, Radu Maftei, Sylvain Maire, Paolo Pigato, Alexandre Richard, Denis Talay, Etienne Tanré, Milica Tomasevic, Denis Villemonais.

6.1.1. Published works and preprints

- M. Bossy with H. Quinteros (UChile) studied the rate of convergence of a symmetrized version of the Milstein scheme applied to the solution of one dimensional CEV type processes. They prove a strong rate of convergence of order one, recovering the classical result of Milstein for SDEs with smooth diffusion coefficient. In contrast with other recent results, the proof does not relies on Lamperti transformation, and it can be applied to a wide class of drift functions. Some numerical experiments and comparison with various other schemes complement the theoretical analysis that also applies for the simple projected Milstein scheme with same convergence rate ([14] accepted for publication in Bernoulli Journal).
- M. Bossy, R. Maftei, J.-P. Minier and C. Profeta worked on numerically determining the rate of convergence of the weak error for the discretised Langevin system with specular reflection conditions. The article [29] presents a discretisation scheme and offers a conjecture for the rate of convergence of the bias produced. Numerically, these conjectures are confirmed for the specular reflection scheme but also for the absorption scheme, which models perfect agglomeration. The scheme numerically follows a linear decrease. The Richardson-Romberg extrapolation is also presented with a quadratic decrease.
- M. Bossy, A. Rousseau (LEMON Inria team), JĖspina, JṀorice and C. Paris (Inria Chile) studied the computation of the wind circulation around mills, using a Lagrangian stochastic approach. They present the SDM numerical method and numerical experiments in the case of non rotating and rotating actuator disc models in [13]. First, for validation purpose they compare some numerical experiments against wind tunnel measurements. Second, they perform numerical experiments at the atmospheric scale and present some features of the numerical method, in particular the computation of the probability distribution of the wind in the wake zone, as a byproduct of the fluid particle model and the associated PDF method.
- Together with M. Baar and A. Bovier (Univ. Bonn), N. Champagnat studied the adaptive dynamics of populations under the assumptions of large population, rare and small mutations [11]. In this work, the three limits are taken simultaneously, contrary to the classical approach, where the limits of large population and rare mutations are taken first, and next the limit of small mutations [57]. We therefore obtain the precise range of parameters under which these limits can be taken, and provide explicit biological conditions for which our approximation is valid.
- 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 QSD of the processes controled by Markov controls [36].
- N. Champagnat and C. Fritsch worked with F. Campillo (Inria Sophia-Antipolis, LEMON team) on the links between a branching process and an integro-differential equation of a growth-fragmentation-death model [15]. They proved that the two representations of the model lead to the same criteria of invasion of a population in a given environment. They also studied the variations of the principal eigenvalue (resp. the survival probability) of an integro-differential equation (resp. branching process) of growth-fragmentation models with respect to an environmental parameter in [35].

- N. Champagnat and D. Villemonais consider, for general absorbed Markov processes, the notion of quasi-stationary distributions (QSD), which is a stationary distribution conditionally on non-absorbtion, and the associated Q-process, degammad as the original Markov process conditioned to never be absorbed. They prove that, under the conditions of [17], in addition to the uniform exponential convergence of conditional distributions to a unique QSD and the uniform exponential ergodicity of the Q-process, one also has the uniform convergence of the law of the process contionned to survival up to time T, when $T \to +\infty$. This allows them to obtain conditional ergodic theorems [41].
- 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.
- Using a new method to compute the expectation of an integral with respect to a random measure, N. Champagnat and B. Henry obtained explicit formulas for the moments of the frequency spectrum in the general branching processes known as Splitting Trees, with neutral mutations and under the infinitely-many alleles model [16]. This allows them to obtain a law of large numbers for the frequency spectrum in the limit of large time.
- N. Champagnat and D. Villemonais obtained criteria for existence, uniqueness and exponential convergence in total variation to QSD for discrete population processes with unbounded absorption rate, using a non-linear Lyapunov criterion [38]. For logistic multidimensional birth and death processes absorbed when one coordinate gets extinct, they show that their criterion covers cases stronger intra-spectific competition than inter-specific competition.
- N. Champagnat and D. Villemonais extended their work [17] to general penalized processes, including time-inhomogeneous Markov processes with absorption and Markov processes in varying environments [40]. Their method allows to improve significantly the former results of [58], [59].
- M. Deaconu worked with L. Beznea and O. Lupaşcu (Bucharest, Romania) and analyzed the description of rupture phenomena like avalanches, by using fragmentation models. The main physical properties of the model are deeply involved in this study. They obtained new results on a stochastic equation of fragmentation and branching processes related to avalanches [12].
- M. Deaconu and S. Herrmann continued and completed the study of the simulation of hitting times of given boundaries for Bessel processes. These problems are of great interest in many application fields, such as finance and neurosciences. In a previous work, the authors introduced a new method for the simulation of hitting times for Bessel processes with integer dimension. The method was based mainly on explicit formula for the distribution of the hitting times and on the connexion between the Bessel process and the Euclidean norm of the Brownian motion. The method does not apply for a non-integer dimension. In this new work they consider the simulation of the hitting time of Bessel processes with non integer dimension and provide a new algorithm by using the additivity property of the laws of squared Bessel processes. Each simulation step is splitted in two parts: one is using the integer dimension case and the other one exhibits hitting time of a Bessel process starting from zero [20].
- M. Deaconu and S. Herrmann studied the Initial-Boundary Value Problem for the heat equation and solved it by using a new algorithm based on a random walk on heat balls [44]. Even if it represents a sophisticated and challenging generalization of the Walk on Spheres (WOS) algorithm introduced to solve the Dirichlet problem for Laplace's equation, its implementation is rather easy. The definition of the random walk is based on a new mean value formula for the heat equation. The convergence results and numerical examples allow to emphasize the efficiency and accuracy of the algorithm.
- M. Deaconu, B. Dumortier and E. Vincent (EPI MULTISPEECH are working with the Venathec SAS on the acoustic control of wind farms. They constructed a new approach to control wind farms based on real-time source separation. They expressed the problem as a non-linear knapsack problem and solve it using an efficient branch-and-bound algorithm that converges asymptotically to the global

optimum. The algorithm is initialised with a greedy heuristic that iteratively downgrades the turbines with the best acoustical to electricity loss ratio. The solution is then regammad using a depth-first search strategy and a bounding stage based on a continuous relaxation problem solved with an adapted gradient algorithm. The results are evaluated using data from 28 real wind farms [46].

- C. Fritsch and B. Cloez (INRA, Montpellier) proved central limit theorems for chemostat models in finite and infinite dimensions in [42]. From these theorems, they obtianed gaussian approximations of individual-based models and made a numerical analysis for the model in finite dimension in order to discuss the validity of these approximations in different contexts.
- Together with R. Azaïs (BIGS Inria team) and A. Genadot (Univ. Bordeaux), B. Henry studied an estimation problem for a forest of size-constrained Galton-Watson trees [31]. Using the asymptotic behavior of the Harris contour process, they constructed estimators for the inverse standard deviation of the birth distribution. In addition to the theoretical convergence results obtained in this work, they used the method to study the evolution of Wikipedia webpages in order, for instance, to detect vandalism.
- In [49], B. Henry showed a central limit theorem for the population counting process of a supercritical Splitting Tree in the limit of large time. Thanks to the results of [16], he also obtained a central limit theorem for the frequency spectrum of Splitting Trees with neutral mutations and under the infinitely-many alleles model.
- In collaboration with Laure Coutin, A. Lejay have studied the sensitivity of solution of rough differential equations with respect to their parameters using a Banach space version of the implicit function theorem. This result unifies and extends all the similar results on the subject [43].
- A. Lejay have studied the parametric estimation of the bias coefficient of skew random walk, as a toy model for the problem of estimation of the parameter of the Skew Brownian motion [50].
- P. Pigato has continued with V. Bally (Univ. Marne-la-Vallée) and L. Caramellino (Univ. Roma Tor Vergata) his PhD work on the regularity of diffusions under Hörmander-type conditions [32], [33].
- A. Richard and D. Talay ended their work on the sensitivity of the first hitting time of fractional SDEs, when $H > \frac{1}{2}$ [54]. This study is being completed by the rough case $H \in (\frac{1}{4}, \frac{1}{2}]$. In relation to fractional SDEs, another short work on accurate Gaussian-like upper bounds on density of one-dimensional fractional SDEs is almost finished.
- In [21], S. Herrmann and E. Tanré propose a new algorithm to simulate the first hitting times of a deterministic continuous function by a one-dimensional Brownian motion. They give explicit rate of convergence of the algorithm.
- E. Tanré and Pierre Guiraud (Univ. of Valparaiso) have studied the synchronization in a model of neural network with noise. 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. [48]
- V. Reutenauer and E. Tanré have worked on extensions of the exact simulation algorithm introduced by Beskos et al. [56]. They propose an unbiased algorithm to approximate the two first derivatives with respect to the initial condition x of quantities with the form $\mathbb{E}\Psi(X_T^x)$, where X is a one-dimensional diffusion process and Ψ any test-function. They also propose an efficient modification of Beskos et al. algorithm. [53]
- During his internship supervised by E. Tanré, A. Papic worked on multi scales generator of Markov processes. He presents a method to approximate such processes with an application in neuroscience for noisy Hodgkin-Huxley model [52].
- D. Villemonais worked with P. Del Moral (Univ. Sydney) on the conditional ergodicity of time inhomogeneous diffusion processes [45]. They proved that, conditionally on non extinction, an elliptic time-inhomogeneous diffusion process forgets its initial distribution exponentially fast. An interacting particle scheme to numerically approximate the conditional distribution is also provided.

- D. Villemonais worked with his Research Project student William Oçafrain (École des Mines de Nancy) on an original mean-field particle system [51]. They proved that the mean-field particle system converges in full generality toward the distribution of a conditioned Markov process, with applications to the approximation of the quasi-stationary distribution of piecewise deterministic Markov processes.

6.1.2. Other works in progress

- M. Bossy and R. Maftei are working on determining the rate of convergence of the weak error of a discretised scheme for the Langevin system with specular boundary reflection on the position. The velocity process allows for a bounded and smooth drift. In order to determine the optimal rate of convergence, the regularity of the associated PDE is required and also regularity results for the derivative of flow of the process w.r.t. the initial conditions.
- N. Champagnat and B. Henry are studying limits of small mutations in Lokta-Volterra type PDEs of population dynamics using probabilistic representations and large deviations.
- N. Champagnat, C. Fritsch and S. Billiard (Univ. Lille) are working on food web modeling.
- M. Deaconu and S. Herrmann are working on numerical approaches for hitting times of general stochastic differential equations.
- M. Deaconu, O. Lupaşcu and L. Beznea (Bucharest, Romania) worked on the numerical scheme for the simulation of an avalanche by using the fragmentation model. This work will be submitted soon.
- M. Deaconu, B. Dumortier and E. Vincent (EPI MULTISPEECH) work on handling uncertainties in the model of acoustic control of wind farms they develop, in order to design a stochastic algorithm based on filtering methods. They will submit another article to IEEE transaction on sustainable energy.
- C. Fritsch is working with F. Campillo (Inria Sophia-Antipolis, LEMON team) and O. Ovaskainen (Univ. Helsinki) about a numerical approach to determine mutant invasion fitness and evolutionary singular strategies using branching processes and integro-differential models. They illustrate this method with a mass-structured individual-based chemostat model.
- C. Fritsch is working with A. Gégout-Petit (Univ. Lorraine and sc Bigs team), B. Marçais (INRA, Nancy) and M. Grosdidier (INRA, Nancy) on a statistical analysis of a *Chalara fraxinea* model.
- B. Cloez (INRA Montpellier) and B. Henry started a work on the asymptotic behavior of splitting trees in random environment. In addition, they begin the study of scaling limits of splitting trees in varying environment.
- Together with Ernesto Mordecki (Universidad de la República, Uruguay) and Soledad Torres (Universidad de Valparaíso), A. Lejay is working on the estimation of the parameter of the Skew Brownian motion.
- A. Lejay, and P. Pigato are working on the estimation of the parameters of diffusions with discontinuous coefficients, with application to financial data.
- Together with Laure Coutin and Antoine Brault (Université Toulouse 3), A. Lejay is studying application of the Trotter-Kato theorem in the context of rough differential equations, in order to solve some Stochastic Partial Differential Equations.
- A. Lejay and H. Mardones are working on a Monte Carlo simulation of the Navier-Stokes equations which is based on a novel probabilistic representation due to F. Delbaen *et al.* [60].
- In a research visit to Chile, P. Pigato has worked with R. Rebolledo and S. Torres on the estimation of parameters of diffusions from the occupation time and the local time of the process.
- Together with Laure Coutin and Antoine Brault (Université Toulouse 3), A. Lejay is studying application of the Trotter-Kato theorem in the context of rough differential equations, in order to solve some Stochastic Partial Differential Equations.

- C. Graham (École Polytechnique) and D. Talay are polishing thesecond volume of their series on Mathematical Foundation of Stochastic Simulation to be published by Springer.
- In collaboration with J. Bion-Nadal (CNRS and École Polytechnique) D. Talay ended the first paper on an innovating calibration method for stochastic models belonging to a family of solutions to martingale problems. The methodology involves the introduction of a new Wasserstein-type distance and stochastic control problems. The manuscript is being finished.
- Motivated by the study of systems of non-linear PDE's by stochastic methods, M. Tomasevic and D. Talay studied a system of differential equations interacting through a singular kernel, depending on all the past of the solutions. They have proved the existence of a solution in the space of Lipschitz functions in short time interval and performed numerical simulations. In the same time, they studied a non-linear stochastic differential equation whose drift is given as a convolution of a singular kernel with the unknown one dimensional time marginals both in time and space. Combining probabilistic and PDE techniques, they are currently finishing the proof of the existence and uniqueness of a weak solution up to an arbitrary finite time horizon. Properties of the corresponding particle system (well-posedness and propagation of chaos) are also studied.
- A. Richard and E. Tanré's work with Patricio Orio (CINV, Chile) on the modelling and measurement of long-range dependence in neuronal spike trains is almost completed. They exhibit evidence of memory effect in genuine neuronal data and compared their fractional integrate-and-fire model with the existing Markovian models. A. Richard and E. Tanré are still working on the convergence of the statistical estimator that measures this phenomenon.
- A. Richard, E. Tanré are working with S. 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 $H > \frac{1}{2}$. In addition, they have proved the existence of a penalization scheme (suited to numerical approximation) to approach this object. When $H \in (\frac{1}{4}, \frac{1}{2})$, they have proved the existence in the elliptic case and are working on the question of uniqueness and on the relaxation of ellipticity.
- During his internship supervised by E. Tanré and Romain Veltz (MATHNEURO team), Pascal Helson studied numerically and theoretically a model of spiking neurons in interaction with plasticity. He showed that a simple model without plasticity could reproduce biological phenomena such as oscillations. In order to add plasticity, he enabled synaptic weights to evolve in a probabilistic way, in agreement with biological laws. He is now studying the convergence of this model and the existence of separable time scales, which is part of his thesis.
- D. Villemonais started a collaboration with Camille Coron (Univ. Paris Sud) and Sylvie Méléard (École Polytechnioque) on the question of simultaneous/non-simultaneous extinction of traits in a structured population
- D. Villemonais currently works on the computation of lower bounds for the Wasserstein curvature of interacting particle systems.
- D. Villemonais started a collaboration with Éliane Albuisson (CHRU of Nancy), Athanase Benetos (CHRU of Nancy), Simon Toupance (CHRU of Nancy), Daphné Germain (École des Mines de Nancy) and Anne Gégout-Petit (Inria BIGS team). The aim of this collaboration is to conduct a statistical study of the time evolution of telomere's length in human cells.

6.2. Financial Mathematics

Participants: Maxime Bonelli, Mireille Bossy, Nicolas Champagnat, Madalina Deaconu, Antoine Lejay, Sylvain Maire, Khaled Salhi, Denis Talay, Etienne Tanré.

6.2.1. Published works and preprints

- K. Salhi, M. Deaconu, A. Lejay and N. Champagnat worked with N. Navet (University of Luxembourg) [28]. They construct a regime switching model for the univariate Value-at-Risk estimation. Extreme value theory (EVT) and hidden Markov models (HMM) are combined to estimate a hybrid model that takes volatility clustering into account. In the first stage, HMM is used to classify data in crisis and steady periods, while in the second stage, EVT is applied to the previously classified data to rub out the delay between regime switching and their detection. This new model is applied to prices of numerous stocks exchanged on NYSE Euronext Paris over the period 2001-2011. The relative performance of the regime switching model is benchmarked against other well-known modeling techniques, such as stable, power laws and GARCH models.
- K. Salhi wrote a survey paper about option pricing and risk management under exponential Lévy models [55]. He detailed some notions that are not well explained in the literature and he proposed new trends in the risk management of derivatives.
- In [26], D. Talay, E. Tanré, Christophe Michel (CA-CIB) and Victor Reutenauer (fotonower) have studied a model in financial mathematics including bid-ask spread cost. They study the optimal strategy to hedge an interest rate swap that pays a fixed rate against a floating rate. They present a methodology using a stochastic gradient algorithm to optimize strategies.

6.2.2. Other works in progress

- M. Bossy and M. Bonelli (Koris International) are working on the optimal portfolio investment problem under the drawdown constraint that the wealth process never falls below a fixed fraction of its running maximum. They derive optimal allocation programs by solving numerically the Hamilton-Jacobi-Bellman equation that characterizes the finite horizon expected utility maximization problem, for investors with power utility as well as S-shape utility. Using numerical experiments they show that implementing the drawdown constraint can be gainful in optimal portfolios for the power utility, for some market configurations and investment horizons. However, their study reveals different results in a prospect theory context.
- When the underlying asset price is given by a exponential Lévy model, the market is almost incomplete. Under this hypothesis, K. Salhi works on derivatives hedging under a budget constraint on the initial capital. He considers, as criterion of optimization, the CVaR of the terminal hedging risk. First, he rewrites the problem an optimisation problem on the random fraction of the payoff that permits to respect the budget constraint. Then, he approximates the problem by relaxing the constraint and considering only a specific equivalent martingale measure. This approximate problem is solved using Neyman-Pearson's Lemma and, in the case of European options, a numerical valuation of the approximated minimal CVaR based on fast Fourier transform. The article will be submitted soon.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- TOSCA Sophia is involved in a Cifre convention with Koris International. M. Bossy supervises M. Bonelli's Ph.D. thesis.
- M. Deaconu is involved in a bilateral contract with Venathec. She is supervising, with E. Vincent (EPI MULTISPEECH), the Ph.D. thesis of B. Dumortier on the acoustic control of wind farms noise.

7.2. Bilateral Grants with Industry

- Mireille Bossy is the Coordinator of the PEPS from AMIES granted with the SME Seatopic, on the wind downscaling, using finer local topography, for coastal activities.
- Mireille Bossy is the Coordinator of the TER project from the PGMO (FMJH) granted with the SME METIGATE, on the statistical description of coupled regional temperatures.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. 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).
- E. Tanré is member of the ANR SloFaDyBio (Slow Fast Dynamics in Biology, ANR-14-CE25-0019, 2015-2017) coordinated by M. Desroches (EPI MATHNEURO, Inria Sophia Antipolis).

8.2. International Initiatives

8.2.1. Inria International Labs

Inria Chile

Associate Team involved in the International Lab:

8.2.1.1. ANESTOC-TOSCA

Title: Stochastic modelling of biology and renewable energies

International Partner (Institution - Laboratory - Researcher):

Pontificia Universidad Católica de Chile (Chile) - ANESTOC Center (ANESTOC) - Rebolledo Rolando

Start year: 2014

See also: http://www.incidechile.cl/anestoc/teams-involved/

This French-Chilean Associated Team deals with stochastic modeling and simulation issues for renewable energies (wind and waves) and neurosciences. It is a follow-up of a long collaboration in which each of the side takes benefit from the other side know-how and structures. In particular, this Associated Team is strongly related to the CIRIC project “Stochastic Analysis of Renewable Energy”. This project aims at transfering and valuing to Chilean companies the results of researches on renewable energies, mainly wind prediction at the windfarm's scale and waves energy potential of a site using video.

8.2.2. Participation in Other International Programs

8.2.2.1. International Initiatives

ECOS Discrelongmem

Title: On discretization procedures in Non-Gaussian long memory processes with applications in non parametric statistics and time series analysis

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).

8.3. International Research Visitors

8.3.1. Visits of International Scientists

- L. Beznea (Simion Stoilow Institute of Mathematics of the Romanian Academy, Bucarest) has been visiting TOSCA Nancy for 11 days in July.
- O. Lupaşcu (Simion Stoilow Institute of Mathematics of the Romanian Academy, Bucarest) has been visiting TOSCA Nancy for one week in October.
- The TOSCA seminar organized by A. Richard in Sophia Antipolis has received the following speakers: Pierre-Emmanuel Jabin (University of Maryland), Christophe Henry (Institute of Lluid Flow Machinery, Polish Academy of Sciences), Tony Lelièvre (ENPC), D. Alberici (University of Bologna), Nicolas Fournier (Université Pierre et Marie Curie), Philip Protter (Columbia University), Jean-François Jabir (CIMFAV – Valparaiso, Chile), Roberto Cortez Milan (CIMFAV – Valparaiso, Chile), Areski Cousin (ISFA, Lyon).

8.3.1.1. Internships

BICHAT Antoine

Subject: Modélisation de populations de cellules irradiées: une approche par processus de branchement

Date: Sep. 2015 - June 2016 (projet recherche)

Institution: Écoles des Mines de Nancy.

CORMIER Quentin

Subject: Study of invariants associated to the dynamic of a neuron network subject to STDP

Date: Oct. 2015 - Feb. 2016

Institution: ENS Lyon

DUPRE Aurore

Subject: Analyse et évaluation de l'adjonction de la modélisation de phénomènes convectifs dans un modèle numérique lagrangien de la couche limite atmosphérique

Date: April 2016 - Oct. 2016

Institution: Université de Reims Champagne-Ardenne

GEORGES Thomas

Subject: Single Particle Tracking Techniques

Date: Sept. 2016 - June 2017 (research project)

Institution: Écoles des Mines de Nancy.

GUERBAB Ismail

Subject: Sums of Pareto distributions

Date: June 2016 - Aug. 2016

Institution: Écoles des Mines de Nancy.

HELSON Pascal

Subject: Spikking Neurons in interaction with Plasticity

Date: April 2016 - Aug. 2016

Institution: Ecole des Ponts et chaussées.

KANTASSI Ameni

Subject: Processus du plus récent ancêtre commun dans des arbres de Galton-Watson

Date: April 2015 - Aug. 2015

Institution: Univ. Lorraine et École Supérieure des Sciences et Technologies d'Hammam Sousse (Tunisie).

PAPIC Alexis

Subject: States Reduction on Markov Processes

Date: Mai 2016 - Aug. 2016

Institution: Univ. Pierre et Marie Curie.

8.3.2. Visits to International Teams

8.3.2.1. Research Stays Abroad

- N. Champagnat and D. Villemonais spent one week in Neuchâtel (Switzerland) in September, to work with Michel Benaïm.
- P. Pigato has spent two weeks in Valparaiso and Santiago (Chile) in March, working with R. Rebolledo and S. Torres.
- P. Pigato has spent one week in Padova (Italy), in June, for a collaboration with P. Dai Pra.
- A. Richard and E. Tanré have spent one week in Valparaíso and one week in Santiago (Chile) in December within the ECOS program (PIs: E. Tanré, S. Torres, C. Tudor), working with S. Torres (Univ. of Valparaiso).
- D. Talay spent ten days at Columbia University in October.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Promotion of Mathematics in the industry

- M. Deaconu and A. Lejay were invited to give a talk at ILAC, Luxembourg in March 2016.
- A. Lejay has been appointed as representative of Inria Nancy-Grand Est in the Agence Mathématiques et Entreprise (AMIES).
- 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.
- 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.

9.1.2. Scientific Events Organisation

- N. Champagnat and M. Deaconu organized the mini-symposium "Un panorama de progrès récents sur les méthodes numériques probabilistes" at CANUM 2016 (Congrès d'Analyse Numérique) at Obernai in July 2016.

9.1.2.1. Member of the Organizing Committees

- A. Lejay was member of the conference organizing committees of *CANUM 2016* (Obernai, France).

9.1.3. Scientific Events Selection

9.1.3.1. Member of the Conference Program Committees

- N. Champagnat served as a member of the program committee of CARI 2016 (13ème Colloque Africain sur la Recherche en Informatique et Mathématiques Appliquées), Tunis, 10–14 octobre 2016.
- A. Lejay is member of the conference program committees of *CANUM 2016* (Obernai, France) and *Journées de Probabilités 2016* (Le Mans, France).
- D. Talay served as a member of the XIIIth France-Romania Colloquium in Applied Mathematics.
- E. Tanré served as a member of the program committee of the International Conference on Mathematical NeuroScience (ICMNS 2016), Juan les Pins.

9.1.4. Journal

9.1.4.1. Member of the Editorial Boards

- M. Bossy served as an Associate Editor of *Annals of Applied Probability*.
- N. Champagnat served as an Associate Editor of *Stochastic Models*.
- A. Lejay is one of the three editors of the *Séminaire de Probabilités*.
- D. Talay served as an Associate Editor of: *Stochastic Processes and their Applications*, *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 the Co-editor in chief of *MathematicS in Action*.

9.1.4.2. Reviewer - Reviewing Activities

- M. Deaconu wrote reviews for manuscripts submitted to *Journal of Computational and Applied Mathematics*.
- A. Lejay wrote reviews for manuscripts submitted to *Journal of Computational Mathematics*, *Mathematics and Computers in Simulation*, *Mathematical Reports*, *SIAM Journal of Control and Optimization*, *Communications in Mathematical Physics,*, *Real Analysis Exchange* , *Annals of Probability*, *Electronic Journal of Probability*.
- E. Tanré wrote reviews for manuscripts submitted to *Applied Mathematical Finance*, *Bernoulli*, *European Journal of Applied Mathematics*.
- E. Tanré serves has a permanent reviewer of *Mathematical Reviews of the American Mathematical Society (MathSciNet)*
- D. Villemonais wrote reviews for *Mathematical Reviews of the American Mathematical Society (MathSciNet)* and for manuscripts submitted to *Stochastic processes and applications* and *Theoretical Population Biology*.

9.1.5. Invited Talks

- M. Bossy has been invited to give a talk at the seminar of the Laboratoire Jacques-Louis Lions, in May.
- M. Bossy has been invited to give a seminar talk at the Rencontre Niçoise de Mécanique des Fluides, at the Observatoire de la Côte d'Azur in Nice, June
- M. Bossy has been invited to give a talk at the symposium *SDE approximation* at the International Conference on Monte Carlo techniques, In Paris, July.
- N. Champagnat has been invited to give talks at the conference *Stochastic PDE's, Large Scale Interacting Systems and Applications to Biology* in Orsay in March, to the CMO-BIRS workshop *Stochastic and Deterministic Models for Evolutionary Biology* in Oaxaca, Mexico, in August and at the conference *Probabilistic structures in deterministic population genetics* in Vienna in November.
- N. Champagnat has been invited to give seminar talks at *TOSCA seminar* in Inria Sophia Antipolis in April, at the *MAPMO probability seminar* in October and at the seminar *Méthodes probabilistes et statistiques en dynamique des populations* in Grenoble in December.
- N. Champagnat has been invited to give a lecture at the CIMPA School *Mathématiques pour la Biologie* (4h) in Tunis in October.
- M. Deaconu was invited to give a talk at the *Colloque Franco Roumain de Mathématiques Appliquées*, Iaşi (Romania) in August 2016.
- C. Fritsch has been invited to give talks at the *Workshop on "Approche Interdisciplinaire en Evolution"* in Saint-Martin-de-Londres in December.
- A. Lejay has been invited to give talk at the *Workshop on Numerical Schemes of SDE and SPDE* in Lille in June 2016, and at the *International Conference on Monte Carlo techniques* in Paris in July 2016.

- A. Lejay has ben invited to give a seminair talk at the Université de Reims in February 2016.
- P. Pigato gave talks at the Probability Seminar of Luxembourg University, in January, at the Seminar of TOSCA-Sophia Antipolis, in February, at the Seminar of CIMFAV (Valparaíso) in March, at the Journées de Probabilités 2016, in May, at the Probability Seminar of Università degli studi di Padova, in June, and at the London-Paris Bachelier Workshop on Mathematical Finance in September.
- A. Richard gave seminar talks at the LPMA (Paris 6) Probability seminar and the IMT (Toulouse) probability seminar in February, at the Groupe de Travail on stochastic models in finance at Ecole Polytechnique and at the Barcelona probability seminar in April.
- A. Richard had an accepted talk at ICMNS 2016.
- D. Talay gave a lecture at the Mean-field and population-level descriptions of brain dynamics Meeting in February at the EITN, Paris, the opeing lecture at the conference in V. Konokov's honor in Moscow in June, a mini-course at Lille University in June, and an invited lecture at the Workshop on the Numerics for Stochastic Partial Differential Equations and their Applications at RICAM, Linz (Austria) in December.
- E. Tanré gave talks at LPMA (Paris 6) and at the workshop on Numerical schemes for SDEs and SPDEs in Lille in June.
- D. Villemonais has been invited to give talks at the workshop *Stochastic processes under constraints* in July in Augsburg, Germany, at the conference *Colloque franco-roumain de mathématiques* in August in Iaşi, Romania, and at the *School on Information and Randomness* in December in Santiago, Chile.
- D. Villemonais has been invited to give seminar talks at *Institut Montpelliérain Alexander Grothendieck* in February, at the *Institut de Recherche Mathématique Avancée* in Strasbourg in November, and at the *Modal'X seminar* in Nanterre in December.

9.1.6. Leadership within the Scientific Community

- A. Lejay is the head of the Probability and Statistics team of the Institut Élie Cartan since September 2016.
- A. Lejay was a member of the Administration Council of the SMAI until June 2016.
- 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 is serveing as a member of the committee in charge of preparing the application of Paris to the International Congress of Mathematicians 2022.

9.1.7. Scientific Expertise

- N. Champagnat reported on an application submitted to CONICYT (Chilean Funding Agency).
- M. Deaconu has been a member of the Committee for junior permanent research positions of Inria Nancy - Grand Est.
- A. Lejay reported on applications to National Science Centre of Poland.
- A. Lejay participated in a Professor position recruitment committee at Université de Lorraine.

9.1.8. Research Administration

- M. Bossy is an elected member of the Inria Evaluation Board.
- M. Bossy has been a member of the DTK-Committee.

- N. Champagnat is a member of the *Commission de Développement Technologique* and the *Commission Information Scientifique et Technique* of Inria Nancy - Grand Est, a subsitute member of the *Comité de Centre* of Inria Nancy - Grand Est (until Nov. 2016), *Responsable Scientifique* for the library of Mathematics of the IECL, member of the *Conseil du laboratoire* of IECL (as *responsable scientifique* of the library). He is also local correspondent of the COERLE (*Comité Opérationel d'Évaluation des Risques Légaux et Éthiques*) for the Inria Research Center of Nancy - Grand Est. This year, together with Aline Wagner (Inria Nancy - Grand Est), he finished to write the new version of the application form for research approval by the COERLE.
- M. Deaconu is a member of the *Bureau du Comité de Projets* of Inria Nancy - Grand Est, and of the *Comité de Projet* of Inria Nancy - Grand Est.
- A. Lejay is a member of the COMIPERS of Inria Nancy Grand-Est and of *Commission des thèses* of the Institut Élie Cartan (Nancy).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master: M. Bossy, *Continuous time stochastic models for quantitative Finance*, 30h, M2 IMAFA (Informatique et Mathématiques Appliquées à la Finance et à l'Assurance), École Polytechnique Universitaire, Univ. Nice - Sophia Antipolis, France.

Master : M. Bossy, *Risk on energetic financial markets*, 27h, Master Spécialisé, Ingénierie et Gestion de l'Énergie, Mine ParisTech, France.

Master : M. Bossy *Stochastic Particle Methods for PDEs*, 18h, M2 Probabilité et Applications, Université Pierre et Marie Curie, France.

PhD-level lectures : M. Bossy *McKean SDEs and related stochastic methods for PDEs*, 18h, University of Edinburgh (UK).

PhD-level lectures : M. Bossy *Stochastic numerical methods for turbulence*, Winter school Numerics for Stochastic Partial Differential Equations and their Applications, 10h, at RICAM - University of Linz.

Master: N. Champagnat, *Introduction to Quantitative Finance*, 18h, M1, École des Mines de Nancy, France.

Master: N. Champagnat, *Introduction to Quantitative Finance*, 13.5h, M2, École des Mines de Nancy, France.

Master: N. Champagnat, *Chaînes de Markov*, 22.5h, M2 "double diplôme" Mathématiques et Applications - École Supérieure des Sciences et de Technologie de Hammam Sousse, Tunisie (lieu des cours) - Université de Lorraine, France.

Master: M. Deaconu, *Équations différentielles stochastiques : résolution numérique et applications*, 21h, M2, École des Mines de Nancy, France.

Master: M. Deaconu, *Modélisation stochastique*, 30h, M2, Université de Lorraine, France.

Master: M. Deaconu, *Simulation Monte Carlo*, 24h, M1, Faculté de Droit, Sciences Economiques et Gestion, Université de Lorraine, France.

Master: C. Fritsch, *Introduction à la finance quantitative*, 3h, M1, École des Mines de Nancy, France.

Licence: C. Fritsch, *Décision et Prévision Statistiques*, 20h, L3, École des Mines de Nancy, France.

Licence: C. Fritsch, *Supervision d'un projet de recherche*, 6h, M2, École des Mines de Nancy, France.

Licence: B. Henry, *Statistiques*, 20h, L3, École des Mines de Nancy, France.

Licence: B. Henry, *Probabilités*, 36h, L3, École des Mines de Nancy, France.

Master: A. Lejay, *Simulation des marchés financiers*, 28.5h, M2, Université de Lorraine (Metz), France.

Master: P. Pigato, *Calcul Intégral*, 15h, M1, Université de Lorraine (Nancy), France.

Licence: K. Salhi, *Mathématiques Appliquées et Probabilités*, 24h, L3, Télécom Nancy, France.

Master: K. Salhi, *Statistiques et analyse de données*, 20h, M1, Télécom Nancy, France.

Master: K. Salhi, *Probabilités et Statistiques*, 20h, M1, ENSEM Nancy, France.

Master: D. Talay *Invariant measures of diffusion processes*, 18h, M2 Probabilité et Applications, Université Paris 6, France.

Master: E. Tanré (courses) and M. Tomasevic (exercices), *Advanced Numerics for Computational Finance*, 30h (20h + 10h), M2, UCA (Mathmods Erasmus Mundus), France.

Master: E. Tanré, *Mathematical Methods for Neurosciences*, 37h, M2, ENS - Master MVA / Paris 6 - Master Maths-Bio, France.

Master: E.Tanré (courses) and A. Richard (practical classes) *Numerical probability for mathematical finance*, 20h (8h + 12h), M2, EPU (Master IMAFA), France.

9.2.2. Supervision

PhD: Maxime Bonelli, *Behavioral finance approach to risk assessment in quantitative portfolio management*, Univ. Nice Sophia Antipolis, September 2016, M. Bossy.

PhD : Benoît Henry, *Processus de branchements non markoviens en dynamique et génétique des populations*, Univ. Lorraine, 17/11/2016, Nicolas Champagnat, D. Ritchie (EPI CAPSID).

PhD : Khaled Salhi, *Risques extrêmes en finance : analyse et modélisation*, Univ. Lorraine, 05/12/2016, M. Deaconu and A. Lejay.

PhD in progress: Antoine Brault, *Formules de Trotter-Kato pour les trajectoires rugueuses*, Université Toulouse 3, L. Coutin (U. Toulouse 3), A. Lejay.

PhD in progress: Baldwin Dumortier, *Contrôle acoustique des éoliennes*, October 2014, M. Deaconu and E. Vincent (EPI MULTISPEECH).

PhD in progress: Pascal Helson, *Plasticity in networks of spikking neurons in interaction*, October 2016, E. Tanré and R. Veltz (MATHNEURO Inria team).

PhD in progress: Kouadio Jean Claude Kouaho, *Modélisations stochastique et déterministe de croissance de tumeurs cancéreuses*, Mar. 2016, N. Champagnat, Pierre Vallois (EPI BIGS, Modest N'Zi (UFHB, Abidjan).

PhD in progress: Radu Maftei, *A stochastic approach to colloidal particle agglomeration in turbulent flows*, November 2014, M. Bossy.

PhD in progress: Hernán Mardones, *Numerical solutions of stochastic differential equations with multiplicative noise*, Universidad de Concepción, A. Lejay, C. Mora (U. Concepción).

PhD in progress: Milica Tomasevic, *Stochastic approaches to Keller–Segel equations*, October 2015, D. Talay.

9.2.3. Juries

- M. Bossy served as a referee for the Ph.D. theses of Anthony LE CAVIL, *Représentation probabiliste de type progressif d'EDP nonlinéaires nonconservatives et algorithmes particulaires associés.* Université Paris Saclay, December 9, 2016.
- M. Bossy served as an examiner for the Ph.D. thesis of Ahmed MTIRAOUI , *EDS Progressives Rétrogrades couplées contrôlées, EDDS Rétrogrades et EDP Stochastiques*. Université de Toulon, November the 25th, 2016.
- N. Champagnat served as a referee for the Ph.D. theses of Elma Nessar, *Modèles probabilistes de l'évolution d'une population dans un environnement variable*, Univ. Aix-Marseille, July 4, 2016, and of Joseba Dalmau, *La quasi-espèce pour une population finie*, Univ. Orsay, November 25, 2016.

- N. Champagnat served as an examiner for the Ph.D. thesis of Lucas Mercier, *Grands graphes et grand arbres aléatoires : Analyse du comportement asymptotique*, Univ. Lorraine, May 11, 2016, and of Benoît Henry, *Processus de branchements non markoviens en dynamique et génétique des populations*, Univ. Lorraine, November 17, 2016.
- A. Lejay served as a referee for the Ph.D. theses of Sarav Mazzonetto, *On the exact simulation of (Skew) Brownian Diffusions with Discontinuous Drift*, Potsdam Universität / Université Lille 1, November 2016, of Anis Al Gerbi, *Ninomiya-Victoir scheme: strong convergence, asymptotics for the normalized error and multilevel Monte Carlo methods*, Université Paris-Est, October 2016, and of Joseph El Maalouf, *Méthodes de Monte Carlo stratifiées pour la simulation des chaînes de Markov*, Université de Grenoble / Université Saint Joseph de Beyrouth, December 2016.
- A. Lejay served as an examiner for the Habilitation Thesis of Pierre Étoré, *Quelques contributions à l'étude et à la simulation des diffusions asymétriques*, Université de Grenoble, December 2016.
- M. Deaconu and A. Lejay served as examiners for the Ph.D. thesis of Khaled Salhi, *Risques extrêmes en finance : analyse et modélisation*, Université de Lorraine, December 2016.
- D. Talay chaired the Ph.D. thesis jury of Ahmed Mtiraoui, *Equations différentielles stochastique rétrogrades progressives et leurs applications aux théories de contrôles*, Université de Toulon.
- D. Talay served as a referee for the Ph.D. theses of Daoud Ounaissi, *Méthodes Quasi Monte-Carlo et Monte-Carlo applications aux calculs des estimateurs Lasso et Lasso bayésien*, université de Lille I; and of Ahmed Bel Hadj Ayed *Robustesse de la stratégie de trading optimale*, École Centrale Paris;
- D. Talay chaired the Habilitation à Diriger les Recherches juries of Christophette Blanhet-Scalliet, *Contribution a` l'analyse des risques financiers : risque de crédit, asymétrie d'information, analyse chartiste*, École Centrale de Lyon, and of Pierre Étoré, *Quelques contributions à l'étude et à la simulation des diffusions asymétriques*, INP Grenoble.

9.3. Popularization

- D. Talay participated in a scientific France Culture radio program in December.

10. Bibliography

Major publications by the team in recent years

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[9] J. INGLIS, D. TALAY.*Mean-field limit of a stochastic particle system smoothly interacting through threshold hitting-times and applications to neural networks with dendritic component*, in "SIAM Journal on Mathematical Analysis", 2015, vol. 47, n^{o} 15, p. 3884–3916 [*DOI :* 10.1137/140989042], https://hal.inria.fr/hal-01069398.

[10] A. LEJAY.*The snapping out Brownian motion*, in "Annals of Applied Probability", September 2015, https://hal.inria.fr/hal-00781447.

Publications of the year

Articles in International Peer-Reviewed Journal

[11] M. BAAR, A. BOVIER, N. CHAMPAGNAT.*From stochastic, individual-based models to the canonical equation of adaptive dynamics - In one step*, in "The Annals of Applied Probability : an official journal of the institute of mathematical statistics", 2016, vol. Online first, https://hal.inria.fr/hal-01188189.

[12] L. BEZNEA, M. DEACONU, O. LUPASCU.*Stochastic equation of fragmentation and branching processes related to avalanches*, in "Journal of Statistical Physics", February 2016, vol. 162, n^{o} 4, p. 824-841, Accepté pour publication, https://hal.inria.fr/hal-01216137.

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[15] F. CAMPILLO, N. CHAMPAGNAT, C. FRITSCH.*Links between deterministic and stochastic approaches for invasion in growth-fragmentation-death models*, in "Journal of Mathematical Biology", 2016 [*DOI :* 10.1007/s00285-016-1012-6], https://hal.archives-ouvertes.fr/hal-01205467.

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Project-Team VIRTUAL PLANTS

Modeling plant morphogenesis at different scales, from genes to phenotype

IN COLLABORATION WITH: Amélioration génétique et adaptation des plantes (AGAP)

IN PARTNERSHIP WITH:
CIRAD

INRA

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Computational Biology

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Project-Team VIRTUAL PLANTS

Creation of the Project-Team: 2007 July 01

Keywords:

Computer Science and Digital Science:

1.1.4. - High performance computing
1.1.13. - Virtualization
2.1.3. - Functional programming
2.1.9. - Dynamic languages
2.1.10. - Domain-specific languages
2.2.6. - Adaptive compilation
2.5. - Software engineering
3.1.1. - Modeling, representation
3.1.3. - Distributed data
3.1.8. - Big data (production, storage, transfer)
3.4.5. - Bayesian methods
5.1.1. - Engineering of interactive systems
5.2. - Data visualization
5.3.3. - Pattern recognition
5.3.4. - Registration
5.4.4. - 3D and spatio-temporal reconstruction
5.4.5. - Object tracking and motion analysis
5.5.1. - Geometrical modeling
5.9.2. - Estimation, modeling
6.1. - Mathematical Modeling
6.2.4. - Statistical methods
6.2.6. - Optimization
6.2.8. - Computational geometry and meshes
6.3. - Computation-data interaction
7.2. - Discrete mathematics, combinatorics
7.3. - Optimization
7.5. - Geometry, Topology
7.8. - Information theory
7.9. - Graph theory

Other Research Topics and Application Domains:

1.1.2. - Molecular biology
1.1.3. - Cellular biology
1.1.4. - Developmental biology
1.1.10. - Mathematical biology
1.1.11. - Systems biology
2.6. - Biological and medical imaging
9.4.1. - Computer science

9.4.2. - Mathematics
9.4.5. - Data science
9.6. - Reproducibility
9.7.1. - Open access

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2. Overall Objectives

2.1. Overall Objectives

The Virtual Plants team is a joint team between Inria, CIRAD and INRA located in Montpellier. The long-term focus of the project is to study plant development, its modulation by the environment and its control by genetic processes.

Plants are branching living organisms that develop throughout their lifetimes. Organs are created by small embryogenetic regions at the tip of each axis, called *apical meristems*. In the project Virtual Plants, we are interested in studying plant apical meristem functioning and development. We develop a detailed analysis of apical meristem processes, based on advanced mathematical and computational methods and tools, to get a deeper and better understanding of plant development.

This study is performed from two complementary perspectives.

- First, at a macroscopic level, we develop an extensive methodology to analyze *the structures produced by meristems*. This can be seen as a methodology that aims to solve an inverse problem in which one tries to infer meristem functioning from the complex structures they produce. This analysis is carried out at different spatial and temporal scales.
- Second, at a more microscopic level, we intend to exploit the recent spectacular scientific and technological progresses in developmental biology in order to understand how physiological and genetic processes control meristem growth at cell scale.

To develop these two scientific axes, we carry out research in three main categories of models and methods:

- multiscale models for the spatial (topological and geometrical) representation of structured biological objects (which range from meristem tissues to branching structures),
- methods and models for deciphering the organization of these complex biological objects,
- and models for morphogenesis.

In order to make our methods and models available to our partners, all our tools are integrated in a common software platform: *V-Plants*. Based on this platform, we coordinate the development of an open software platform, *OpenAlea*, for plant modeling at a national and international level.

3. Research Program

3.1. Analysis of structures resulting from meristem activity

To analyze plant growth and structure, we focus mainly on methods for analyzing sequences and tree-structured data. Theses methods range from algorithms for computing distance between sequences or tree-structured data to statistical models.

- *Combinatorial approaches*: plant structures exhibit complex branching organizations of their organs like internodes, leaves, shoots, axes, branches, etc. These structures can be analyzed with combinatorial methods in order to compare them or to reveal particular types of organization. We investigate a family of techniques to quantify distances between branching systems based on non-linear structural alignment (similar to edit-operation methods used for sequence comparison). Based on these techniques, we study the notion of (topology-based) self-similarity of branching structures in order to define a notion of degree of redundancy for any tree structure and to quantify in this way botanical notions, such as the physiological states of a meristem, fundamental to the description of plant morphogenesis.
- *Statistical modeling*: We investigate different categories of statistical models corresponding to different types of structures.

  - Longitudinal data corresponding to plant growth follow up: the statistical models of interest are equilibrium renewal processes and generalized linear mixed models for longitudinal count data.
  - Repeated patterns within sequences or trees: the statistical models of interest are mainly (hidden) variable-order Markov chains. Hidden variable-order Markov chains were in particular applied to characterize permutation patterns in phyllotaxis and the alternation between flowering and vegetative growth units along sympodial tree axes.
  - Homogeneous zones (or change points) within sequences or trees: most of the statistical models of interest are hidden Markovian models (hidden semi-Markov chains, semi-Markov switching linear mixed models and semi-Markov switching generalized linear models for sequences and different families of hidden Markov tree models). A complementary approach consists in applying multiple change-point models. The branching structure of a parent shoot is often organized as a succession of branching zones while the succession of shoot at the more macroscopic scale exhibit roughly stationary phases separated by marked change points.

  We investigate both estimation methods and diagnostic tools for these different categories of models. In particular we focus on diagnostic tools for latent structure models (e.g. hidden Markovian models or multiple change-point models) that consist in exploring the latent structure space.

- *A new generation of morphogenesis models*: Designing morphogenesis models of the plant development at the macroscopic scales is a challenging problem. As opposed to modeling approaches that attempt to describe plant development on the basis of the integration of purely mechanistic models of various plant functions, we intend to design models that tightly couple mechanistic and empirical sub-models that are elaborated in our plant architecture analysis approach. Empirical models are used as a powerful complementary source of knowledge in places where knowledge about mechanistic processes is lacking or weak. We chose to implement such integrated models in a programming language dedicated to dynamical systems with dynamical structure $(DS)^2$, such as L-systems or MGS. This type of language plays the role of an integration framework for sub-models of heterogeneous nature.

3.2. Meristem functioning and development

In this second scientific axis, we develop models of meristem growth at tissue level in order to integrate various sources of knowledge and to analyze their dynamic and complex spatial interaction. To carry out this integration, we need to develop a complete methodological approach containing:

- algorithms for the automatized segmentation in 3D, and cell lineage tracking throughout time, for images coming from confocal microscopy,
- design of high-level routines and user interfaces to distribute these image analysis tools to the scientific community,
- tools for structural and statistical analysis of 3D meristem structure (spatial statistics, multiscale geometric and topological analysis),
- physical models of cells interactions based on spring-mass systems or on tensorial mechanics at the level of cells,
- models of biochemical networks of hormonal and gene driven regulation, at the cellular and tissue level, using continuous and discrete formalisms,
- and models of cell development taking into account the effects of growth and cell divisions on the two previous classes of models.

4. Highlights of the Year

4.1. Highlights of the Year

- *Stochastic model of Phyllotaxis*: Exploration of developmental mechanisms classically relies on analysis of pattern regularities. Whether disorders induced by biological noise may carry information on building principles of developmental systems is an important debated question. In this work, we addressed theoretically this question using phyllotaxis, the geometric arrangement of plant aerial organs, as a model system. Phyllotaxis arises from reiterative organogenesis driven by lateral inhibitions at the shoot apex. Motivated by recurrent observations of disorders in phyllotaxis patterns, we revisited in depth the classical deterministic view of phyllotaxis. We developed a stochastic model of primordia initiation at the shoot apex, integrating locality and stochasticity in the patterning system. This stochastic model recapitulates phyllotactic patterns, both regular and irregular, and makes quantitative predictions on the nature of disorders arising from noise. Altogether, we show that disorders in phyllotaxis instruct us on the parameters governing phyllotaxis dynamics, and thus that disorders can reveal biological watermarks of developmental systems [27].
- *Statistical methods*: One of our main activities consists of identifying and characterizing developmental patterns in plant phenotyping data. Phenotyping data are very diverse ranging from the tissular to the whole plant scale but are often highly structured in space, time and scale. We intend to analyse such data using state-of-the-art methods at the crossroad between statistical modelling, machine learning and pattern recognition. This generates regularly new methodological results as illustrated this year by [18] and [25].

5. New Software and Platforms

5.1. OpenAleaLab

KEYWORDS: Bioinformatics - Biology - Workflow - Modelling Environment
FUNCTIONAL DESCRIPTION

OpenAleaLab is an integrated modelling environment (IME) designed for scientists based on IPython and on OpenAlea components. This open source environment is extensible via plug-ins and allows user to work with a set of diverse modelling paradigms like imperative languages (Python, R), scientific workflows (visual programming) or rule-based language (L-System). This IME, built using PyQt, provides an IPython shell, a text editor, a project manager, a graphical package installer and a world, containing the objects and state variables shared by the different paradigms. The world can be graphically interpreted in 3D or 2D. Different paradigms and tools for plant modelling are available as plug-ins, such as a visual programming environment, a L-system language, a 3D viewer, and an R editor and interpreter. The plug-in system is based on setuptools entry-points and provide both functional and GUI components. This environment is designed to be easily extensible in order to include new plant modelling paradigms in the future or to be customized for other scientific domains. Several dedicated extensions (TissueLab, PlantLab) have been developed or are in development.

- Participants: Christophe Pradal, Christophe Godin.
- Contact: Christophe Pradal, Christophe Godin
- URL: http://virtualplants.github.io/

5.2. TissueLab

KEYWORDS: Bioinformatics - Biology - Modelling Environment
FUNCTIONAL DESCRIPTION

TissueLab is an OpenAleaLab extension dedicated to study plant morphogenesis at the scale of the tissues. This extension was built on the basis of several key concepts of OpenAleaLab (project, world, interactive panels, etc.) and using its plugin mechanism (dynamically discovered, modular, extensible, etc.). TissueLab provides a framework for the visualization, exploration, interaction, reconstruction, analysis and simulation of tissue development based on image sequences. It contains for instance the PyThor module, dedicated to 3D real-time interaction and modification of segmented images for the creation of ground truth segmentations.

- Participants: Sophie Ribes, Guillaume Baty, Guillaume Cerutti, Alizon Konig, Grégoire Malandain, Christophe Pradal, Christophe Godin.
- Contact: Christophe Godin
- URL: https://github.com/virtualplants/tissuelab

5.3. Draco-Stem

KEYWORDS: 3D Reconstruction - Triangular Mesh - Biomechanical Simulations
FUNCTIONAL DESCRIPTION

A computational tool called DRACO-STEM (Dual Reconstruction by Adjacency Complex Optimization - SAM Tissue Enhanced Mesh) has been made available, with the aim of bridging the gap between experimental data and tissue biomechanics models. It provides the necessary tools to generate a FEM-ready, topologically accurate, complete 3D triangular mesh of meristematic tissue, based on a segmented image obtained from a confocal microscopy acquisition. The produced meshes proved to be useable as an input for computational simulations of biomechanical and physiological cellular processes.

- Participants: Guillaume Cerutti, Christophe Godin, Olivier Ali
- Contact: Guillaume Cerutti
- URL: https://github.com/VirtualPlants/draco_stem/

5.4. ASTEC

KEYWORDS: Segmentation - Tracking - High resolution
FUNCTIONAL DESCRIPTION

A new algorithmic pipeline, ASTEC (Adaptative Segmentation and Tracking of Embryonic Cells), has been developed to segment and track cell shapes in 3D from movies with high spatio-temporal resolution of embryos where the membranes have been labeled (using dye or genetic markers for example). To segment the 3D embryo image at a given time-point, ASTEC takes advantage of the high spatial resolution of the movie in order to propagate the segmentation of the previous time points. This, coupled to biological knwoledge on the studied system, allows to constrain the segmentation and to track cells throughout time simulataneously. Moreover, the propagation allows to bound the potential mistakes of segmentation (e.g. a cells cannot disappear) which enables powerful post-correction based on the study of the resulting tracking.

- Participants: Léo Guignard, Emmanuel Faure, Grégoire Malandain, Patrick Lemaire, Christophe Godin
- Contact: Christophe Godin
- URL: https://gforge.inria.fr/projects/marsalt/

5.5. AutoWIG

KEYWORDS: Syntaxic Analysis
FUNCTIONAL DESCRIPTION

High-level programming languages, such as Python and R, are popular among scientists. They are concise, readable, lead to rapid development cycles, but suffer from performance drawback compared to compiled languages. However, these languages allow to interface C, C++ and Fortran code. In this way, most of the scientific packages incorporate compiled scientific libraries to both speed up the code and reuse legacy libraries. While several semi-automatic solutions and tools exist to wrap these compiled libraries, the process of wrapping a large library is cumbersome and time consuming. We developped AutoWIG [40], [47], a Python library that wraps automatically compiled libraries into high-level languages. Our approach consists in parsing C++ code using the LLVM/Clang technologies and generating the wrappers using the Mako templating engine. Our approach is automatic, extensible, and applies to very complex C++ libraries, composed of thousands of classes or incorporating modern meta-programming constructs. The usage and extension of AutoWIG have been illustrated on a set of statistical libraries (StructureAnalysis).

- Participants: Pierre Fernique, Christophe Pradal
- Contact: Pierre Fernique
- URL: https://github.com/VirtualPlants/AutoWIG

5.6. Phenomenal

KEYWORDS: Image Analysis, Phenotyping
FUNCTIONAL DESCRIPTION

Phenomenal [65] is a Python library dedicated to the analysis of high throughput phenotyping data and models. It has been developed in the frame of the Phenome high throughput phenotyping infrastructure. It is based on the OpenAlea platform [76], [77] that provides methods and softwares for the modelling of plants, together with a user-friendly interface for the design and execution of scientific workflows. OpenAlea is also part of the InfraPhenoGrid infrastructure that allows high throughput computation and recording of provenance during the execution [26].

- Participants: Simon Artzet, Jérôme Chopard, Tsu-Wei Chen, Nicolas Brichet, Christian Fournier, Christophe Pradal
- Contact: Christian Fournier, Christophe Pradal
- URL: https://gitlab.inria.fr./phenome/phenomenal

5.7. Platforms

5.7.1. Platform OpenAlea

OpenAlea is an open-software platform for interdisciplinary research in plant modeling and simulation. This scientific workflow platform is used for the integration and comparison of different models and tools provided by the research community. It is based on the Python (http://www.python.org) language that aims at being both a *glue* language for the different modules and an efficient modeling language for developing new models and tools. *OpenAlea* currently includes modules for plant simulation, analysis and modeling at different scales (*V-Plants* modules), for modeling ecophysiological processes (*Alinea* modules) such as radiative transfer, transpiration and photosynthesis (*RATP*, *Caribu*, *Adel*, *TopVine*, *Ecomeristem*) and for 3D visualization of plant architecture at different scales (*PlantGL*).

OpenAlea is the result of a collaborative effort associating 20 french research teams in plant modeling from Inria, CIRAD, INRA and ENS Lyon. The Virtual Plants team coordinates both development and modeling consortia, and is more particularly in charge of the development of the kernel and of some of the main data structures such as multi-scale tree graphs and statistical sequences.

OpenAlea is a fundamental tool to share models and methods in interdisciplinary research (comprising botany, ecophysiology, forestry, agronomy, applied mathematics and computer science approaches). Embedded in Python and its scientific libraries, the platform may be used as a flexible and useful toolbox by biologists and modelers for various purposes (research, teaching, rapid model prototyping, communication, etc.).

New methodological developments around scientific workflows in *OpenAlea* have been done recently.

5.7.2. Platform Sofa

Our team is increasingly using the platform SOFA developed at Inria by other teams, in conjunction with OpenAlea, to model biomechanics of plant tissues. SOFA (https://www.sofa-framework.org) is an Open Source framework primarily targeted at real-time simulation, with an emphasis on biological 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. It has been extensively used by our team in the recent years to conduct virtual mechanical experiments on plant tissues (see section 6.2.3).

6. New Results

6.1. Analysis of structures resulting from meristem activity

6.1.1. Acquisition and design of plant geometry

Participants: Frédéric Boudon, Christophe Pradal, Christophe Godin, Christian Fournier, Ibrahim Chedaddi, Mathilde Balduzzi, Julien Diener.

Virtual 3D model of plants are required in many areas of plant modeling. They can be used for instance to simulate physical interaction of real plant structures with their environment (light, rain, wind, pests, ...), to set up initial conditions of growth models or to assess their output against real data. In the past decade, methods have been developed to digitize plant architectures in 3D [81], [68]. These methods are based on direct measurements of position and shape of every plant organ in space. Although they provide accurate results, they are particularly time consuming. More rapid and automated methods are now required in order to collect plant architecture data of various types and sizes in a systematic way. In this aim, we explore the use of laser scanner and pictures.

- *Reconstruction of tree structures from 3D laser scanner data.* (Olivier Simler [AFEF, AGAP], Chakkrit Preuksakarn, Frédéric Boudon, Christophe Godin, Benoit Pallas [AFEF, AGAP], Evelyne Coste [AFEF, AGAP])

  We investigate the possibility to use 3D laser scanners to automate plant digitizing. We are developing algorithms to reconstruct branching systems without leaves or foliage from scanner data or from scan simulated on plant mock-up obtained using different digitizing method.

  For the branching systems, we previously proposed a reconstruction method to reconstruct plausible branching structures from laser scanner data based on the concept of space colonization [78]. Additionally, a number of automatic methods were proposed in the literature. A graphical editor has been developed and makes it possible to test these different methods and correct manually the reconstruction on laser scans. An additional validation pipeline makes it possible to compares automatic reconstruction with ground truth data using two indices of geometrical and structural similarities [59].

  This year, the editor has been augmented for better user control over the different step of the reconstruction process. Some first alignment procedures of scans and reconstructions made at different times of the year have been also implemented. An application for the reconstruction of an apple tree core collection has been conducted during the internship of O. Simler in a collaboration with the AFEF Team of UMR AGAP.

- *Characterizing wheat canopy characteristics from LiDAR measurements.* (Shouyang Liu [Emmah,Inra], Fred Baret [Emmah,Inra], Frédéric Boudon, Christian Fournier)

Green area index (GAI) has been difficult to estimate accurately at large scales due to the cost prohibitive nature of classical in-situ methods. We propose to use LiDAR to overcome this problem. Through this work, we proposed a self-learning method to estimate GAI using LiDAR-derived metrics over a wheat field.

Specifically, we developed a LiDAR simulator to carry out scanning on digital 3D objects, mimicking the measuring principle and setups of actual LiDAR sensors. The footprint and the geometrical configuration of the LiDAR are explicitly accounted for. Comparison with measurements of actual LiDAR demonstrates that the simulator generates a 3D point cloud having the same statistical properties as those derived from the actual LiDAR measurements.

We then used a machine learning algorithm to correlate LiDAR-derived metrics and GAI over synthetic datasets. 3D wheat canopy scenes were generated with AdelWheat model for two contrasting development stages across a wide range of combination of the model parameters. The scenes were transformed into 3D point clouds using the LiDAR simulator. Results demonstrate that emerging properties, such as leaf area index (GLAI), could be retrieved with a good accuracy.

- *Reconstruction of annual plants from multi-view images.* (Simon Artzet, Jerome Chopard, Christian Fournier, Christophe Pradal, Christophe Godin, Xavier Sirault [CSIRO-HRPPC, Canberra], Tsu-Wei Chen[Inra, LEPSE])

  Image-based phenotyping platforms in semi-controlled conditions offer large possibilities to perform genetic analyses of plant growth, architecture, light interception, and biomass accumulation over large time series for thousands of plants. However, methods for image analysis currently available are still very crude and need improvement and robustness to process huge amount of data. We are developing a python software framework dedicated to the analysis of high throughput phenotyping data and models named Phenomenal. This software framework currently consists of 2D and 3D image analysis workflow which ranges from 2D organs segmentation, 3D multi-view reconstruction, image-base meshing transformation, 2D/3D morphological thinning/skeletonization, 3D segmentation and tracking of plant organs maize (under development). We have processed images from phenoarch platform of the last four years and have built for each plant (maize, cotton, etc.) a voxel point cloud and image-base meshing representation and also for 725 maize plants a voxel point cloud automatically segmented (currently stem and mature leaf). Each process is run on distant server (private or virtual machines on FranceGrille cloud) and results can be viewed via a jupyter notebook server. Furthermore, 3D FSPM model for maize architectural development (named ADEL), is used to help segmenting plant images and to automate the mapping between segmented 3D objects and plant organs defined in the model. The 3D reconstructed model is combined with meteorological data to feed a light distribution model and estimate light use efficiency. This software framework was presented to “BMVA technical meeting: Plants in Computer Vision”.

- *Reconstruction of virtual fruits from pictures.* (Ibrahim Chedaddi, Mik Cieslak, Nadia Bertin [Inra, Avignon], Frédéric Boudon, Christophe Godin, Michel Genard [Inra, Avignon], Christophe Goz-Bac [Université Montpellier 2])

  This research theme is supported by the Agropolis project MecaFruit3D.

  The aim of this work is to provide methods for generating fruit structure that can be integrated with models of fruit function. To this end, a modeling pipeline has been developed in the OpenAlea platform. It involves two steps: (1) generating a 3D volumetric mesh representation of the entire fruit, and (2) generating a complex vascular network that is embedded within this mesh using the concept of space colonization [80]. Previous studies demonstrated the possibility to create species-specific models of fruit structure with relatively low effort [63]. We focus now on validating the vascular networks by comparing them to experimental data from the literature. This work has been presented at the ISHS symposium in Montpellier [60] and resulted in a publication [17].

  Using these fruit virtual structures, a mechanical model of fruit growth is also developed (see section 6.3.2) taking into account the distribution of water fluxes in the fruit.

- *Review on morphological plant modelling.* (Christophe Pradal, Mathilde Balduzzi, Alexander Bucksch [Georgia Univ., USA], Daniel H. Chitwood [Donald Danforth Plant Science Center, USA])

  Plant morphology is inherently mathematical. The geometries of leaves and flowers and intricate topologies of the root have fascinated plant biologists and mathematicians alike. Beyond providing aesthetic inspiration, understanding plant morphology has become pressing in an era of climate change and a growing population. Gaining an understanding of how to modify plant architecture through molecular biology and breeding is critical to improving agriculture, and the monitoring of ecosystems and global vegetation is vital to modeling a future with fewer natural resources. In this review [45], we begin by summarizing the rich history and state of the art in quantifying the form of plants, mathematical models of patterning in plants, and how plant morphology manifests dynamically across disparate scales of biological organization. We then explore the fundamental challenges that remain unanswered concerning plant morphology, from the barriers preventing the prediction of phenotype from genotype to modeling the fluttering of leaves in a light breeze. We end with a discussion concerning the education of plant morphology synthesizing biological and mathematical approaches and ways to facilitate research advances through outreach, cross-disciplinary training, and open science.

6.1.2. Modeling the plant ontogenic program

Participants: Christophe Godin, Yann Guédon, Jean-Baptiste Durand, Pierre Fernique, Marc Labadie, Christophe Pradal, Jean Peyhardi.

This research theme is supported by one PhD program.

The remarkable organization of plants at macroscopic scales may be used to infer particular aspects of meristem functioning. The fact that plants are made up of the repetition of many similar components at different scales, and the presence of morphological gradients, e.g. [54], [70], [71], [67], provides macroscopic evidence for the existence of regularities and identities in processes that drive meristem activity at microscopic scales. Different concepts have been proposed to explain these specific organizations such as "morphogenetic program" [75], "age state" [66] or "physiological age" [56]. All these concepts state that meristem fate changes according to position within the plant structure and during its development. Even though these changes in meristem fate are specific to each species and lead to the differentiation of axes, general rules can be highlighted [66], [56]. Here we develop computational methods to decipher these rules.

- *Relating branching structure to the shoot properties.* (Jean Peyhardi, Yann Guédon, Evelyne Coste [AGAP, AFEF team], Catherine Trottier [I3M], Yves Caraglio [AMAP], Pierre-Eric Lauri [AGAP, AFEF team])

  Shoot branching structures often take the form of a succession of homogeneous branching zones and have been analyzed using segmentation models such as hidden semi-Markov chains. Axillary meristem fates are influenced by local properties of the parent shoot such as for instance its growth rate or local curvature. The objective of this work is to develop statistical models that generalize hidden semi-Markov chains with the capability to incorporate explanatory variables that vary along the parent shoot (e.g. leaf growth rate, leaf surface, internode length, local curvature of the parent shoot). More precisely, the simple multinomial distributions that represent the axillary productions observed in the different branching zones are replaced by multinomial generalized linear models (GLMs). Since the two classical categories of multinomial GLMs that correspond either to nominal or ordinal categorical response variables were not appropriate, we chose to develop a new family of multinomial GLMs called partitioned conditional GLMs [25] that enable to tackle hierarchically-structured categorical response variables. Typically, we need to distinguish different timing of branching events (e.g. immediate shoot, one-year-delayed shoot and latent bud), different categories of offspring shoots (e.g. among one-year-delayed shoots, vegetative short shoot, vegetative long shoot and flowering shoot) and to specialize the explanatory variables for certain categories of offspring shoots (e.g. the growth of the parent shoot influence the immediate offspring shoots but not the one-year-delayed offspring shoots). The resulting integrative models are called semi-Markov switching partitioned conditional GLMs and have been applied to apple and pear tree branching structures.

- *Genetic determinisms of the alternation of flowering in apple tree progenies.* (Jean-Baptiste Durand, Alix Allard [AGAP, AFEF team], Evelyne Costes [AGAP, AFEF team])

  A first study was published to characterize genetic determinisms of the alternation of flowering in apple tree progenies [64]. Data were collected at two scales: at whole tree scale (with annual time step) and a local scale (annual shoots, which correspond to portions of stems that were grown during the same year). Two replications of each genotype were available.

  Indices were proposed for early detection of alternation during the juvenile phase. They were based on a trend model and a quantification of the deviation amplitudes and dependency, with respect to the trend. This allowed early quantification of alternation from the yearly numbers of inflorescences at tree scale. Some quantitative trait loci (QTL) were found in relation with this indices.

  For better interpretation of the relationships of alternation at both scales, new models and indices were developed for sequences of flowering events at axis scale. New data sets where collected in other F1 progenies. Ancestral relationships between parents of different progenies were taken into account to enhance the power of QTL detection using Bayesian methods, and other QTL were found using these new indices.

- *Characterizing tree patchiness using a tree segmentation/clustering approach.* (Pierre Fernique, Anaëlle Dambreville, Jean-Baptiste Durand, Christophe Pradal, Yann Guédon, Frédéric Normand [CIRAD, HortSys, Réunion Island], Pierre-Eric Lauri [INRA, System]).

  Patchiness is characterized by clumps of homogeneous botanical entities (e.g. a clump of flowering growth units) within tree canopy. It is therefore assumed that there are subtrees within which the characteristics of the botanical entities follow the same or nearly the same distribution, and between which these characteristics have different distributions. The detection of such subtrees can thus be stated as tree-indexed data segmentation. We therefore transposed multiple change-point models to tree-indexed data. The output of the segmentation procedure is a partition of trees such that two non-adjacent subtrees can be very similar in terms of botanical entity characteristics. We thus incorporated a second stage of clustering of subtrees based on a mixture model in order to group non-adjacent similar subtrees. This statistical modeling framework was applied to young mango trees [32].

- *Simulating fruit tree phenology.* (A.S. Briand, Frédéric Boudon, Frédéric Normand [CIRAD, Hort-Sys, Réunion Island], Anaëlle Dambreville, Jean-Baptiste Durand, Pierre Fernique, Yann Guédon, Christophe Pradal, Pierre-Eric Lauri [INRA, System])

  Mango is a tropical tree characterized by strong asynchronisms within and between trees. To study more precisely the interplay between the plant structural components, we built an integrative model to simulate the plant development based on the L-system formalism and GLM to model the dependencies between events. With such model, we showed the importance of architectural and temporal factors in the development of the units of the trees, see 1. The model also simulates the phenology of shoots and inflorescences. For this, the sizes of the different organs is modelled by statistical laws estimated from measurements that depends on their locations in the architecture. The growth speed of organs is modulated by the temperature. The model has been then coupled with an ecophysiological model of fruit growth [73], [74]. The global aim is to have a crop simulation model to predict fruit yield and quality on mango tree. An overview of this global model based on the coupling of different structural or ecophysiological sub-models has been also presented in the FSPMA conference [44].

  In the context of the PhD of S. Persello, we aim at extending this model with the effect of agricultural practices. For this, a number of experiment has been conducted this year with some mango trees being pruned with different intensity (global mass removed) and severity (depth of the removed elements). Analysis and characterization of the effect of pruning on the subsequent vegetative development of the tree in currently under investigation.

Figure 1. Simulation of the development of a mango tree over two cycles [58]. The first and last image corresponds to the end of the vegetative period of the 3rd and 5th growing cycle (June), respectively while the second and third images correspond to the flowering phase (August) of the 3rd and 4th cycles, respectively. The different colours of the inflorescences of the 3rd image show different developmental stages and the flowering asynchronism over the tree.

- *Characterizing the successive flowering phases of strawberry in relation to genetic determinants.* (Yann Guédon, Marc Labadie, Béatrice Denoyes [INRA, UMR BFP, Villenave d'Ornon], Justine Perrotte)

  Our aim was to characterize the phenology of perpetual flowering strawberry genotypes, which is of particular importance for better predicting fruit production. We applied multiple change-point models for the synchronous segmentation of the individuals of a given genotype in successive flowering phases [24]. We identified two groups of genotypes that differ by the intensity of the flowering at the end of the flowering period. Using a genetic approach, we identified a locus controlling the flowering intensity at the end of the flowering period that likely explain these two groups of genotypes. A multivariate generalization of the synchronous segmentation approach is developed in the context of Marc Labadie's PhD [50], the idea being to characterize not only the flowering pattern as in our first study but more generally the developmental pattern combining vegetative development, branching and flowering.

- *Self-nested structure of plants.*(Christophe Godin, Romain Azaïs, Farah Ben Naoum, Jean-Baptiste Durand, Alain Jean-Marie)

  In a previous work [6], we designed a method to compress tree structures and to quantify their degree of self-nestedness. This method is based on the detection of isomorphic subtrees in a given tree and on the construction of a DAG (Directed Acyclic Graph, equivalent to the original tree, where a given subtree class is represented only once (compression is based on the suppression of structural redundancies in the original tree). In the compressed graph, every node representing a particular subtree in the original tree has exactly the same height as its corresponding node in the original tree.

  The method proposed in [6] thus compresses a tree in width, but not in height. In a new work, we designed an extension of this compression method in which a tree is compressed in both width and height. The method is based on the detection of so-called *quasi-isomorphic paths* in a tree and on the compression of these paths in height. A paper describing the corresponding algorithms has been recently accepted in the Journal of Theoretical Biology [16].

  The class of self-nested trees presents remarkable compression properties because of the systematic repetition of subtrees in their structure. In a collaboration with two other Inria project-teams (MISTIS and BIGS), studied methods to approximate a tree with a tree in the class of self-nested trees. We first provided a better combinatorial characterization of this specific family of trees. We then showed that self-nested trees may be considered as an approximation class of unordered trees. We finally compared our approximation algorithms with a competitive approach of the literature on a simulated dataset. [42]

6.1.3. Analyzing the influence of the environment on the plant ontogenic program

Participants: Jean-Baptiste Durand, Christian Fournier, Christophe Godin, Yann Guédon, Christophe Pradal, Jean Peyhardi, Pierre Fernique, Guillaume Garin.

This research theme is supported by three PhD programs.

The ontogenetic programme of a plant is actually sensitive to environmental changes. If, in particular cases, we can make the assumption that the environment is a fixed control variable (see section 6.1.2), in general the structure produced by meristem results from a tight interaction between the plant and its environment, throughout its lifetime. Based on observations, we thus aim to trace back to the different components of the growth (ontogenetic development and its modulation by the environment). This is made using two types of approaches. On the one hand, we develop a statistical approach in which stochastic models are augmented with additional time-varying explanatory variables that represent the environment variations. The design of estimation procedures for these models make it possible to separate the plant ontogenetic programme from its modulation by the environment. On the other hand, we build reactive models that make it possible to simulate in a mechanistic way the interaction between the plant development and its environment.

- *Investigating how architectural development interfere with epidemics and epidemic control.* (Christian Fournier, Corinne Robert [Ecosys, INRA], Guillaume Garin [ITK, Montpellier], Bruno Andrieu [Ecosys, INRA], Christophe Pradal)

  Sustainable agriculture requires the identification of new, environmentally responsible strategies of crop protection. Modelling of pathosystems can allow a better understanding of the major interactions inside these dynamic systems and lead to innovative protection strategies. In particular, functional–structural plant models (FSPMs) have been identified as a means to optimize the use of architecture-related traits. A current limitation lies in the inherent complexity of this type of modelling, and thus the purpose of this work is to provide a framework to both extend and simplify the modelling of pathosystems using FSPMs. Complex models are disassembled into separate *knowledge sources* originating from different specialist areas of expertise and these can be shared and reassembled into multidisciplinary models. This year, we worked on four application studies that used the framework. In the frame of the PhD of Guillaume Garin, we perform a validation of the wheat septoria model, an analysis of the influence of the wheat architecture on the competition between septoria and brown rust, and a sensitivity analysis of the response of the severity of septoria to architectural traits. In the frame of the Echap project, we use the wheat-septoria model to indentify optimal date of pesticide application. All these studies allows to populate the framework with consistent example of application, and lead to the development of operational modules that allows the fitting and validation of pathosystem models with experimental data.

- *Investigating how hydraulic structure interfere with gas-exchange dynamics of complex plants canopies under water deficit* (Christophe Pradal, Christian Fournier, Rami Albasha [LEPSE, Inra] and Eric Lebon [LEPSE, Inra])

  Individual leaves positioning within a plant canopy is a major determinant of the spatial distribution pattern of gas-exchange rates and energy budget within that canopy. Under water deficit, this distribution may be altered since soil drying affects stem hydraulic conductivity and, consequently, leaves stomatal conductance, suggesting that the hydraulic structure of the shoot may shape the intra-canopy variability of gas-exchange rates under water deficit. In this project, we design HydroShoot [30], a functional-structural plant model which allows simulating the hydraulic structure, energy budget and gas-exchange fluxes of complex plant canopies under water deficit. Model parameters are calibrated and validated using sapflow and entire plant gas exchange data collected in 2009 and 2012 from grapevine (Vitis vinifera L. cv. Syrah) experiments under three training systems (Lyre, GDC and VSP) having contrasted canopy structures. The model is then used to evaluate the role of the hydraulic structure in predicting the intra-canopy variability of temperature and intrinsic water use efficiency of trained grapevines. The resulting HydroShoot model allows to capture the effect of the different training systems on the spatial distribution of temperature and foliar photosynthesis within the canopy. We show that the intra-canopy variability of gas-exchange dynamics were mainly explained by the variability of local climate conditions, while the role of the hydraulic structure appeared only as secondary. Finally, the proposed HydroShoot model has been implemented for grapevine in the OpenAlea platform and will be extended to other plant architectural systems.

- *Eucalyptus development in response to different water stress and fertilization levels* (Yann Guédon, Charlène Arnaud (CIRAD AMAP and BioWooEB), Sylvie Sabatier (CIRAD AMAP)

  Eucalyptus grandis has been grown successfully in plantations in many tropical regions including southern Brazil. The objective of the PhD of Charlène Arnaud (CIRAD AMAP and BioWooEB) is to study the modulation of the development of Eucalyptus main stems in response to water stresses and different levels of potassium or sodium fertilization. Eucalyptus main stem is characterized by a two-scale growth pattern with (i) at coarse scale, roughly stationary growth phases with phase changes likely corresponding to cold seasons and (ii) at fine scale, more ore less systematic alternation of short and long internodes as a consequence of the phylotactic pattern. We thus developed specific multiple change-point models (piecewise 1st-order autoregressive models) for characterizing this two-scale growth pattern. The objective will be now to study the modulation of this pattern in response to different water stress and fertilization levels.

- *Quantifying the impact of water deficit on the production and flowering of apple trees* (Jean-Baptiste Durand, Benoit Pallas [AGAP, AFEF team], Evelyne Costes [AGAP, AFEF team])

  Water stress generates a number of physiological and morphological responses in plants that depend on the intensity and duration of stress as well as the plant species and development stage. In perennial plants, WS may affect plant development through cumulative effects that modify plant functions, architecture and production over time. Plant architecture depends on the fate of the terminal and axillary buds that can give rise, in the particular case of apple, to reproductive or vegetative growth units (GUs) of different lengths. In this study, the impact of long-term WS (7 years) on the fate of terminal and axillary buds was investigated in relation to flowering occurrence and production pattern (biennial vs regular) in the "Granny Smith" cultivar. It was observed that water stress decreased the total number of GUs per branch, regardless of their type. Conversely, water stress did not modify the timing of the two successive developmental phases characterized by the production of long and medium GUs and an alternation of floral GUs over time, respectively. The analysis of GU successions over time using a variable-order Markov chain that included both the effects of the previous flowering events and water treatment, revealed that water stress reduced the transition towards long and medium GUs and increased transition probabilities toward floral, short and dead GUs. Water stress also slightly increased the proportion of axillary floral GUs. The higher relative frequency of floral GUs compared with vegetative ones reduced the tendency to biennial bearing under water stress. The accelerated ontogenetic trend observed under water stress suggests lower vegetative growth that could, in turn, be beneficial to floral induction and fruit set [29], [37]. Ongoing work is conducted to determine the role of external (temperature and water stress) and internal (hormonal signalling, C source-sink relationships) factors in floral induction and consequently, in the regular or biennial behaviour in fruiting in apple trees. Particularly, its aim is to determine at which scale within the plant the production patterns are impacted by each factor. To analyse the carbon source-sink relationships from shoot to tree scales, this study is based on a set of genotypes displaying a large variability in flowering and production patterns.

6.2. Meristem functioning and development

In axis 2 work focuses on the creation of a *virtual meristem*, at cell resolution, able to integrate the recent results in developmental biology and to simulate the feedback loops between physiology and growth. The approach is subdivided into several sub-areas of research.

6.2.1. Data acquisition and design of meristem models

- *Improvement of the MARS-ALT pipeline robustness.*

  Meristem, laser microscopy, image reconstruction, cell segmentation, automatic lineaging
  Participants: Léo Guignard,, Christophe Godin, Christophe Pradal, Grégoire Malandain [Morpheme, Inria], Gaël Michelin [Morpheme, IPL Morphogenetics, Inria], Guillaume Baty, Sophie Ribes [IBC, UM], Jan Traas [RDP, ENS Lyon], Patrick Lemaire [CRBM, CNRS], Yassin Refahi [RDP, ENS-Lyon / Sainsbury Lab, Cambridge, UK].

  This research theme is supported by a PhD FRM grant, Jan Traas's ERC, Inria ADT programme and the Morphogenetics Inria Project Lab.

  The MARS-ALT (Multi-Angles Registration and Segmentation - Automatic Lineage Tracking) software pipeline [5] automatically performs a segmentation at cell resolution from 3D or 2D voxel images where the membranes/walls are marked (by a die for example) and makes it possible to follow the lineage of these cells through time.

  This year, the ALT tracking pipeline has been reformulated by using a generic cell modeling approach (enabling for example more than one cell division), and both stability and robustness were improved. The modeling approach is generic and can be used on other kind of data (nuclei, human cells, ...). Moreover, the architecture of the image processing components has been modified (plugin approach) and integrated with the TissueLab platform. The new segmentation-tracking library is called TimageTK will be released at the beginning of next year.

  We also finalize the development of a a new segmentation and tracking pipeline, ASTEC (Adaptive Segmentation and Tracking of Embryonic Cells). ASTEC is a one-pass algorithm (in contrast to MARS-ALT, that perform first the segmentation and then the tracking in two-passes) that is best suited for movies with numerous close time-points acquired at high spatio-temporal resolution. This pipeline takes advantage of information redundancy across the movies and biological knowledge on the segmented organism to constrain and improve the segmentation and the tracking. We used this one-pass algorithm to segment and track all cell shapes of a developing embryo of the marine invertebrate *Phallusia mammillata*. As a result we obtained the full track of the shapes of all the cells from the 64 cell stage up to the early tailbud stage (1030 cells undergoing 640 division events followed across 180 time-points through 6 hours of development imaged every 2 minutes, Figure 2).

  Based on this quantitative digital representation, we systematically identified cell fate specification events up to the late gastrula stage. Computational simulations revealed that remarkably simple rules integrating measured cell-cell contact areas with spatio-temporal expression data for extracellular signalling molecules are sufficient to explain most early cell inductions. This work suggests that in embryos developing with stereotyped cell shapes and positions (like *Phallusia mammillata* embryos), the genomic constraints for precise gene expression levels are relaxed, thereby allowing rapid genome evolution.

- *Creating mesh representation of cellular structures.*
  Participants: Guillaume Cerutti, Sophie Ribes, Christophe Godin, Géraldine Brunoud [RDP, ENS], Carlos Galvan-Ampudia [RDP, ENS], Teva Vernoux [RDP, ENS], Yassin Refahi [RDP, ENS, Sainsbury Lab].

  This research theme is supported the HFSP project Biosensors.

  To produce a more efficient data structure accounting for the geometry of cellular tissues, we studied the problem of reconstructing a mesh representation of cells in a complex, multi-layered tissue structure, based either on membrane/wall images segmented using MARS or on nuclei images of shoot apical meristems. The construction of such mesh structures for plant tissues is currently a missing step in the existing image analysis pipelines.

  We developed tools to reconstruct a 3D cell complex representing the tissue, based on the dual simplicial complex of cell adjacencies. This set of tetrahedra is optimized from a reasonable initial

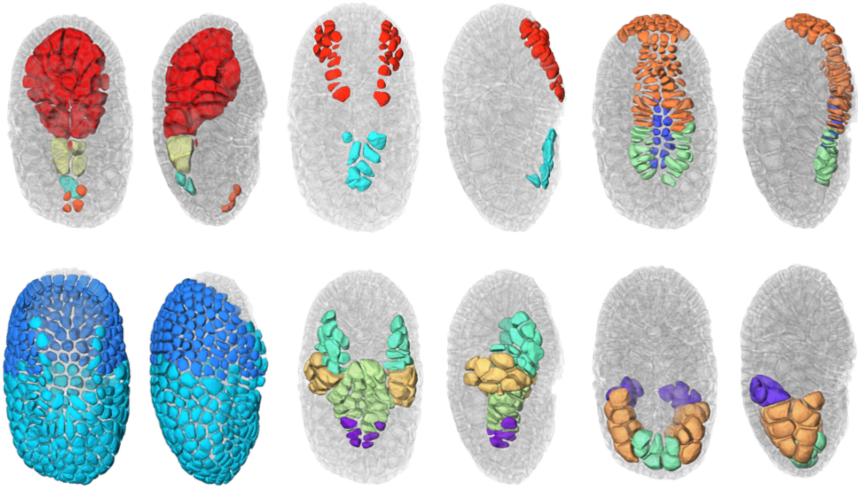

Figure 2. 3D projection of the segmented embryo at the early tailbud stage. The cells are colored by tissue type. The cells are slightly roded to allow their distinction. The other cells of the embryo are in transparent grey. The doral and lateral sides are shown.

guess to match the adjacencies in the tissue, which proved to produce a very faithful reconstruction [62]. We also developed a set of methods to triangulate such reconstructions, and enhance the quality of triangular mesh representations of plant tissue, simultaneously along several criteria [61].

These tools are integrated in the DRACO-STEM computational pipeline released as an independent package to enable biomechanical simulations on real-world data.

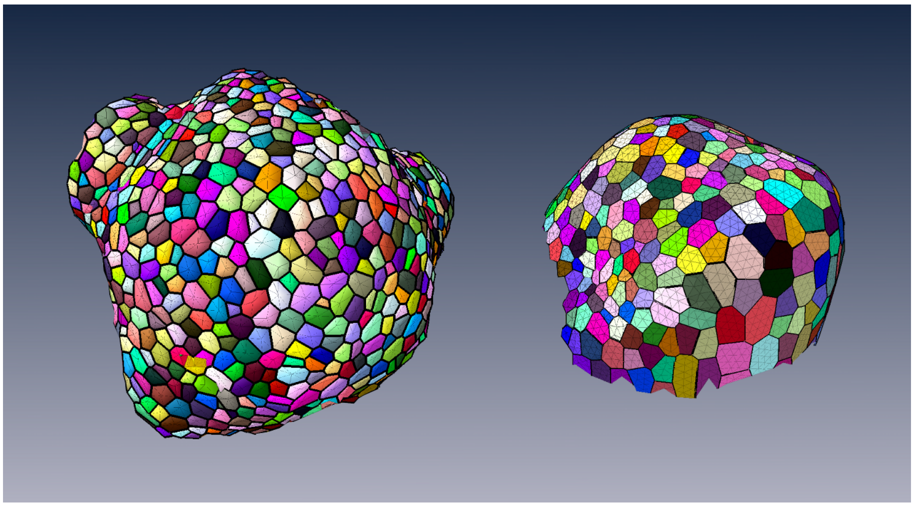

Figure 3. Triangular mesh representations of shoot apical meristem and flower meristem tissues obtained from MARS segmentations

- *Design of 3D digital atlases of tissue development.*
  Participants: Sophie Ribes, Yassin Refahi [RDP, ENS, Sainsbury Lab], Guillaume Cerutti, Christophe Godin, Christophe Pradal, Christophe Pradal, Frédéric Boudon, Gregoire Malandain [RDP, ENS], Gaël Michelin [RDP, ENS], Jan Traas [RDP, ENS], Teva Vernoux [RDP, ENS], Patrick Lemaire [CRBM, CNRS].

  This research theme is supported the Inria Project Lab Morphogenetics, the ADT Mars-Alt and the HFSP project Biosensors.

  To organize the various genetic, physiological, physical, temporal and positional informations, we build a spatialized and dynamic database [72]. This database makes it possible to store all the collected information on a virtual 3D structure representing a typical organ. Each piece of information has to be located spatially and temporally in the database. Tools to visually retrieve and manipulate the information, quantitatively through space and time are being developed. For this, the 3D structure of a typical organ has been created at the different stages of development of the flower bud. This virtual structure contains spatial and temporal information on mean cell numbers, cell size, cell lineages, possible cell polarization (transporters, microtubules), and gene expression patterns. Such 3D digital atlas is mainly descriptive. However, like for classical databases, specific tools make it possible to explore the digital atlas according to main index keys, in particular spatial and temporal keys. Both a dedicated language and a 3D user interface are being designed to investigate and query the 3D virtual atlas. Current developments of this tool consist in using directly the segmented images produced from laser microscopy to build the atlas. To better represent the development of a biological population, a method to compute an "average" structure is being investigated.

6.2.2. Shape analysis of meristems

Participants: Jonathan Legrand, Guillaume Cerutti, Pierre Fernique, Frédéric Boudon, Yann Guédon, Christophe Godin, Pradeep Das [RDP, ENS], Arezki Boudaoud [RDP, ENS].

The MARS-ALT pipeline provides rich spatio-temporal data sets for analyzing the development of meristems, since it allows to performs 3D cell-segmentation and to compute cell-lineage. This enable the extraction and study of spatio-temporal properties of a tissue at cellular scale. To facilitate the analysis and to structure the obtained data have implemented a dedicated temporal graph structure. In this graph, vertex are cells and edges are spatial or temporal relationships, thus proposing a natural representation of the growing tissue. Various variables can be attached either to the vertices (e.g. cell volume, inertia axes) or the edges (e.g. wall surface, distance between cell centroids). This graph may be augmented by new variables resulting from various spatial or temporal filtering (e.g. cell volumetric growth). Looking at homogeneous regions in the variable space, cellular patterns can be identified, by clustering methods for instance.

Considering the highly-structured nature of our data (time and space structuring) and the potential diversity and heterogeneity of possible cell descriptors, we developed two complementary approaches:

- A first one that favours the spatial structuring: In this approach, the cell neighbourhood and the cell descriptors are jointly taken into account in a clustering approach whose objective is to identify a small number of clusters corresponding to well-defined cell identities. Once the cells have been labelled using the clustering algorithm, cell generation distributions may be estimated on the basis of the labelled lineage trees.
- A second one that favours the temporal structuring: In this approach, the data of interest are lineage forest and the only spatial structuring taken into account corresponds to siblings with respect to a given parent cell. In a first step, cell identities are inferred on the basis of the cell descriptors taking into account lineage relationships using hidden Markov tree models and the spatial regions that emerge from the cell identity labelling are then characterized. This second approach is supported by the fact that cell topology is only affected by division which makes highly relevant the local spatial information taken into account in this approach.

6.2.3. Mechanical models of plant tissues

Participants: Jean-Philippe Bernard, Olivier Ali, Christophe Godin, Benjamin Gilles, Frédéric Boudon, Ibrahim Cheddadi, Jan Traas [ENS-Lyon], Olivier Hamant [ENS-Lyon], Arezki Boudaoud [ENS-Lyon].

This research theme is supported by the Inria Project Lab Morphogenetics and Jan Traas's ERC.

During the previous years, we set up a mechanical model of a growing *shoot apical meristem* (the specific tissue at the very tip of plants where stem cells are active and produce new organs such as branches, leafs and flowers). The aim of this project is to provide a computational framework for simulating growth of multicellular plant tissue. This framework integrates a theoretical description of the major biophysical processes at stake. A first version of the model, based on a static description of the tissues rheological properties, has been published last year [57].

This year, we used this model in close collaboration with biologists to investigate the coupling between growth and cell wall remodeling required in early stages of organogenesis. Our simulations pointed out that cell wall remodelling and growth initiation have to be co-regulated in order to initiate young organs formation. Biologists unraveled a biochemical signaling pathway that could explain this synergy. This joint work has been submitted to a high factor Biology journal.

In parallel, we also improved the underlying biophysical theory. One important aspect of the problem is the multiscale interconnections between mechanical forces generated at the scale of the whole tissue and the molecular response to these forces at the subcellular level. To tackle this issue, we established a parcimonous molecular description of the cell wall (one of the main organelle involded in growth) attesting for its biochemical behavior under mechanical loading. This description has been formalized as a unidimensional toy-model. With this toy-model we exposed how large-scale behavior of an expanding cell wall could be controlled by the biochemical behavior of a limited set of molecular actors. This work has been published [14].

Additionally, we started to work on the integration of a feedback loop between mechanical stresses and growth (PhD work of Hadrien Oliveri started in Oct. 2015). A close study of this feedback mechanism made us refine several aspects of our modelling approach. On the molecular scale, we introduced a tensor formalism to quantify cell polarity, based on the description of its cortical microtubule network. Microtubules being stress-sensitive, we described this feedback loop through the coupling between this polarity tensor and the mechanical stress field. In parallel, through a parcimonous model of microtubule-guided cell wall turnover, we derived an expression of the stiffness tensor as a function of cell polarity. This enabled us to relate subcellular stress-induced dynamics of microtubules to the evolution of large scale rheological properties of the tissue. We also started to work on the numerical implementation of this feedback mechanism. FEM-based simulations have been carried out on simple structures as proof of concept. By doing so we assessed the numerical valididy of our resolution scheme along with the relevance of our biophysical description.

6.2.4. Mechanical modelling of embryo morphogenesis.

Participants: Bruno Leggio, Emmanuel Faure, Patrick Lemaire [CRBM, CNRS], Christophe Godin.

A work on data analysis and modelling of morphogenesis and development in embryos of ascidians has been started this year. It comprises two main branches: starting from segmented data at cellular resolution, global and local symmetries of embryo development were analyzed. An analysis in terms of entropy of conserved embryonic properties was developed in order to characterise different stages of development as well as different tissues.

In parallel, a mechanical and topological analysis of cell-cell interactions was carried out. This lead us to develop a new and original physical model of cleavage-plane determination in different tissues, with the goal of understanding the role of purely mechanical interactions in shaping ascidian embryos.

6.2.5. Modelling the influence of dimerisation sequence dissimilarities on the auxin signalling network

Participants: Jonathan Legrand, Yann Guédon, Jean-Benoist Léger [INRA, MIA, Paris], Stéphane Robin [INRA, MIA, Paris], Teva Vernoux [ENS-Lyon].

Auxin is a major phytohormone involved in many developmental processes by controlling gene expression through a network of transcriptional regulators. In *Arabidopsis thaliana*, the auxin signalling network is made of 52 potentially interacting transcriptional regulators, activating or repressing gene expression. All the possible interactions were tested in two-way yeast-2-hybrid experiments. Our objective was to characterise this auxin signalling network and to quantify the influence of the dimerisation sequence dissimilarities on the interaction between transcriptional regulators [20]. We applied model-based graph clustering methods relying on connectivity profiles between transcriptional regulators. Incorporating dimerisation sequence dissimilarities as explanatory variables, we modelled their influence on the auxin network topology using mixture of linear models for random graphs. Our results provide evidence that the network can be simplified into four groups, three of them being closely related to biological groups. We found that these groups behave differently, depending on their dimerisation sequence dissimilarities, and that the two dimerisation sub-domains might play different roles. We propose here the first pipeline of statistical methods combining yeast-2-hybrid data and protein sequence dissimilarities for analysing protein-protein interactions. We unveil using this pipeline of analysis the transcriptional regulator interaction modes.

6.2.6. Model integration

Participants: Frédéric Boudon, Christophe Godin, Guillaume Cerutti, Jean-Louis Dinh, Eugenio Azpeitia, Jan Traas.

This research theme is supported by the Morphogenetics Inria Project Lab.

One key aspect of our approach is the development of a computer platform dedicated to programming virtual tissue development, TissueLab. This platform, based on *OpenAlea*, will be used to carry out integration of the different models developed in this research axis. In the past year, progress has been made in defining a generic tissue data structure that would be visualized, manipulated and updated through this platform. Currently, robust geometric operations such as division are implemented and tested. Moreover, a redesign of the structure based on more elaborated formalisms such as combinatorial maps is being investigated. A 2D version is being developed in the context of Jean-Louis's Dinh PhD thesis, and will be described in a forthcoming book chapter.

6.3. Multi-scale models and analysis: from cells to plant architecture (and back)

6.3.1. Modeling water transport in roots

Participants: Mikaël Lucas [IRD], Christophe Pradal, Christophe Godin, Yann Boursiac [BPMP], Christophe Maurel [BPMP].

This research theme is supported by the ANR project HydroRoot.

A model of Arabidopsis thaliana root hydraulics at the cellular level was developed in the OpenAlea modeling platform. The model relies on the integration throughout root architecture of elementary hydraulic components. Each component integrates local radial and axial water flows. Axial hydraulic conductivity is calculated according to Poiseuille's law, based on local size of xylem vessels. Radial hydraulic conductivity is determined in part by aquaporin activity and was set constant throughout root architecture in the first model versions. In its current state, the model is parameterized using architectural, tissular and physiological data that were experimentally determined in the Aquaporin group at UMR BPMP. The architectural reconstruction of the root system is based on a tridimensional multi-scale tree graph (MTG). The current model is capable of predicting the water flow that is transported by a root system in the standard experimental conditions used in the Aquaporin group. This model was used to perform sensitivity analyses and determine the respective contributions to root hydraulic dynamics of various biological parameters (axial and radial hydraulic conductivites, root architecture). One major finding is that the root hydraulic conductivity (Lpr) computed from the model is highly dependent on root architecture. This is due to the limiting role of axial (xylem) conductance, one feature that had been neglected in previous representations of root water transport. The radial hydraulic conductivity may primarily be limiting in conditions of Lpr inhibition, since its increase from values in control roots has marginal effects on Lpr. A new set of experimental data including root diameter repartitions in wild-type plants, and xylem vessel diameters in mutants with altered xylem morphology (irx3, esk1) will be used to challenge the model. Root cell hydraulic conductivities will also be measured in these and aquaporin mutant phenotypes. Our aim is to check whether, based on anatomical and morphological data, the model can properly predict the radial hydraulic conductivity of these genotypes.

As the simulations may be time consuming and results sometimes difficult to interpret on complex branching systems, we started to investigate new methods to compute efficiently hydraulic conductivities and corresponding flows on complex root systems using architecture compression technics developed in the 1st axis of the project. First results show that very efficient computations of complex hydraulic architectures can be derived from the use of these compression techniques on idealized root architectures. These encouraging results provide a new abstraction that will be used in combination with the detailed modeling approach described above to break down the complexity of the analysis these huge branching systems.

6.3.2. Mechanical modeling of fruit growth

Participants: Ibrahim Cheddadi [Inra, Avignon], Mik Cieslak [U. Calgary], Frédéric Boudon, Valentina Baldazzi [Inra, Avignon], Nadia Bertin [Inra, Avignon], Michel Genard [Inra, Avignon], Christophe Godin.

This research theme is supported by the Agropolis project MecaFruit3D.

Fruits and plants in general are large scale hydraulic systems in which growth is closely linked to water fluxes: thanks to osmotic pressure difference, the cells are able to absorb water from their environment and therefore increase their volume; as the cells are bounded by rigid walls, this results in both hydrostatic pressure (the so-called turgor pressure) in the cell and tension in the cell walls; above a threshold, synthesis of new cell wall material occurs and relaxes the tension. This process allows cells to grow, and along with cell division, is responsible for plant growth. In fruits, phloem and xylem vascular networks provide the water fluxes necessary for growth, while the osmotic pressure is mainly regulated by sugar intake from the phloem. The goal of this project is to combine a description of water and sugar fluxes at the fruit scale (see section 4) with a modelling of growth at cell level, as described above.

As a first step in this direction, we have developed a bidimensional multicellular model that couples, on the one hand, water fluxes between cells (symplastic pathway) and between cells and intercellular space (apoplastic pathway), and on the other hand, mechanical properties of the cell walls and mechanical equilibrium of this complex system. Existing multicellular models for plant growth overlook this coupling. From a mathematical point of view, it corresponds to a coupling between (1) the ordinary differential equations that describe fluxes and cell walls properties and (2) the highly non linear system of equations that describes the mechanical equilibrium of the cell walls.

We have developed a numerical method for this coupled system, that allows to simulate in a reasonable amount of time a hundred of connected cells. Numerical simulations exhibit a highly non linear behaviour with respect to the governing parameters. Thanks to the detailed analysis of a simplified setup, we have identified two clearly distinct growth regimes: one regime that allows large growth heterogeneities by amplifying the effect of differences between cells, and conversely another regime that smoothes differences out and yields a homogeneous growth. On the biological level, the first regime is well adapted to morphogenesis, whereas the second one is well adapted to homothetic growth after the differentiated tissues have been created. A publication of these completely new results is in preparation.

We have developped a collaboration with biophysicists in RDP laboratory in Lyon (Arezki Boudaoud and Yuchen Long) in order to compare the results of this model to experiments at the microscopic scale of the meristem. A publication is in preparation.

In the longer term, we plan extend this model to the larger scale of tissues and organs in order to model fruit growth.

6.3.3. Analyzing root growth and branching

Participants: Beatriz Moreno Ortega, Sixtine Passot, Yann Guédon, Laurent Laplaze [IRD, DIADE], Mikaël Lucas [IRD, DIADE], Bertrand Muller [INRA, LEPSE].

This research theme is supported by two PhD programmes.

New 2D and 3D root phenotyping plateforms are emerging with associated image analysis toolbox (e.g. SmartRoot, RhizoScan) and the identification of developmental patterns within these complex phenotyping data requires new approaches. Here, we aim at developing a pipeline of methods for analyzing root systems at three scales:

1. tissular scale to identify and characterize the division, elongation and mature zones along a root apex using piecewise heteroscedastic linear models for segmenting epidermal cell length profiles [35].
2. individual root scale to analyze the dynamics of lateral root elongation. We in particular applied semi-Markov switching linear models for classifying roots on the basis of the identification of phases within growth rate profiles,
3. root system scale to analyze the primary root branching structure.

This pipeline of analysis methods was applied to different species (maize, Pearl millet [23]) with contrasting biological objectives (study of genetic diversity for Pearl millet and of metabolic and hormonal controls of morphogenesis for maize).

6.3.4. Analyzing shoot and leaf elongation

Participants: Maryline Lièvre, Yann Guédon, Leo Guignard, Christine Granier [INRA, LEPSE].

This research theme is supported by the labex Agro project "Integrated model of plant organ growth".

This study is based on the observation that there is a lack of methods enabling the integrated analysis of the processes controling the vegetative development in *Arabidopsis thaliana*.

The change in leaf size and shape during ontogeny associated with heteroblastic development is a composite trait for which extensive spatio-temporal data can be acquired using phenotyping platforms. However, only part of the information contained in such data is exploited, and developmental phases are usually defined using a selected organ trait. We introduced new methods for identifying developmental phases in the *Arabidopsis* rosette using various traits and minimum a priori assumptions [21]. A first pipeline of analysis was developed combining image analysis and statistical models to integrate morphological, shape, dimensional and expansion dynamics traits for the successive leaves of the *Arabidopsis* rosette. Dedicated segmentation models called semi-Markov switching models were built for selected genotypes in order to identify rosette developmental phases. Four successive developmental phases referred to as seedling, juvenile, transition and adult were identified for the different genotypes. We show that the degree of covering of the leaf abaxial surface with trichomes is insufficient to define these developmental phases. Using our pipeline of analysis, we were able to identify the supplementary seedling phase and to uncover the structuring role of various leaf traits. This enabled us to compare on a more objective basis the vegetative development of *Arabidopsis* mutants.

We developed a second pipeline of analysis methods combining a semi-automatic method for segmenting leaf epidermis images based on the ilastik software, and the analysis of the obtained cell areas using a gamma or inverse Gaussian mixture models whose component parameters are tied by a scaling rule. These mixture models allowed us to estimate the distribution of the number of endocycles. We highlighted in this way that the mean number of endocycles changes drastically with leaf rank. We extended the inference approach to take into account not only complete cell areas but also censored cell areas (corresponding to cells that intercept the edges of the images). We also investigated possible temporal interpretations of endoreduplication using stochastic processes.

6.3.5. A stochastic model of phyllotaxis

Participants: Yassin Refahi, Christophe Godin, Etienne Farcot, Teva Vernoux [RDP, ENS].

This research theme has been supported by IBC and the Inria Project Lab Morphogenetics.

The geometric arrangement of lateral organs along plant stems, named phyllotaxis, shows a variety of striking patterns with remarkable regularities and symmetries. This has interested biologists, physicists, mathematicians and computer scientists for decades. These studies have lead to a commonly accepted standard interpretation of phyllotaxis that postulates that organs inhibit the formation of new organs in their vicinity. At a molecular scale, these inhibitory fields have been shown to result from the spatio-temporal distribution of the plant hormone auxin. This model theoretically explains a large part of the diversity of phyllotactic patterns observed in plants.

Recently, our colleagues from ENS-Lyon observed intriguing perturbation in *arabidopsis* mutants. These perturbations were also present, to a lesser extent in the wild type. In a series of works [79], [69], [1], we could show that these perturbations patterns in both wild-type and mutant plants could be explained by permutations in the order of insertion along the stem of 2 or 3 consecutive organs. After closer inspection, we realized that the mutated gene encodes a protein diffusing from the organs and creating a field around the organs that regulates the plastochron. We could demonstrate that in the mutant, the absence of this field leads to co-initiations and subsequently to the observed permutations.

To proceed further and find a mechanistic interpretation of this phenomenon, we developed a stochastic extension of the standard model of phyllotaxis. We first analyzed the properties of the inhibitory fields created by the existing primordia on the initiation of new primordia, and concluded that the angular positions of organs are very robust to perturbations while plastochrons may be dramatically affected. This suggested that there exists a strong decoupling between space and time in the patterning process. To account for this observation, we modeled the perception of the initiation signal by cells using stochastic processes coupled with the intensity of inhibitory fields and showed that the observed permutation patterns emerge spontaneously from this purely local processes. This model recapitulates accurately the classical phyllotactic patterns and, in addition, produces realistic pattern disorders at higher organization levels as a result of stochasticity in signal perception. We show that these subtle disorders surprisingly reveal key information on the functioning of the developmental system and can therefore be regarded as *biological watermarks* of the system. In genetically or environmentally modified plants, these biological watermarks inform us on the molecular mechanisms that have been affected in the experiment. Our theoretical analysis allows us to predict the specific pattern variations that would arise from perturbations of the signaling pathways involved in lateral inhibition signaling at the shoot apex [27].

6.3.6. The role of auxin and sugar in rose bud outgrowth control

Participants: Jessica Bertheloot [INRA, Angers], Frédéric Boudon, Christophe Godin.

Auxin in the stem is known to be a key regulator of apical dominance. Over the last decades, many studies have been undertaken to understand its action mode, which is indirect because auxin in the main stem does not enter into the bud. Recently, apical dominance over basal buds in pea has been related to low sugar availability caused by high sugar demand of growing apical organs. Auxin and sugar are two signals regulating the entrance of bud into sustained growth in opposite ways. In the last year, it has also been demonstrated that sugar effect on bud outgrowth was preceded by a modification of the hormonal levels involved in bud outgrowth, which suggests that auxin and sugar pathways do interact in a non- trivial way. However, auxin and sugar effects have been studied separately until now. In this work, we investigate what is the combined effect of sugar and auxin on bud outgrowth, and how they integrate to regulate bud entrance into sustained growth. For this, a series of experiments has been carried out on a single-node cuttings of Rosa hybrida grown in vitro in which different combinations of sugar and auxin levels have been tested. A model of the regulatory networks controlling stem-bud molecular interaction has been developed.

6.4. Generic methodological results

In the context of our research work on biological questions, we develop concepts and tools in mathematics, statistics and computer science. This paragraph is intended to put emphasis on the most important results obtained by the team during the current year in these disciplins, independently of their biological application.

6.4.1. OpenAlea scientific workflows and grid computing

Participants: Christophe Pradal, Sarah Cohen-Boulakia, Christian Fournier, Didier Parigot [Inria, Zenith], Patrick Valduriez [Inria, Zenith].

Plant phenotyping consists in the observation of physical and biochemical traits of plant genotypes in response to environmental conditions. Challenges, in particular in context of climate change and food security, are numerous. High-throughput platforms have been introduced to observe the dynamic growth of a large number of plants in different environmental conditions. Instead of considering a few genotypes at a time (as it is the case when phenomic traits are measured manually), such platforms make it possible to use completely new kinds of approaches. However, the data sets produced by such widely instrumented platforms are huge, constantly augmenting and produced by increasingly complex experiments, reaching a point where distributed computation is mandatory to extract knowledge from data. We design the infrastructure InfraPhenoGrid [26] to efficiently manage data sets produced by the PhenoArch plant phenomics platform in the context of the French Phenome Project. Our solution consists in deploying *OpenAlea* scientific workflows on a Grid using a middleware, SciFloware, to pilot workflow executions. Our approach is user-friendly in the sense that despite the intrinsic complexity of the infrastructure, running scientific workflows and understanding results obtained (using provenance information) is kept as simple as possible for end-users.

6.4.2. Reproductibility in Scientific workflows

Participants: Christophe Pradal, Sarah Cohen-Boulakia, Jerome Chopard.

With the development of new experimental technologies, biologists are faced with an avalanche of data to be computationally analyzed for scientific advancements and discoveries to emerge. Faced with the complexity of analysis pipelines, the large number of computational tools, and the enormous amount of data to manage, there is compelling evidence that many if not most scientific discoveries will not stand the test of time: increasing the reproducibility of computed results is of paramount importance. In the context of the project 8.2.5.4, we study how scientific workflows can help to improve the reproducibility of computational experiment in the domain of life science. We characterize and define the criteria that need to be catered for by *reproducibility-friendly* scientific workflow systems, and use such criteria to place several representative and widely used workflow systems and companion tools within such a framework.

6.4.3. Statistical modeling

Participants: Yann Guédon, Jean Peyhardi, Jean-Baptiste Durand Peyhardi, Catherine Trottier [IMAG, Montpellier].

We develop statistical models and methods for identifying and characterizing developmental patterns in plant phenotyping data. Phenotyping data are very diverse ranging from the tissular to the whole plant scale but are often highly structured in space, time and scale. Problems of interest deal with the definition of new family of statistical models specifically adapted to plant phenotyping data and the design of new methods of inference concerning both model structure, model parameters and latent structure. This is illustrated this year by [18] and [25].

6.4.4. Lossy compression of tree structures

Participants: Christophe Godin, Romain Azaïs, Jean-Baptiste Durand, Alain Jean-Marie.

In in [6], we defined the degree of self-nestedness of a tree as the edit-distance between the considered tree structure and its nearest embedded self-nested version. Indeed, finding the nearest self-nested tree of a structure without more assumptions is conjectured to be an NP-complete or NP-hard problem. We thus introduced a lossy compression method that consists in computing in polynomial time for trees with bounded outdegree the reduction of a self-nested tree that closely approximates the initial tree. This approximation relies on an indel edit distance that allows (recursive) insertion and deletion of leaf vertices only. We showed in a conference paper presented at DCC'2016 [55] with a simulated dataset that the error rate of this lossy compression method is always better than the loss based on the nearest embedded self-nestedness tree [6] while the compression rates are equivalent. This procedure is also a keystone in our new topological clustering algorithm for trees. In addition, we obtained new theoretical results on the combinatorics of self-nested structures and their ability to approximate complex trees in a costless manner [42].

6.4.5. Version climber

Participants: Christophe Padal, Dennis Shasha, Sarah Cohen-Boulakia, Patrick Valduriez.

Imagine you are a data scientist (as many of us are/have become). Systems you build typically require many data sources and many packages (machine learning/data mining, data management, and visualization) to run. Your working configuration will consist of a set of packages each at a particular version. You want to update some packages (software or data) to their most recent possible version, but you want your system to run after the upgrades, thus perhaps entailing changes to the versions of other packages.

One approach is to hope the latest versions of all packages work. If that fails, the fallback is manual trial and error, but that quickly ends in frustration.

We advocate a provenance-style approach in which tools like *ptrace* and *reprozip*, combine to enable us to identify version combinations of different packages. Then other tools like *pip* and *VirtualEnv* enable us to fetch particular versions of packages and try them in a sandbox-like environment.

Because the space of versions to explore grows exponentially with the number of packages, we have developed a memorizing algorithm that avoids exponential search while still finding an optimum version combination.

Experimental results have been tested (with full reproducibility) on well known packages used in data science to illustrate the effectiveness of our approach as well as life science computational experiment.

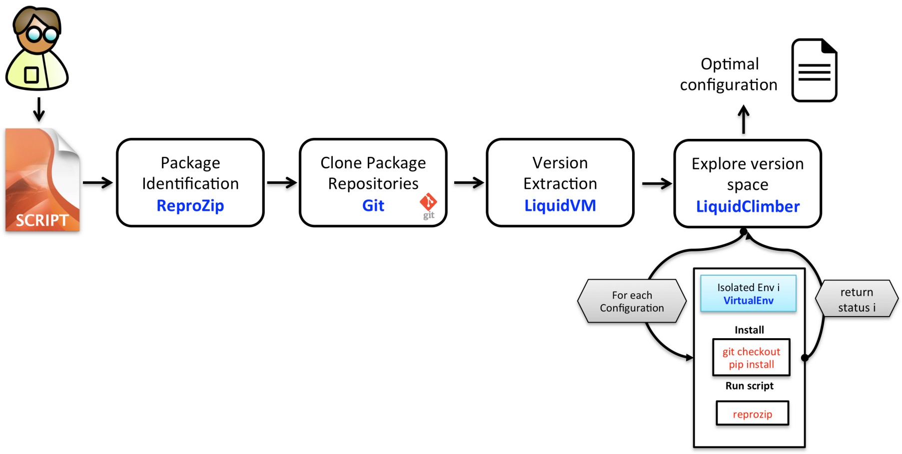

Figure 4. The steps of the operational subsystem: capture the execution of the initial configuration, liquify, fetch versions from git/svn etc., then deploy as directed by VersionClimber.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

Guillaume Garin has been funded by itk (http://www.itk.fr/en/). With itk, a generic model of plant pathosystem was developed in the OpenAlea platform and illustrated on Vine and Wheat.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. New pearl

Participants: Sixtine Passot, Yann Guédon, Soazig Guyomarc'h [Montpellier University, DIADE], Laurent Laplaze [IRD, DIADE].

Funding: Labex Agro (Contractor for Virtual Plants: CIRAD, from 2014 to 2017)

Pearl millet is an orphan crop regarding research effort despite its key role for food safety in Sub-Saharan Africa. The objective of the New Pearl project is to develop basic biological knowledges concerning Pearl millet development and genetic diversity. We are more specifically involved in the study of the root system development and the genetic diversity on the basis of root phenotypic traits.

8.1.2. MecaFruit3D

Participants: Mik Cieslak, Frédéric Boudon, Christophe Godin, Nadia Bertin [PSH, Avignon].

Funding: Labex Agro (Contractor for Virtual Plants: INRA, from 2013 to 2016)

The fruit cuticle plays a major role in fruit development and shelf-life. It is involved in water losses, cracking, and protection against stress, and thus it may have major economic impacts. Objectives of the project are to better understand the multiple roles of the fruit cuticle in the control of fleshy fruit growth and quality.

The multicellular model for fruit growth that we develop (see section 6.3.2) will be used to study qualitatively the impact of the cuticle mechanical properties.

Partners: PSH, INRA, Avignon; LCVN, IES, Université Sud de France, Montpellier.

8.1.3. *Integrated model of plant organ growth*

Participants: Yann Guédon, Christine Granier [INRA, LEPSE], Garance Koch [INRA, LEPSE], Nadia Bertin [INRA, PSH], Valentina Baldazzi [INRA, PSH].

Funding: Labex Agro (Contractor for Virtual Plants: CIRAD. From 2015 to 2018)

The objective of this project is to develop a generic model which will predict interactions among the main processes controlling the development of source and sink organs in tomato, i.e. cell division, cell expansion and endoreduplication in relation to carbon and water fluxes under fluctuating environment. To achieve this objective we will i) capitalize on expertise, multi-scale phenotyping tools and genetic resources already compiled on the fruit model tomato and the model plant *Arabidopsis thaliana*; ii) perform new experiments to collect phenotyping data currently missing in this field, especially concerning the early phase of fruit and leaf development in tomato and the interactions between genes and environment; iii) develop a process-based model of organ growth which will integrate knowledge collected at the different scales.

Partners: PSH, INRA, Avignon; LEPSE, INRA, Montpellier, Biologie du fruit et Pathologie INRA, Bordeaux;

8.2. National Initiatives

8.2.1. *HydroRoot*

Participants: Mikaël Lucas [IRD], Christophe Pradal, Christophe Godin, Yann Boursiac [BPMP], Christophe Maurel [BPMP].

Funding: ANR (Contractor for Virtual Plants: Cirad, From 2012 to 2016)
The HydroRoot project proposes a unique combination of approaches in the model plant Arabidopsis thaliana to enhance our fundamental knowledge of root water transport. Accurate biophysical measurements and mathematical modeling are used, in support of reverse and quantitative genetics approaches, to produce an integrated view of root hydraulics. The HydroRoot project will address as yet unknown facets of root water transport. It will lead to an integrated view of root hydraulics that considers both tissue hydraulics and root architecture and explains how these components are controlled at the molecular level by physiological and/or environmental cues. Because of its strong physiological and genetic background, this research may also directly impact on breeding programs, for production of crops with optimised water usage and stress responses.

8.2.2. *Phenome*

Participants: Christian Fournier, Christophe Pradal, Yann Guédon, Sarah Cohen-Boulakia, Simon Artzet, Jerome Chopard, Patrick Valduriez.

Funding: ANR-Investissement d'avenir (Contractor for Virtual Plants: INRA, From 2015 to 2018)
The goal of Phenome is to provide France with an up-to-date, versatile, high- throughput infrastructure and suite of methods allowing characterisation of panels of genotypes of different species under climate change scenarios. We are involved in the methodological part of the project, that aims at developping a software framework dedicated to the analysis of high throughput phenotyping data and models. It will based on the OpenAlea platform that provides methods and softwares for the modelling of plants, together with a user-friendly interface for the design and execution of scientific workflows. We also develop the InfraPhenoGrid infrastructure that allows high throughput computation and recording of provenance during the execution of Workflows.

8.2.3. *DigEM*

Participants: Christophe Godin, Grégoire Malandain, Patrick Lemaire.

Funding: ANR (Contractor for Virtual Plants: Inria, From 2015 to 2019)

In this project, we will use advanced ligh-sheet imaging of live embryos to quantitatively describe embryonic morphogenesis in ascidians, a class of animals that undergo very rapid genomic divergence, yet show an extraordinary stasis of embryonic morphologies, based on invariant early cell lineages shared by all studied species. The global aims of the proposal, which will bridge micro- and macroevolutionary scales of analysis, are: i) to provide a global systems-level description at cellular resolution of an animal embryonic program; ii) to use this description to characterize intra-specific and inter-specific patterns of morphogenetic variations; iii) to analyze possible molecular mechanisms explaining the unusual robustness of this program to environmental and genetic perturbations. To achieve these aims, we will combine advanced live light-sheet microscopy, computational biology, functional gene assays and evolutionary approaches.

8.2.4. Leaf Serration

Participants: Christophe Godin, Eugenio Azpeitia.

Funding: ANR (Contractor for Virtual Plants: Inria, From 2014 to 2019)
Leaf growth and development result from the coordination in time and space of cellular divisions and cellular expansion, and expansion of certain plant cells reaches up to one thousand times their size when living the meristem. Transcription factors belonging to the CUP-SHAPED COTYLEDON (CUC) genes and homeodomain genes of the KNOTTED-LIKE (KNOXI) family were shown to be essential for the control of leaf size and shape. In addition, the phytohormone auxin is a critical regulator of growth and development, involved in the regulation and coordination of cell division and cell expansion. The mechanisms of auxin signalling are based on a complex set of co-receptors exhibiting high to low affinity for auxin and an even more complex modular network of transcriptional repressors and activators tightly controlling the expression of a large set of genes.

The SERRATIONS project is based on recent data relative to key transcription factors regulating leaf morphogenesis and advanced knowledge on the generic signalling mechanisms of the phytohormone auxin that plays a critical role in the control and coordination of cellular responses sustaining leaf size and shape. The goal of the project is to identify auxin signalling modules involved in leaf morphogenesis and to integrate these data in mathematical modelling to provide new insights into complex regulatory networks acting on leaf morphogenesis and to further test model-derived hypotheses.

8.2.5. Other national grants

8.2.5.1. SCOOP

Participants: Pierre Fernique, Yann Guédon, Christophe Pradal, Christophe Godin, Frédéric Boudon, Jean-Baptiste Durand.

Funding: Inria ADT (Contractors for Virtual Plants: Inria from 2014 to 2016)
The goal of this project is to improve the software quality and the dissemination of Vplants components for plant phenotyping. Virtual Plants team has played a pioneering role in the development of methods for analyzing plant development that take account of the complexity of plant architecture. Numerous software components has been developed for more than 20 years and a profound re- engineering is now necessary to facilitate the collaborations with biologist and agronomists of CIRAD, INRA and IRD and to help the dissemination of ours methods in the scientific community.

8.2.5.2. Morphogenetics

Participants: Christophe Godin, Frédéric Boudon, Olivier Ali, Jean Phillipe Bernard, Hadrien Oliveri, Christophe Pradal, Guillaume Cerutti, Grégoire Malandain, François Faure, Jan Traas, François Parcy, Arezki Boudaoud, Teva Vernoux.

Funding: Inria Project Lab (From 2013 to 2017)

Morphogenetics is an Inria transversal project gathering 3 Inria teams and two Inra teams. It aimed at understanding how flower shape and architecture are controlled by genes during development. Using quantitative live-imaging analysis at cellular resolution we will determine how specific gene functions affect both growth patterns and the expression of other key regulators. The results generated from these experiments will be integrated in a specially designed database (3D Atlas) and used as direct input to new predictive computational models for morphogenesis and gene regulation. Model predictions will then be further tested through subsequent rounds of experimental perturbation and analysis. A particular emphasis will be put on the modeling of mechanics in tissues for which different approaches will be developed.

Partners: RDP ENS-Lyon; Imagine Inria Team (Grenoble); Morpheme Inria Team (Sophia-Antipolis), UMR PCV (Grenoble).

8.2.5.3. Rose

Participants: Christophe Godin, Frédéric Boudon.

Funding: INRA - PhD project (From 2016 to 2019)
In this project we want to quantify and understand how sugars interfere with hormonal signals (auxin, cytokinins) to regulate lateral bud outgrowth of aerial stems of roses. Experiments will be made on Rose stems to test different levels of sugar conditions and hormonal concentrations on bud outgrowth. An extension of the recently published hormonal model of apical dominance will be made to take into account the role of carbon as a signaling molecule.

Partners: UMR SAGAH, Angers

8.2.5.4. ReProVirtuFlow

Participants: Christophe Pradal, Sarah Cohen-Boulakia, Jerome Chopard.

In the life science domain, scientists are facing the deluge and the size of available data, the composition of a myriad of existing tools, and the complexity of computational experiment. In this context, reproducing an experiment is particularly difficult, as evidenced by numerous recent studies. The aim of this GDR CNRS project is to make a complete review of existing approaches in this field, considering in priority as elements of solution: (i) scientific worklfows, (ii) data provenance, and (iii) virtual machines. This project brings together experts in data bases, algorithms and virtual environments, working in the domain of life science.

Funding: GDR - CNRS

8.3. European Initiatives

8.3.1. Collaborations with Major European Organizations

8.3.1.1. Hook

Participants: Christophe Godin, Olivier Ali.

A new collaboration started with the University of Umeä (Sweden) on the modeling of the apical hook in the hypocotyl of *Arabidopsis thaliana*. The question we want to answer is what regulates the opening dynamics of the apical hook at the tip of the hypocotyl and how. For this, a multidisciplinary approach, combining 3D laser imaging, molecular biology, genetics and modeling will be developed by the partners.

Partners: University of Umeä, RDP ENS-Lyon.

8.4. International Initiatives

8.4.1. ANR-DFG

8.4.1.1. AlternApp

Participants: Yann Guédon, Maryam Aliee.

Funding: ANR-DFG (Contractor for Virtual Plants: INRA, From 2015 to 2019)

The aim of the AlternApp project is to investigate functional hypotheses on the genetic and environmental control of floral induction in apple tree progenies. Two segregating populations will be studied in two different environmental conditions for floral induction and bearing behavior, in order to identify genomic regions associated with regular phenotypes. The specific contribution of the team will be to develop statistical methods to quantify phenotype and genotype, as well as years and climatic effects on alternation. Transcriptome of varieties contrasted in their bearing behavior and artificially set into high or low cropping conditions will be explored by New Generation Sequencing Technology (NGS) to identify new candidate genes and allelic variations of interest. By this project, new results are expected on floral induction in apple tree in relation to their alternate bearing behavior and more applied results linked to the discovery of allelic variation in key genes that could be used in breeding programs.

Partners: AFEF INRA team (Montpellier), PIAF INRA team (Clermont-Ferrand), JKI (Dresden, Germany), UHOH (Hohenheim, Germany), Foundation E. Mach (San Michele all'Adige, Italy)

8.4.2. Inria International Partners

8.4.2.1. BioSensors

Participants: Guillaume Cerutti, Sophie Ribes, Frédéric Boudon, Christophe Godin, Teva Vernoux [ENS-Lyon], Géraldine Brunoud [ENS-Lyon], Carlos Galvan-Ampudia [ENS-Lyon].

Funding: Human Frontiers - HFSP (From 2014 to 2017)
We propose to elucidate the basis for positional information by hormones during plant morphogenesis. While it is known that cell fate decisions require simultaneous input from multiple hormones, to-date a precise understanding of how these signals are coordinated and act together to drive morphogenesis does not exist. Our limited mechanistic understanding is largely due to the difficulty to quantify the distribution of these small molecules in space and time. To explore this fundamental question, we will exploit recent advances in synthetic biology to engineer an RNA-based biosensor platform applicable to a broad range of small molecules and in particular to hormones. Using live-imaging technologies, we will use the sensors to obtain quantitative dynamic 3D maps of hormone distributions and relate these maps to the spatio-temporal distribution of cell identities, both during normal morphogenesis and upon perturbations of hormone levels. This analysis will be done on the shoot apical meristem, one of the bestcharacterized developmental systems in higher plants. In this context, mathematical approaches will be essential to analyze and establish a predictive model for how multiple hormones influence cell fate in a spatio-temporal manner.

8.4.2.2. Informal International Partners

An important collaboration with the CIRAD research unit HortSys at the Reunion island and in particular Frédéric Normand, Yann Guédon, Pierre Fernique and Christophe Pradal has been established for several years. The topic of the collaboration is the study of the phenology of mango tree. This is a tripartite collaboration that also involves Pierre-Eric Lauri of the System research unit (INRA, Montpellier).

We have for several years a strong partnership with Ted de Jong group at UC Davis concerning the influence of various agronomic practices (water stress, pruning) on fruit tree branching and production. This is a tripartite collaboration that also involves Evelyne Costes of the AGAP/AFEF team.

A collaboration in plant phenotyping with the CSIRO and the INRA/Lepse team has been established for several years. The topic of the collaboration is to develop a full pipeline using OpenAlea 2.0 on plant phenotyping platforms. This is a joint collaboration with UMR LEPSE in Montpellier (François Tardieu).

A collaboration started in the last two years with the group of Henrik Jönsson of the Sainsbury Lab, Cambridge, UK. The collaboration is related to several modeling projects in the context of shoot apical and flower meristems development, with a particular focus on the use of quantitative 3D reconstructions of meristem structures. Yassin Refahi from the Sainsbury Lab is regularly paying visits to Montpellier. The Virtual Plants team is also regularly invited to Cambridge.

8.5. International Research Visitors

8.5.1. Visits of International Scientists

Julia Pulwicki from the University of Calgary, Canada, spent 10 days at our lab in May to study the opportunity to define a post-doctoral project for her and to set up the basis of a joint scientific project. This project has lead us to submit to the Inria post-doctoral programme a project on that was accepted. Julia arrived for a 12 month post-doctoral project in November.

In this study, we want to formalize the analogy between the development of shapes in biology and the feedback between mass and space curvature in general relativity. Our aim is to propose a quantitative approach of such a vision by developing a mathematical and computational framework combining formalisms from non-euclidean geometry developed in general relativity and models of signal propagation and gene regulation in plant tissues.

8.5.1.1. Research Stays Abroad

In the context of the project on mango modelling and the PhD of S. Persello, F. Boudon is currently positioned in the Reunion island in the Hortsys unit for one year. He develops there a project on Mango modelling in collaboration with F. Normand.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. Member of the Organizing Committees

Yann Guédon was member of the organizing committee of the 48ème journées de statistique de la SFdS.

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

Christophe Godin and Yann Guédon were members of the program committee of the IEEE International Conference on Functional-Structural Plant Growth Modeling, Simulation, Visualization and Applications (FSPMA 2016).

9.1.2.2. Reviewer

Frédéric Boudon was referee for papers submitted to Eurographics and Siggraph Asia and was a rewiever and a member of the jury for best paper of the Journée Francaise d'Informatique Graphique (jFIG).

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

Christophe Godin is a member of the Editorial Board of Frontiers in Plant Sciences. He was also a guest editor for PLoS Computational Biology, *9.1.3.2. Reviewer - Reviewing Activities*

- Yann Guédon was referee for papers submitted to Functional Ecology and Journal of Internet Services and Applications.
- Christophe Godin reviewed papers for several journals in plant sciences and modelling.

9.1.4. Invited Talks

- C. Godin gave invited talks at RDP-ENS-Lyon research unit in Lyon (January), at the African Institute for Mathematical Sciences (AIMS), Dakar, Senegal, (February), at the University of Lund, Sweden (June), at the Journées scientifiques Inria, Rennes, (June), at the European Conference on Computational Biology and Bioinformatics, The Hague, The Netherlands (September), Inria/Inra joint meeting programme, Aix-en-Provence, (October), at CRBM research unit in Montpellier (October), BPMP research unit in Montpellier (December), and a plenary talk at the International workshop on multiscale modeling of complex systems in plant and developmental biology, U. Riverside, USA (December).
- F. Boudon gave invited talks at the workshop "Tree data and modelling", Tampere, Finland (June), in the AGAP scientific seminar and at the journée AGAP.
- Y Guédon gave an invited talk at the AGAP scientific seminar.
- C. Pradal gave invited talk at the "Agricultural Model Exchange Initiative" in Bologna, Italy (June), at the workshop "Multi-scale Plant Modeling" at the Pacific Northwest National Laboratory, USA (August), and at the workshop SUCCES, in Paris (November).

9.1.5. Leadership within the Scientific Community

- Christophe Godin is member of the Board of the Functional Structural Plant Models series of conferences.
- Christophe Godin is co-coordinator with Patrick Lemaire of the 4th Research Axis on Imaging in Biology and Modeling of the Institute for Computational Biology (IBC) of Montpellier.
- Christophe Godin spent 3 days at the African Institute for Mathematical Sciences (AIMS) to study potential future collaborations between Inria and AIMS in Dakar.

9.1.6. Scientific Expertise

- Christophe Godin is a member of the International Scientific Advisory Committee of the new Plant Phenotyping and Imaging Research Centre (P2IRC), Saskatchewan, Canada.
- Christophe Godin is a member of the Review and Mentoring committee of James Lock's group in Sainsbury Lab, Cambridge, UK.
- Christophe Godin is a member of the scientific councils of the Environnement-Agronomie department (up to August 2016) and of the Biologie et Amélioration des Plantes Department at Inra (Starting September 2016).

9.1.7. Research Administration

- Christophe Godin is a member of the project committee board at Sophia-antipolis Mediterrannée Reacher Center
- Christophe Godin is also part of the steering board of the Institute for Computational Biology (IBC) of Montpellier.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master Computer Science: Frédéric Boudon, Guillaume Cerutti, Christophe Godin, Christophe Pradal and David Vanderhaege and Loïc Barthe [IRIT, Toulouse], Computer graphics, 45h, M2, University Montpellier, France.

Master Computer Science: Christophe Godin, Frédéric Boudon, Computational and Discrete Geometry and graphics, 15h, M1, University Montpellier, France.

Master Functional Plant Biology: Christophe Godin, Introduction to plant modeling, 25h, M2, University Montpellier, France.

Master Life Sciences (IMaLiS): module co-organized by Patrick Lemaire and Christophe Godin, Animal and Vegetal Morphogenesis, 6 days, 4 h + TD supervision every afternoon, ENS Paris, Montpellier, France.

Master Functional Plant Biology: Christophe Godin, Phyllotaxis class in a module on Mathematical modeling in biology, 4h, M2, University Montpellier, France.

Master Functional Bioinformatics: Christophe Godin and Patrick Lemaire (Coordination O. Radulescu), Modeling in biology, 5h, M2, University Montpellier, France.

Master Biostatistics: Yann Guédon and Pierre Fernique, Stochastic processes, 32h, M2, University Montpellier, France.

Master Bioinformatique - Biomathématiques: Christophe Godin, iPlant, Modeling organ development, 4h, M2, Cheikh Anta Diop University (UCAD), Dakar, Senegal.

Master Plant Breeding: Christophe Pradal, Plant modelling, 4h, M2, Project CultiVar, University Montpellier, France.

Engineering Degree: SupAgro Montpellier. Christophe Pradal and Christian Fournier. "Introduction to modelling" (1st year, 12h).

9.2.2. Supervision

- PhD in progress : Anne Schneider, *"Modeling branching in Roses"*, Angers University, Jessica Bertheloo, C. Godin, F. Boudon.
- PhD in progress : Hadrien Oliveri, *"Mechanical modeling of organ growth"*, Montpellier University, C. Godin, J traas and O. Ali.
- PhD in progress : Jean-Louis Dinh, *"Coupling flux and growth models in plant development"*, Nottingham University, C. Hodgman, C. Godin.
- PhD in progress : Jean-Philippe Bernard, *"Meshless methods for organ development"*, Montpellier University, C. Godin, B. Gilles.
- PhD in progress : Severine Persello, *"Structural-Functional modeling of yield and fruit quality build-up of the mango, and integration of the effects of cultural practices"*, Montpellier University, F. Normand, I. Grechi, F. Boudon.
- PhD : Beatriz Moreno-Ortega, Developmental instability in lateral roots of maize: a multi-scale analysis, Montpellier SupAgro, December 12th 2016, Betrand Muller, Yann Guédon.
- PhD : Sixtine Passot, Exploring pearl millet root system and its outcome for drought tolerance, Montpellier University, September 30th 2016, Laurent Laplaze, Yann Guédon.
- PhD in progress : Marc Labadie, Study of the alternation between vegetative and floral development in strawberry: spatio-temporal architecture and analysis of key flowering genes, Bordeaux University, Béatrice Denoyes, Yann Guédon.

9.2.3. Juries

- Christophe Godin was the Opponent of Beruz Bozorg, June, University of Lund, Sweden, a member of the PhD Jury of Gaël Michelin, October University Cote d'Azur, Président of the PhD Jury of Sam Caullodin, December ENS-Lyon. He also participated in the PhD committees of Adrien Corot (AgroparisTech), Léo Serra (AgroParisTech) and Mathilde Dumond (ENS-Lyon).
- Yann Guédon was referee of Philippe Cuvillier PhD: On temporal coherency of probabilistic models for audio-to-score alignment, Pierre and Marie Curie University, Paris, December 15th 2016, Arshia Cont (supervisor).

9.3. Popularization

- Olivier Ali is a member of the writing committee of the newsletter of the Sophia-Antipolis Méditerrannée Inria Centre.
- High School: Christophe Godin gives regular 2h classes at Lycée Pompidou (Montpellier) and in other Lycées.
- Christophe Godin gave two invited seminars in the context of the Maths Week (March), at the Lycée International de Valbonne, France.
- Christophe Godin gave an interview to the European Journal Labtimes about their paper published in eLife: Alejandrolvido (2016). Green noise. Labtimes 5, 34–35.

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Major publications by the team in recent years

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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

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Computer Science and Digital Science:

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3.1.1. - Modeling, representation
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3.1.5. - Control access, privacy
3.1.7. - Open data
3.2. - Knowledge
3.2.1. - Knowledge bases
3.2.2. - Knowledge extraction, cleaning
3.2.3. - Inference
3.2.4. - Semantic Web
3.2.5. - Ontologies
3.3.2. - Data mining
3.5. - Social networks
3.5.2. - Recommendation systems
4.7. - Access control
5.1. - Human-Computer Interaction
5.1.1. - Engineering of interactive systems
5.1.2. - Evaluation of interactive systems
5.2. - Data visualization
5.8. - Natural language processing
5.10.5. - Robot interaction (with the environment, humans, other robots)
8. - Artificial intelligence
8.1. - Knowledge
8.4. - Natural language processing
8.7. - AI algorithmics

Other Research Topics and Application Domains:

1.3.2. - Cognitive science
5.6. - Robotic systems
5.8. - Learning and training
6.3.1. - Web
6.3.4. - Social Networks
6.5. - Information systems
8.2. - Connected city
8.5. - Smart society
8.5.1. - Participative democracy

9. - Society and Knowledge
9.1. - Education
9.1.1. - E-learning, MOOC
9.1.2. - Serious games
9.4.1. - Computer science
9.4.5. - Data science
9.5. - Humanities
9.5.1. - Psychology
9.5.2. - Juridical science
9.5.5. - Sociology
9.5.8. - Linguistics
9.5.10. - Digital humanities
9.7. - Knowledge dissemination
9.7.1. - Open access
9.7.2. - Open data
9.8. - Privacy
9.10. - Ethics

This report is dedicated to the memory of Papa Fary Diallo †, PhD student in the Wimmics team and University Gaston Berger, Saint-Louis, Sénégal.

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2. Overall Objectives

2.1. Presentation

2.1.1. Context and Objectives

The Web became a virtual place where persons and software interact in mixed communities. These large scale mixed interactions create many problems that must be addressed with multidisciplinary approaches [75]. 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. [74]

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 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.

2.1.2. Research Topics

The research objectivs of Wimmics can be grouped according to four topics 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 ?*”. Wimmics focuses on specific sub-questions: ”How can we capture and model the users' characteristics?” ”How can we represent and reasons 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 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 - 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

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 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. 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 also 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 to 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. and this will raise the specific problem of interaction design for security and privacy. In addition, from the point of view of the content, this requires to foster the publication and coexistence of heterogeneous data with different points of views and conceptualizations of the world. We intend to pursue the extension of formalisms to allow different representations of the world to co-exist and be linked and we will pay special attention to the cultural domain and the digital humanities. Examples of collaboration and applied projects: Zoomathia, Seempad, SMILK,

4.5. Artificial Web intelligence

We intend to build on our experience in artificial intelligence (knowledge representation, reasoning) and distributed artificial intelligence (multi-agent systems - MAS) to enrich formalisms and propose alternative types of reasoning (graph-based operations, reasoning with uncertainty, inductive reasoning, non-monotonic, etc.) and alternative architectures for linked data with adequate changes and extensions required by the open nature of the Web. There is a clear renewed interest in AI for the Web in general and for Web intelligence in particular. Moreover distributed AI and MAS provide both new architectures and new simulation platforms for the Web. At the macro level, the evolution accelerated with HTML5 toward Web pages as full applications and direct Page2Page communication between browser clearly is a new area for MAS and P2P architectures. Interesting scenarios include the support to 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 we built targeting more support for non expert to access and analyze data on a topic or 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 his current mental and physical state, the emotion he just expressed or his 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 one 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. 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

5.1.1. Awards & Nominees

The Wimmics team received collectively the Université Côte d'Azur Award in recognition of the ISWC best demo.

Best demo award at ISWC for *Semantic Web Technologies for improving remote visits of museums, using a mobile robot* [32].

Best poster nominee at ISWC for *Materializing the Editing History of Wikipedia as Linked Data in DBpedia* [60].

Michel Buffa was finalist for the first-ever edX Prize for Exceptional Contributions in Online Teaching and Learning (11 teachers have been selected among 2500 others and 1200 online courses) for his MOOCs on HTML5.

Valerio Basile was awarded the first prize, granted by IBM, at the *Evaluation of NLP and Speech Tools for Italian (Evalita)* workshop.

6. New Software and Platforms

6.1. Corese

COnceptual REsource Search Engine

KEYWORDS: Semantic Web - Web of Data - Search Engine - RDF - SPARQL
FUNCTIONAL DESCRIPTION

Corese is a Semantic Web Factory that implements W3C RDF, RDFS, SPARQL 1.1 Query and Update. Furthermore, Corese query language integrates original features such as approximate search. It provides a SPARQL Template Transformation Language for RDF, a SPARQL based Inference Rule Language for RDF and a Linked Data Script Language. Corese also provides distributed federated query processing, a Semantic Web server and a SPARQL endpoint. Corese development is supported by an Inria grant (ADT).

- Participants: Olivier Corby, Erwan Demairy, Catherine Faron-Zucker, Fabien Gandon. Alumni: Virginie Bottollier, Olivier Savoie, and Fuqi Song.
- Partners: I3S - Mnemotix
- Contact: Olivier Corby
- URL: http://wimmics.inria.fr/corese, http://corese.inria.fr

6.2. DBpedia.fr

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 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. In addition, Wimmics extended the open source DBpedia platform with new capabilities and in particular DBpedia Historic to extract the entire edition history of a chapter as linked data.

- Participants: Fabien Gandon and Raphaël Boyer
- Contact: Fabien Gandon
- URL: http://dbpedia.fr

6.3. Discovery Hub

Discovery Hub Exploratory Search Engine
KEYWORD: Search Engine
FUNCTIONAL DESCRIPTION

Discovery Hub is an exploratory search engine built on top of linked data sources and, in particular, DBpedia. The exploratory search is a new way to search the web to find new topics the users were not aware of but which may be interesting for them. It allows users performing queries in an innovative way and helps them navigate rich results. As a hub, it proposes redirections to others platforms to let users benefit from their discoveries. It relies on an extension of spreading activation algorithms over linked data to recommend and explain results.

- Participants: Nicolas Marie, Fabien Gandon, Emilie Palagi and Alain Giboin
- Partner: Alcatel-Lucent
- Contact: Fabien Gandon
- URL: http://discoveryhub.co/

6.4. Licentia

License you Data
KEYWORDS: Licenses - Normative Reasoning - Semantic Web - RDF
FUNCTIONAL DESCRIPTION

Licentia is a web service application with the aim to support users in licensing data. Our goal is to provide a full suite of services to help in the process of choosing the most suitable license depending on the data to be licensed. The core technology used in our services is powered by the SPINdle Reasoner and the use of Defeasible Deontic Logic to reason over the licenses and conditions. The dataset of RDF licenses we use in Licentia is the RDF licenses dataset where the Creative Commons Vocabulary and Open Digital Rights Language (ODRL) Ontology are used to express the licenses.

- Participants: Serena Villata, Fabien Gandon. Alumni: Cristian Cardellino
- Partners: I3S
- Contact: Serena Villata
- URL: http://licentia.inria.fr/

6.5. Qakis

Question-Answening wiki framework based system
FUNCTIONAL DESCRIPTION

The QAKiS system (figure 2) implements question answering over DBpedia. QAKiS allows end users to submit a query to an RDF triple store in English and 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: Elena Cabrio, Julien Cojan, Amine Hallili, Alessio Palmero Aprosio, Fabien Gandon and Serena Villata.
- Contact: Elena Cabrio
- URL: http://www.qakis.org/

6.6. KNEWS

Versatile Text-to-Knowledge Pipeline
KEYWORD: NLP
FUNCTIONAL DESCRIPTION

KNEWS is a versatile text-to-knowledge pipeline for machine reading, configurable to use different external modules for word sense disambiguation and entity linking. KNEWS works by running these components separately on a text, then it aligns the output of a semantic parser (Boxer) to the output of the other two modules, to produce complete semantic structures linked to DBpedia and Wordnet and represented as RDF graphs. KNEWS provides different kind of outputs: frame instances (based on the FrameBase scheme), word-aligned frames, and first-order logic formulas.

- Participants: Valerio Basile, Elena Cabrio and Fabien Gandon.
- Contact: Valerio Basile & Elena Cabrio
- URL: https://github.com/valeriobasile/learningbyreading

7. New Results

7.1. Users Modeling and Designing Interaction

7.1.1. User-centered Heuristics for the Control of Personal Data

Participants: Patrice Pena, Alain Giboin.

This work is done in collaboration with Karima Boudaoud, SPARKS, I3S. In the context of the PadDOC FUI project, we elaborated 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 is 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 [71].

7.1.2. User Modeling of Collaborative Ontology Editors/Environments

Participant: Alain Giboin.

To demonstrate the importance of an in-depth modeling of users in the design of collaborative ontologies editors or environments (COEs), we began a study on the evolution of the user modeling techniques and the resulting user models from the origins of the design of COEs.

7.1.3. Recommendation of Pedagogical Resources Adapted to User Profile and Context

Participants: Oscar Rodríguez Rocha, Catherine Faron-Zucker.

In the continuation of the Semantic Educloud project, we constructed an ontology and associated thesaurus to represent an official standard of knowledge and skills. We proposed a process to extract knowledge and skills from the official texts describing the French educational program and to automatically populate our ontology with the knowledge extracted from the official texts which we further enrich by aligning it with the Web of Data. This work has been presented at the EKM 2016 workshop [49].

Together with researchers from DUIN (Italy), we worked on the design of a recommendation algorithm based on Linked Data, that could be used to recommend pedagogical resources. The algorithm exploits existing relationships between resources by dynamically analyzing both the categories to which they belong to and their explicit references to other resources. The algorithm has been applied in a mobile application to recommend movies by relying on DBpedia. This work has been presented at the RecSys workshop [50]

7.1.4. Requirements Analysis

Participant: Isabelle Mirbel.

Requirements representation in agile methods is often done on the basis of User Stories (US) which are short sentences relating a WHO, WHAT and (possibly) WHY dimension. They are by nature very operational and simple to understand thus very efficient. Previous research allowed to build a unified model for US templates associating semantics to a set of keywords based on templates collected over the Web and scientific literature. Since the semantics associated to these keywords is mostly issued of the i* framework [0], we overviewed in this work how to build a custom rationale diagram on the basis of a US set tagged using that unified template. The rationale diagram is strictly speaking not an i* strategic rationale diagram but uses parts of its constructs and visual notation to build various trees of relating US elements in a single project. Indeed, the benefits of editing such a rationale diagram is to identify depending US, identifying EPIC ones (EPIC: large User Story) and group them around common Themes. The results of this research have been published in [51].

[0] http://www.cs.toronto.edu/km/istar/

7.1.5. Design of a User-Centered Evaluation Method of Exploratory Search Systems Based on a Model of the Exploratory Search Process

Participants: Emilie Palagi, Alain Giboin, Fabien Gandon.

This work was undertaken in the context of the PhD of Emilie Palagi, in cooperation with with Raphaël Troncy (Eurecom). Our method takes into account users's Exploratory Search (ES) behavior and will be based on a cognitive model of an ES task. We will specially work on Discovery Hub and 3cixty 4 (EURECOM project) ESSs.

During the first year of the PhD, we were looking for a model of ES process on which the method will be based. To achieve this objective, several models of information seeking process were analyzed and we compared them with our own grid of the typical characteristics of exploratory search activities. The chosen model will fill the grid as much as possible with suitable adaptations if needed. It is an on-going work and we are actually designing an ES search model. We also performed a comparative analysis of 15 ESSs in order to identify the relevant functionalities supporting an exploratory search. We want to associate these functionalities to our grid of exploratory search characteristics. We will select some of these systems to test and validate the future method.

Contrary to lookup search engines that help users to retrieve specific items (e.g., names, numbers, short statements, or specific documents), Exploratory Search Systems (ESSs) are search engines that help users to explore a topic of interest. ES tasks are open-ended, multi-faceted, and iterative like learning or topic investigation [77], [80]. Currently, the evaluation methods of ESSs are not entirely adapted to the special features of ES tasks, and do not effectively assess that ESSs support users in performing those tasks. Our research goal is to elaborate methods that effectively lead to this assessment.

7.2. Communities and Social Interactions Analysis

7.2.1. Ontologies-Based Platform for Sociocultural Knowledge Management

Participants: Papa Fary Diallo, Olivier Corby, Isabelle Mirbel.

This work is done in the PhD Thesis of P. F. Diallo †. We designed a sociocultural platform aiming at persevering and capitalizing sociocultural events in Senegal. This platform relies on Semantic Web technologies. We provided two ontologies to support our platform: an upper level sociocultural ontology (USCO) and a human time ontology (HuTO). To build our upper level ontology we proposed a methodology based on the theory of Russian psychologist Lev Vygotsky called "Vygotskian Framework". We designed the Human Time Ontology [0] (HuTO) of which major contributions are (i) the modeling of non convex intervals (repetitive interval) like every Monday, (ii) the representation of deictic temporal expressions (e.g. *today*) which form specific relations with time speech and (iii) qualitative temporal notions which are temporal notions relative to a culture or a geographical position. The platform allows Senegalese communities to share and co-construct their sociocultural knowledge. This work was published in the Journal of Data Semantics [14].

7.2.2. SMILK - Social Media Intelligence and Linked Knowledge

Participants: Farhad Nooralahzadeh, Elena Cabrio, Molka Dhouib, Fabien Gandon.

Automated Natural Language Processing (NLP), Web Open Data (Linked Open Data) and social networks are the three topics of the SMILK ANR LabCom including their coupling studied in three ways: texts and Linked Data, Linked Data and social resources, texts and social resources. It is a Joint laboratory between the Inria research institute and the VISEO company to develop research and technologies, retrieve, analyze, and reason about linking data from textual Web resources and other to use open Web data taking into account the social structures and interactions in order to improve the analysis and understanding of textual resources.

[0] http://ns.inria.fr/huto

In this context, we have developed an entity discovery tool by adopting the semantic spreading activation, and we integrated it in the SMILK framework. The goal of such a tool is to semantically enrich the data by linking the mentions of named entities in the text to the corresponding known entities in knowledge bases. In our approach multiple aspects are considered: the prior knowledge of an entity in Wikipedia (i.e. the keyphraseness and commonness features that can be precomputed by crawling the Wikipedia dump), a set of features extracted from the input text and from the knowledge base, along with the correlation/relevancy among the resources in Linked Data. More precisely, this work explores the *collective ranking approach* formalized as a weighted graph model, in which the mentions in the input text and the candidate entities from knowledge bases are linked using the local compatibility and the global relatedness. Experiments on the datasets of the Open Knowledge Extraction (OKE) [0] challenge with different configurations of our approach in each phase of the linking pipeline reveal its optimum mode. We investigate the notion of semantic relatedness between two entities represented as sets of neighbors in Linked Open Data that relies on an associative retrieval algorithm, with consideration of common neighborhood. This measure improves the performance of prior link-based models and outperforms the explicit inter-link relevancy measure among entities (mostly Wikipedia-centric). Thus, our approach is resilient to non-existent or sparse links among related entities.

In parallel, an approach to automatically annotate texts in the cosmetics field with the vocabularies ProVoc and GoodRelations in RDF has been proposed, resulting in a knowledge base in the format of the Semantic Web that can be used in various applications. Given the entity linking tool described before (that allows to link named entities in a text with entities in the LOD), we focused on the extraction of relations between these entities (in French texts). In the extraction process, particular attention is given to the contribution of syntactic rules, in order to improve accuracy with respect to existing systems.

7.2.3. Community Detection and Interest Labeling

Participants: Zide Meng, Fabien Gandon, Catherine Faron-Zucker.

7.2.3.1. Temporal Analysis of User and Topic

Based on previous work on overlapping community detection in Question-Answer sites, we proposed an approach to jointly model topic, expertise, activity and trends, we were able to retrieve many meaningful latent information from the user generated contents. We proposed a method to track the dynamics of topics and users. It can also track the dynamics with a specific granularity of time level such as, yearly, monthly, daily and hourly. Besides, the model can overcome a comparison problem of LDA (Latent Dirichlet Allocation) based model by modeling the reverse distribution. This work has been published in IEEE/WIC/ACM Web Intelligence [62].

7.2.3.2. Topic labeling

The output of topic model is normally a bag of words. Each topic consists of closely related words. An interesting question is to assign one or more topic label to this set in order to indicate the general meaning of a bag of words. By integrating the original dataset with linked open data sources, we are now planning to propose a generic method to automatically label the detected topics.

7.2.4. Default Knowledge based on the Analysis of Natural Language

Participants: Elena Cabrio, Valerio Basile, Fabien Gandon.

In the context of the ALOOF project, we developed new methods to build repositories of default knowledge based on the analysis of natural language. The first efforts are aimed at extracting information about common objects, in particular their location and their typical usage [24].

One of the methods to extract general knowledge from text is implemented in the KNEWS pipeline, of which a demo was presented at ECAI [25]. At the same conference, we also presented the results of another system that helps robots identifying unknown objects based on their proximity with known objects observed at the scene [52]. KNEWS was also used to automatically build a large collection of text aligned with RDF semantics representation of its meaning. The first envisioned application of such resource is to provide a basis for robust natural language generation from RDF triples using statistical methods [22].

[0] https://github.com/anuzzolese/oke-challenge

We also explored the application of distributional semantics to the general knowledge extraction problem. We computed vector-based models of objects and used supervised statistical models to predict their typical locations (e.g. knife-kitchen, printer-office) [27]. Once our models were successfully tested experimentally against a gold standard of human judgments, we were able to build a large knowledge base of object locations freely available [0].

7.2.5. *Semantic Modeling of Social, Spatiotemporal and Dedicated Networks*

Participants: Amel Ben Othmane, Nhan Le Thanh, Andrea Tettamanzi, Serena Villata.

During the academic year 2015/2016, we have been working partially on validating the model we proposed in [72]. A long version of this former paper, entitled *An Agent-based Architecture for Personalized Recommendations* will be published in January 2017 in the LNCS series published by Springer. For this purpose, we proposed in [29] a multi-agent based simulation on NetLogo environment in order to illustrate the usefulness and feasibility of the proposed framework in a realistic scenario. For that purpose, we evaluated the performance of the agent behaviors adopting two different strategies:

- Selfish agents: agents do not communicate with each others;
- Social agents: agents communicate and try to influence each other's to adopt some beliefs or desires.

Results show that agents achieve a better performance collectively when they are in "communities", i.e., agents with shared interests (thus similar to each other), than when they are acting as solitary agents. We believe that the issues of trust and recommendation are tightly related. For that reason, we analyzed the behavior of social agents with and without a trust model. Results show that exchanging beliefs or desires with trustworthy agents can improve the whole performance of agents.

We have been also working on extending the proposed model with spatial and temporal reasoning. A spatio-temporal belief or desire is considered as an event that is defined as a spatial relation holding in a temporal interval. For reasoning with such information, we propose to combine the Region Connection Calculus (RCC-8) formalism with Allen's intervals algebra. Spatio-temporal data is often affected by imprecision and vagueness. To tackle this problem we believe that a fuzzy set, because its ability to represent a degree of membership, is more suitable for modeling spatio-temporal data. A fuzzy version of RCC-8 and Allen's interval is proposed. Then we combined both approaches in order to represent and reason about imprecise spatio-temporal beliefs and desires. We worked also in validating this approach in a real-world scenario.

7.3. Vocabularies, Semantic Web and Linked Data based Knowledge Representation

7.3.1. *Semantic Web Technologies and Natural Language*

Participants: Serena Villata, Elena Cabrio.

Together with Sara Tonelli (FBK, Italy) and Mauro Dragoni (FBK, Italy), we have presented the integration, enrichment and interlinking activities of metadata from a small collection of verbo-visual artworks in the context of the Verbo-Visual-Virtual project. We investigate how to exploit Semantic Web technologies and languages combined with natural language processing methods to transform and boost the access to documents providing cultural information, i.e., artist descriptions, collection notices, information about technique. We also discuss the open challenges raised by working with a small collection including little-known artists and information gaps, for which additional data can be hardly retrieved from the Web. The results of this research have been published at the ESWC conference [37].

[0] https://project.inria.fr/aloof/data/

Together with Vijay Ingalalli (LIRMM), Dino Ienco (IRSTEA), Pascal Poncelet (LIRMM), we have introduced AMbER (Attributed Multigraph Based Engine for RDF querying), a novel RDF query engine specifically designed to optimize the computation of complex queries. AMbER leverages subgraph matching techniques and extends them to tackle the SPARQL query problem. AMbER exploits structural properties of the query multigraph as well as the proposed indexes, in order to tackle the problem of subgraph homomorphism. The performance of AMbER, in comparison with state-of-the-art systems, has been extensively evaluated over several RDF benchmarks. The results of this research have been published at the EDBT conference [39].

7.3.2. Semantic Web Languages and Techniques for Digital Humanities

Participants: Catherine Faron-Zucker, Franck Michel, Konstantina Poulida, Safaa Rziou, Andrea Tettamanzi.

In the framework of the Zoomathia project, we conducted three complementary works, with the ultimate goal of exploiting semantic metadata to help historians in their studies of knowledge transmission through texts. First, together with Olivier Gargominy and other MNHN researchers, and Johan Montagnat (I3S, UNS), we continued a work initiated last year on the construction of a SKOS (Simple Knowledge Organization System) thesaurus based on the TAXREF taxonomical reference, designed to support studies in Conservation Biology [73]. We deployed the Corese Semantic Web factory as a backend to publish this SKOS thesaurus on the Web of Linked Open Data. This work was presented at the SemWeb.Pro 2016 conference.

Second, together with Irene Pajon (UNS) and Arnaud Zucker (UNS), we continued a work initiated last year on the construction of a SKOS thesaurus capturing zoological specialities (ethology, anatomy, physiology, psychology, zootechnique, etc.). This thesaurus was constructed while manually annotating books VIII-XI of Pliny the Elder's Natural History, chosen as a reference dataset to elicit the concepts to be integrated in the Zoomathia thesaurus. This work has been published in the ALMA journal [79] (Archivum Latinitatis Medii Aevi).

Third, together with Arnaud Zucker (UNS), we developed an approach of knowledge extraction from ancient texts consisting in semantically categorizating text segments based on machine learning methods applied to a representation of segments built by processing their translations in modern languages with Natural Language Processing (NLP) methods and by exploiting the above described thesaurus of zoology-related concepts. We applied it to categorize Pliny the Elder's Natural History segments. The above describe manually annotated dataset served us as goldstandard evaluate our approach. This work has been presented at the ESWC 2016 workshop on Semantic Web for Scientific Heritage [38].

Relatedly, together with Emmanuelle Kuhry (UNS) and Arnaud Zucker (UNS), we developed an approach which originates in seeing copying as a special kind of "virtuous" plagiarism and consists in paradoxically using plagiarism detection tools in order to measure *distances* between texts, rather than similarities. We first applied it to the *Compendium Philosophie*'s tradition, whose manuscript tradition is well studied and mostly understood and can therefore be considered as a gold standard. Then we applied the validated and calibrated method to investigate the *Physiologus latinus*'s tradition, which is a complex manuscript tradition for which our knowledge is much less sure, with the aim of supporting the elaboration of stemmatological hypotheses.

7.3.3. Argumentation Theory and Multiagent Systems

Participants: Andrea Tettamanzi, Serena Villata.

Together with Célia da Costa Pereira (I3S, UNS) we have proposed a formal framework to support belief revision based on a cognitive model of credibility and trust. In this framework, the acceptance of information coming from a source depends on *(i)* the agent's goals and beliefs about the source's goals, *(ii)* the credibility, for the agent, of incoming information, and *(iii)* the agent's beliefs about the context in which it operates. This makes it possible to approach belief revision in a setting where new incoming information is associated with an acceptance degree. In particular, such degree may be used as input weight for any possibilistic conditioning operator with uncertain input (i.e., weighted belief revision operator). The results of this research have been published at the SUM conference [56].

Moreover, together with Célia da Costa Pereira (UNS) and Mauro Dragoni (FBK, Italy), we have provided an experimental validation of the fuzzy labeling algorithm proposed by da Costa Pereira et al. at IJCAI-2011 with the aim of carrying out an empirical evaluation of its performance on a benchmark of argumentation graphs. Results show the satisfactory performance of our algorithm, even on complex graph structures as those present in our benchmark. The results of this research have been published at the SUM conference [55].

Serena Villata, together with the other organizers, has also reported about the results of the first Computational Argumentation Challenge (ICCMA) in a AI Magazine paper [17].

7.3.4. RDF Mining

Participants: Amel Ben Othmane, Tran Duc Minh.

In collaboration with Claudia d'Amato of the University of Bari, Italy, we have carried on our investigation about extracting knowledge from RDF data, by proposing a level-wise generate-and-test [53] and an evolutionary [54] approach to discovering multi-relational rules from ontological knowledge bases which exploits the services of an OWL reasoner.

7.3.5. LDScript Linked Data Script Language

Participants: Olivier Corby, Catherine Faron-Zucker, Fabien Gandon.

We design and develop LDScript, a Linked Data Script Language [68]. It is a DSL (domain-specific programming language) the objects of which are RDF terms, triples and graphs as well as SPARQL query results. Its main characteristic is to be designed on top of SPARQL filter language in such a way that SPARQL filter expressions are LDScript expressions. Mainly speaking, it introduces a function definition statement into SPARQL filter language. The main use case of LDScript is the definition of SPARQL extension functions and custom aggregates. With LDScript, we were able to develop a W3C DataShape SHACL [0] validator using STTL and we provide a Web service [0].

7.3.6. Ontology-based Workflow Management Systems

Participants: Tuan-Anh Pham, Nhan Le Thanh.

The main objective of the PhD work is to improve Coloured Petri Nets (CPNs) and Ontology engineering to support the development of business process and business workflow definitions of the various fields and to develop a Shared Workflow Management System (SWMS) using the ontology engineering. Everybody can share a semi-complete workflow which is called ”Workflow template”, and other people can modify and complete it to use in their system. This customized workflow is called ”Personalized workflow”. The challenges of a SWMS is to be simple, easy to use, friendly with the user and not too heavy. But it must have all functions of a WMS. There are three major challenges in this work: How to allow the users to customize the workflow template to correspond to their requirements, but with their changes compliant with the predefined rules in the workflow template? How to build an execution model to evaluate step by step a personalized workflow?

7.3.7. A Service Infrastructure Providing Access to Variables and Heterogeneous Resources

Participants: The-Cân Do, Nhan Le Thanh.

This work is done together with Gaëtan Rey (I3S, PhD co-director). The aim of this PhD work is to develop an adaptation of applications to their context. However, in view of the difficulties of context management in its entirety, we choose to approach the problem by decomposing context management from different points of views (or contextual concerns). A concern (or point of view) may be the business process of the application, security, etc. or any other cross-functionality. In addition to simplifying the context management, sharing between different experts the analysis to be performed, this approach aims to allow the reuse of specifications of each point of view between different applications. Finally, because of the independence of points of view (from their specification to implementation), it is easily conceivable to add and/or delete dynamically points

[0] https://www.w3.org/TR/shacl/
[0] http://corese.inria.fr

of view during the execution of the application we want to adapt. The scientific challenge of this thesis is based on the automatic resolution of conflicts between the points of view made to the adaptation of the target application. Of course, this must be done at runtime.

7.3.8. DBpdia.fr & DBpedia Historic

Participants: Raphaël Boyer, Fabien Gandon, Olivier Corby, Alexandre Monnin.

A new version of the DBpedia historic extractor has been developed and the database is publicly accessible on a dedicated Web server footnote http://dbpedia-historique.inria.fr/sparql. We redesigned the DBpedia Live mechanism from the international DBpedia community to deploy a DBpedia live instance that is able to update itself in near real time by following the edition notification feed from Wikipedia; it is available on our server [0].

We also designed a new DBpedia extractor materializing the editing history of Wikipedia pages as linked data to support queries and indicators on the history [61], [60]. An example of application supported by this service is showed in figure 1 where we provide a Web portal based on STTL [18] crossing linked data from DBpedia.fr and DBpedia Historic to detect events concerning artists.

Finally, we redesigned the DBpedia.fr Web site with a responsive interface, a modern design and a technical documentation. The Web site is also available in English because internationalizing the document allows a wider audience8 to use the data extracted.

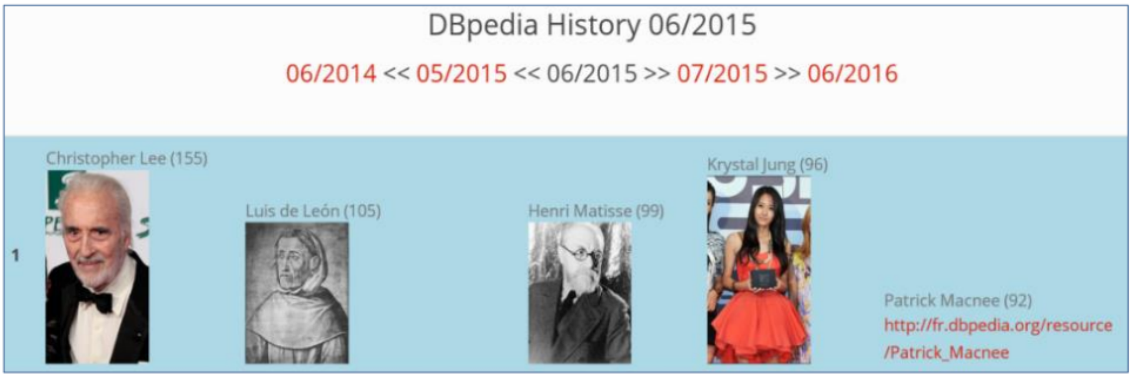

Figure 1. DBpedia Artist category with edition history

7.3.9. Provoc Ontology from SMILK

Participants: Fabien Gandon, Elena Cabrio.

ProVoc [0] (Product Vocabulary) is a vocabulary that can be used to represent information about Products and manipulate them through the Web. This ontology reflects: the basic hierarchy of a company (Group/Company, Divisions of a Group, Brand names attached to a Division or a Group) and the production of a company (products, ranges of products, attached to a Brand, the composition of a product, packages of products, etc.).

[0] http://dbpedia-live.inria.fr/sparql
[0] http://ns.inria.fr/provoc

7.4. Analyzing and Reasoning on Heterogeneous Semantic Graphs

7.4.1. SPARQL Template Transformation Language

Participants: Olivier Corby, Catherine Faron-Zucker, Raphaël Gazzotti.

In the continuation of our work on the design of the STTL SPARQL Template Transformation Language [18], we showed that it can be used as a constraint language for RDF and we applied our approach to implement the semantics of OWL 2 profiles, each viewed as a set of constraints to be validated: we defined an STTL transformation to represent each of the three OWL 2 profiles (OWL RL, OWL QL and OWL EL). The application of one of these STTL transformations to an ontology (in OWL/RDF syntax) enables users to validate it against the OWL 2 profile this transformation represents. This work has been presented at the RR 2016 conference [34].

7.4.2. Exposing Heterogeneous Data Sources on the Web of Linked Open Data

Participants: Catherine Faron-Zucker, Franck Michel.

While the emerging Web of Data continuously grows as data sets are published as Linked Open Data, data is produced ever faster in data silos where it often remains locked. In particular, NoSQL systems have gained a remarkable success during recent years. Consequently, harnessing the data available in NoSQL databases to populate the Web of Data, and more generally achieving RDF-based data integration and SPARQL querying of NoSQL databases, are timely questions.

Together with Johan Montagnat (I3S, UNS), we previously proposed a generic mapping language, xR2RML, able to describe the mapping of most common types of databases into an arbitrary RDF representation [78]. In the continuation of this work, we developed a two-step approach to execute SPARQL queries over heterogeneous databases based on the xR2RML mapping of the database to RDF. We demonstrated the effectiveness of this approach by providing SPARQL access over MongoDB, the popular NoSQL document store. This work was undertaken in the context of the PhD of Franck Michel, and was published in the WebIST 2016 conference [43], and in the DEXA 2016 conference [44].

7.4.3. Combining Argumentation Theory and Natural Language Processing

Participants: Serena Villata, Valerio Basile, Elena Cabrio, Andrea Tettamanzi, Tom Bosc.

We have proposed a new approach to text exploration combining argumentation theory and natural language processing. They define bipolar entailment graphs, i.e., graphs whose nodes are text fragments and the edges represent the entailment or non entailment relations. They adopt abstract dialectical frameworks to define acceptance conditions for the nodes such that the resulting framework returns us relevant information for the text exploration task. The results of this research have been published at the ICAART conference [33].

Moreover, we have proposed a new approach to argument mining for Twitter data. The proposed approach consists first in detecting argumentative tweets from a stream of tweets, and second, starting from this set of argument-tweets, in predicting the relations, i.e., attack and support, holding between two argument-tweets. The annotated corpus resulting from this research line has been described in a paper published at the LREC conference [30], while the results of the argument mining task have been published at the COMMA conference [31].

Following a novel research direction, we investigated the relationship between the emotions displayed by the participants to our experiments and the sentiment expressed in the natural language of their arguments. We ran state-of-the-art sentiment analysis software on the transcriptions of the debates and compared the result with the output of the emotion reading systems. The results of our analysis were presented at the Artificial Intelligence and Cognition Workshop [26] and at the Italian Conference on Computational Linguistics [23].

Finally, together with Celia da Costa Pereira (UNS) and Mauro Dragoni (FBK, Italy), we have proposed an opinion summary application built on top of an argumentation framework, used to exchange, communicate and resolve possibly conflicting viewpoints in distributed scenarios. They show how this application is able to extract relevant and debated opinions from a set of documents containing user-generated content from online commercial Web sites. The result of this research has been published as a short paper at the IJCAI conference [35], and an extended version has been submitted to the AI Comm. journal and it is currently under review.

7.4.4. Opinion Mining

Participants: Andrea Tettamanzi, Serena Villata.

Together with Célia da Costa Pereira of I3S and Mauro Dragoni of FBK, Trento, who visited our team for three months from April to June 2014, we have proposed DRANZIERA, an evaluation protocol for the evaluation of multi-domain opinion mining methods [36] and an argumentation framework for opinion mining [35].

7.4.5. SMILK - Automatic Generation of Quizzes through Semantic Web Technologies

Participant: Oscar Rodríguez Rocha.

The research work focuses on the automatic generation of quizzes using Semantic Web technologies. It takes inspiration from the existing research works about automatic generation of multi choice questions from domain ontologies and aims to apply such existing techniques and contibute to its extension, in order to semantically generate statements that allow to describe the content of a given Web ontology. This research work is carried out in the context of SMILK. SMILK (Social Media Intelligence and Linked Knowledge) is a joint laboratory (LabCom, 2013-2016) between the Wimmics team and the Research and Innovation unit of VISEO (Grenoble). Natural Language Processing, Linked Open Data and Social Networks as well as the links between them are at the core of this LabCom. The purpose of SMILK is both to develop research and technologies in order to retrieve, analyze, and reason on textual data coming from Web sources, and to make use of LOD, social networks structures and interaction in order to improve the analysis and understanding of textual resources. Topics covered by SMILK also include: use of data and vocabularies published on the Web in order to search, analyze, disambiguate and structure textual knowledge in a smart way, but also to feed internal information sources; reasoning on the combination of internal and public data and schemes, query and presentation of data and inferences in natural formats.

7.4.6. Event Identification & Tracking

Participants: Amosse Edouard, Elena Cabrio, Nhan Le Thanh.

In the past year, we have been working on approaches for detecting, classifying and tracking events on Twitter. In the context of social media, an event is considered as "An occurrence causing change in the volume of text data that discusses the associated topic at a specific time. This occurrence is characterized by topic and time, and often associated with entities such as people and location". This definition shows that Named Entities (NE) play a key role in events on social medias and particularly on Twitter. In our approaches we exploit the NE in tweets to analyse events on Twitter.

7.4.6.1. Event Identification and Classification

We developed an approach that exploit occurrences of Named Entities in tweets to train a supervised model for two purposes:

- To classify tweets as either related or not related to events.
- To classify tweets related to events as event categories such as Economy, Politics or Sport.

We combined techniques from Natural Language Processing, Linked Open Data and Machine Learning to build a supervised model for classifying tweets. More specifically, we replaced the NE in tweets by their related class in ontologies (e.g DBpedia or YAGO) and used the modified content to train machine learning algorithms (e.g. SVM, Naive Bayes and Neural Network). Our experiments on two gold standard datasets shown that the NER mechanism helped in reducing overfitting on the output of classifiers.

7.4.6.2. Event Tracking

More recently, we started to work on an approach for tracking planned events on Twitter. In this work, we were particularly interested in tracking the evolution of existing events over time. For example, important actions in a soccer game (goal, yellow/red cards). We proposed an unsupervised approach based on NE in tweets and graph analysis to process the Twitter stream in real time. In this approach, we dynamically update a local gazetteer with actors involved in the events such as player and team names as well as terms that describe the actions of interests (e.g. goal, yellow card for football). The preliminary evaluations are quite promising since we are able to track the most important events in a soccer game as well as the player or teams involved in the actions.

7.4.7. Software and Hardware Architecture of EMOTICA: an Emotions Detection System

Participant: Nhan Le Thanh.

This work is performed with Chaka Kone (3rd year PhD student - LEAT, UNS) and Cécile Belleudy (Thesis Director - LEAT, UNS). The aim of this PhD work is to propose a complete low power system for the recognition of emotions satisfying all application constraints such as energy consumption, size and positioning of sensors. To achieve this goal, our work focuses on two main axes: the detection of emotions and the architectural exploration of objects communicating for health, with particular emphasis on the energy consumption of such systems.

7.4.8. Conversational Agent Assistant

Participants: Raphaël Gazzotti, Catherine Faron-Zucker, Fabien Gandon.

This CIFRE PhD Thesis is performed in collaboration with SynchroNext, a company located in Nice. As part of this thesis, we will be interested in setting up an ECA (Embodied Conversational Agents) for FAQs to advisers. The ECA will need to integrate a question and answer system to address the most common issue types without human intervention [76], [81]. For this purpose, it must be able to understand the questions asked in natural language by the users and to reason with the knowledge acquired. Beyond such a system of questions and answers, the ECA must be able to reopen the conversation with the Internet user according to the nature of his requests or the sequence of questions formulated. 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.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

We have CIFRE PhD funding with Synchronext for the design of a conversational agent assistant endowed with natural language and intuition.

We have CIFRE PhD funding with Educlever on the topic of semantic analysis of activities in a learning environment.

8.2. Bilateral Grants with Industry

8.2.1. Semantic EDUCLOUD Carnot Project

Participants: Oscar Rodríguez Rocha, Catherine Faron-Zucker.

Partner : GAYAtech. This project was just accepted this year on the topic of *semantic Web for e-learning*. This is a joint project with Gayatech on the recommendation of pedagogical resources adapted to user profile and context in the EDUCLOUD 06 Serious Game. To get help in his quests and various quiz testing his knowledge, the gamer can use external digital resources (books, video, TV, Web) and an in-game social network to work with his teacher and comrades. In this context, and to meet the needs of GAYATECH developing edutainment solutions, the Semantic EDUCLOUD project aims to improve the recommendation of educational resources to learners in EDUCLOUD 06, by using semantic Web and social Web models and techniques.

8.2.2. Vigiglobe Carnot Project

Participants: Elena Cabrio, Serena Villata.

Partner : Vigiglobe.

This project was just accepted this year on the topic of *Natural Language Argumentation on Twitter: Retrieval of Argumentative Structures and Reasoning*. this is a joint project with Vigiglobe on the natural language processing of argumentation on Twitter to retrieve argumentative structures and reason on them. The goal of the project is to : (1) Automate the selection and annotation of tweets, i.e., retrieval of those tweets that can be considered as arguments (2) Automate the assignment of labels to the type of relation holding between arguments - positive relation or negative relation. (3) Create an argumentation graph illustrating the relations between the arguments about a certain subject, and the further application of argumentation semantics to compute the set of ”winning” arguments This graph-based visualization provides a summary of the ongoing discussion on Twitter.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. SPARKS Team (I3S)

Wimmics is member of the I3S SPARKS team (Scalable and Pervasive softwARe and Knowledge Systems). It is structured according to three axes: FORUM, ELK and S3.

9.1.1.1. SPARKS ELK Axis

Wimmics contributes to the SPARKS ELK research axis (Knwoledge Extraction and Learning). Andrea Tettamanzi is co-animator of this axis together with Frédéric Precioso (I3S).

9.1.1.2. SPARKS FORUM Axis

Wimmics contributes to the SPARKS FORUM research axis (FORmalizing with Users and Models). Catherine Faron-Zucker and Alain Giboin are co-animators of FORUM. This year, three seminars were organized: (1) Visualisation des données liées (Emilie Palagi, Erwan Demairy, Raphaël Boyer, Olivier Corby); (2) Agents BDI possibilistes (Célia Da Costa-Pereira, Serena Villata, Andrea Tettamanzi); (3) Adaptation Dynamique : des processus métiers à l'environnement opérationnel. Application à la continuité de services ambiants (Jean-Yves Tigli, Isabelle Mirbel).

9.1.1.3. SPARKS S3 Axis

Wimmics contributes to the SPARKS S3 research group (Scalable Software Systems). Olivier Corby, Fuqi Song and Erwan Demairy contribute with federated distributed query processing in Corese with Johan Montagnat and Abdoul Macina. Catherine Faron-Zucker and Franck Michel contribute on it with Johan Montagnat on heterogeneous databases federation.

9.1.1.4. SPARKS HCI Group

The HCI Group brings together researchers from the SPARKS team conducting or wishing to conduct research related to Human-Computer Interaction. The group specifically addresses the issues of how to conduct user experiments to evaluate the UIs of the software developed in GLC. The group establishes collaborations between researchers in the design and implementation of experiments. The HCI group is animated by Anne-Marie Dery (I3S).

9.1.1.5. MSHS Axis-2: ICT, Usage and Communities

Participants: Alain Giboin, Alexandre Monnin, Fabien Gandon, Emilie Palagi.

Axis-2 of the *Maison des Sciences Humaines et Sociales (MSHS) du Sud-Est (Nice)* aims to federate interdisciplinary research on the relationships between ICT, Practices and Communities. Wimmics is mainly involved in one of the Axis-2 groups-projects, "Artifacts and Coordination." This group-project studies the impact of cognitive technologies on the social and cognitive coordination between individuals in organizational and community contexts. Alain Giboin is member of the Axis-2 scientific committee and co-animator (with Lise Arena, GREDEG, until September 2016; and Evelyne Rouby, GREDEG, from October 2016) of the "Artifacts and Coordination" group-project. He is also co-animator (with Pierre Thérouanne (Lapcos), Lise Arena and Agnès Festré (GREDEG)) of the project "Acceptabilitity of digital devices: an interdisciplinary perspective". This group is animated by Alain Giboin, Alexandre Monnin, Fabien Gandon and Emilie Palagi.

9.1.2. TCP-IP + Blockchain UCA Idex Submission

Participant: Alexandre Monnin.

We submitted a project proposal around the "TCP-IP + Blockchain (Transdisciplinary Collaborative Plaform for Internet of things and Platformcooperativism)" platform, launched and coordinated by Alexandre Monnin inside the UCA Jedi Idex (Wimmics, LEAT, Aoste, Indes, I3S, GREDEG, LAPCOS, SKEMA, Sustainable Design School, Villa Arson, module D, club Cap EF, SCITIAM, Fabrique des Mobilités, Mnémotix, etc.). A host of projects were submitted inside this platform:

- ACCEPT by Lise Arena and Alain Giboin (Idex Academy 5)

- SMART by François Verdier (Idex Academy 1)

- Polisthelia by Alexandre Monnin (ANR, PCRI with Luxemburg)

- SMARTIOT by François Verdier (ANR project on Smart Contracts)

among which ValueModels submitted by Alexandre Monnin (Idex Academy 1) was accepted.

9.2. National Initiatives

9.2.1. NiceCampus Research Lab

Participant: Nhan Le Thanh.

NiceCampus Research Lab (from training to/and through research to a Joint International Laboratory) is a framework for cooperation for research training. This framework is proposed by the University of Nice Sophia Antipolis to support the 911 Vietnamese research training program that aims to support the development of Vietnamese universities. The NiceCampus Lab Project was a winner of the AUF Call for Proposals 2016-2017. In this context, the MIRE (Maison de l'innovation et de la recherche NiceCampus) was created at University of Da Nang (Vietnam).

9.2.2. DILPROSPECT

Participant: Andrea Tettamanzi.

We participated in the interdisciplinary DILPROSPECT CNRS Project, with researchers of many other research units, including the UMR 7300 ESPACE and INRA on the study of the interface between constructed and natural land on the French Riviera.

9.2.3. AZKAR

Participants: Alain Giboin, Thierry Bergeron, Michel Buffa, Catherine Faron-Zucker.

AZKAR is a two years French project funded by BPI (Banque Publique d'Investissement), focused on *Fast Control of Mobile Robots over the Internet*.

The project started in September 2014. The first step of the project has been the evaluation and benchmarking of video and data solutions over Internet, based on the WebRTC technology. The second step consists in implementing these solutions on a real mobile robot that has been deployed in museums or in homes for helping seniors in their daily tasks. Semantic Web technologies, have been used in the project for describing the services, the context of the application domain, the content transmitted, etc. We got a best demo award at ISWC this year, for a demo that shown a robot located in France that has been remote controlled from Kobe in Japan during the conference [32].

9.2.4. ANR WASABI

Participants: Michel Buffa, Elena Cabrio.

We will be project leader of this 42 month ANR project that starts in January 2017. Partners are IRCAM, Deezer, Radio France and a french startup named Parisson. WASABI aims to build the biggest song metadata semantic database, mixing audio and cultural content analysis. Client applications target music school, sound engineer schools, composers and musicians, journalists, radios and streaming services.

9.2.5. ANR LabCom SMILK

Participants: Elena Cabrio, Catherine Faron-Zucker, Fabien Gandon, Zide Meng, Oscar Rodríguez Rocha, Molka Tounsi.

SMILK (Social Media Intelligence and Linked Knowledge) is a joint laboratory (LabCom, 2013-2016) between the Wimmics team and the Research and Innovation unit of VISEO (Grenoble). Natural Language Processing, Linked Open Data and Social Networks as well as the links between them are at the core of this LabCom. The purpose of SMILK is both to develop research and technologies in order to retrieve, analyze, and reason on textual data coming from Web sources, and to make use of LOD, social networks structures and interaction in order to improve the analysis and understanding of textual resources. Topics covered by SMILK include: use of data and vocabularies published on the Web in order to search, analyze, disambiguate and structure textual knowledge in a smart way, but also to feed internal information sources; reasoning on the combination of internal and public data and schemes, query and presentation of data and inferences in natural formats.

9.2.6. Inria LabCom EduMICS

Participants: Catherine Faron-Zucker, Fabien Gandon, Chihabeddine Bouchenaki, Olivier Corby.

EduMICS (Educative Models Interactions Communities with Semantics) is a joint laboratory (LabCom, 2016-2018) between the Wimmics team and the Educlaver 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. Topics covered by EduMICS include: ontology-based modeling of educational resources; ontology-based integration of heterogenous data sources; ontology-based reasoning; semantic analysis of a social network of learners; pedagogical resource recommendation adpated to learner profiles.

9.2.7. Ministry of Culture: DBpedia.fr

Participants: Raphaël Boyer, Fabien Gandon.

This DBpedia.fr project proposes the creation of a French chapter of the DBpedia database. This project was the first project of the Semanticpedia convention signed by the Ministry of Culture, the Wikimedia foundation and Inria.

Web site: http://dbpedia.fr

9.2.8. Ministry of Culture: GT 6 for a convention between Inria and the Ministry of Culture

Participant: Fabien Gandon.

We supervised the working group GT6 Ministry of Culture on the creation of a research convention to foster research and development at the crossroad of culture and digital sciences. This convention signed between Inria and the Ministry of Culture the 12 December 2016 will provide a framework to support projects at the cross-road of the cultural domain and the digital sciences.

9.2.9. ANR OCKTOPUS

Participants: Fabien Gandon, Catherine Faron-Zucker, Zide Meng.

OCKTOPUS is an ANR project (2012-2016) which ended during this year. Its general objective was to increase the potential social and economic benefit of the large and quickly growing amounts of user-generated content, by transforming it into useful knowledge. We showed how it is possible to considerably improve upon existing generic Information Retrieval techniques by exploiting the specific structure of this content and of the online communities which produce it. Specifically, we focused on a multi-disciplinary approach in order to address the problem of finding relevant answers to questions within forums and question-answer sites. To create metrics and predictors of content quality and use them to improve the search experience of a user, we took advantage of:

- the experience of the CRG (the management research institute of Ecole Polytechnique and CNRS) to understand better the incentives of, and interactions between individuals who produce online content within large communities;
- the experience of the Wimmics research team to analyze the structural and temporal aspects of the complex typed social graphs found within these communities;
- the ability of Alcméon (a start-up developing a search application dedicated to user-generated content) to integrate and test the results of OCKTOPUS within a common demonstration framework, in order to assess their practical usefulness when applied to concrete large-scale datasets.

Partners: Alcméon, CRG, Inria Wimmics.

Web site: http://ocktopus.alcmeon.com

9.2.10. GDRI Zoomathia

Participants: Olivier Corby, Catherine Faron-Zucker, Alexandre Monnin, Andrea Tettamanzi.

Wimmics is partner of the International Research Group (GDRI) Zoomathia funded by two CNRS institutes: INEE and INSHS. It aims at studying transmission of zoological knowledge from Antiquity to Middle-Age through material resources (bio residues, artefacts), iconography and texts.

One of the goals of the project is to design a thesaurus and semantically annotate resources, capturing different types of knowledge: zoonyme, historical period, zoological speciality (ethology, anatomy, physiology, psychology, zootechnique, etc.), litterary genre or iconography.

We collaboratively work with MNHN and CEPAM researchers on the construction of a SKOS thesaurus of zoonyms and a SKOS thesaurus of animal specialties the automatic and on the automatic semantic categorization of text fragments. The ultimate goal is the exploitation of these semantic metadata to help historians in their studies of knowledge transmission through these texts.

Web site: http://www.cepam.cnrs.fr/zoomathia/

9.2.11. FUI PadDOC

Participants: Patrice Pena, Alain Giboin.

PadDOC goal is to contribute to accelerating the digital transition of citizen, local and regional authorities, administrations and enterprises, by : (1) developing an open standard and innovative software and hardware resources to facilitate nearby or distant administrative formalities and procedures; (2) improving the security of the holder's personal data by putting these data under the exclusive control of the holder; (3) by exploiting unmarked communicating supports (such as smartphones or tablets) for all chain actors. PadDOC partners are: Docapost BPO, Anyces, ABC SmartCard and the teams Rainbow, Media-Coding and Wimmics.Wimmics will contribute to: (1) the analysis, design and evaluation of the PadDOC security-oriented user interfaces; (2) the impact assessment of the chain of actors participating in the experiment to validate the viability of the PadDOC social system. The PadDOC project officially began in November 2014.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. MIREL RISE

Participants: Serena Villata, Elena Cabrio, Oscar Rodríguez Rocha, Raphaël Gazzotti, Fabien Gandon.

Program: Research and Innovation Staff Exchange (RISE) project, funding under Marie Skłodowska-Curie grant.

Project acronym: MIREL

Project title: MIning and REasoning with legal text

Duration: 2016-2019

Coordinator: Leendert van der Torre, University of Luxembourg

Other partners: 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).

Abstract: 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/

9.3.1.2. ALOOF CHIST-ERA

Participants: Valerio Basile, Elena Cabrio, Fabien Gandon.

ALOOF (Autonomous Learning of the Meaning of Objects) is a European project (CHIST-ERA 2015-2018) to enable robots to use the ever-growing amount of knowledge available on the Web, by learning from there about the meaning of previously unseen objects, expressed in a form that makes them applicable when acting in situated environments. Partners include: University of Rome La Sapienza (Italy), University of Birmingham (United Kingdom), Technische Universität Wien (Austria), Inria Sophia Antipolis Méditerranée (France).

Web site: https://project.inria.fr/aloof/

9.4. International Initiatives

9.4.1. MoReWAIS

Participants: Papa Fary Diallo, Mahamadou Toure, Olivier Corby, Isabelle Mirbel, Fabien Gandon.

Title: Mobile Read Write Access and Intermittent to Semantic Web

International Partner (Institution - Laboratory - Researcher):

UGB (Senegal) - LANI - Moussa Lo, Seydina Ndiaye

Start year: 2016

See also: https://project.inria.fr/morewais/

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).

We will design and develop algorithms, methods and tools for mobile devices allowing users to:

- co-construct locally and on the road the Semantic Web of Data RDF triple stores representing the sociocultural shared knowledge.
- Access and visualize in context relevant data from the knowledge platform. This requires a complete rethinking of RDF storage and SPARQL querying in a mobile and unreliable network environment. This will also require dedicated interaction design to ease and encourage access and contribution.

9.4.2. SEEMPAD

Title: Social Exchanges and Emotions in Mediated Polemics - Analysis and Data

International Partner (Institution - Laboratory - Researcher):

University of Montréal (Canada) - Higher Educational Research ON tutoring systems (Heron) - Claude Frasson

Start year: 2014

See also: https://project.inria.fr/seempad/

Generating, annotating and analyzing a dataset that documents a debate. We aim at synchronizing several dimensions: social links (intensity, alliances, etc.); interactions happening (who talks to whom); textual content of the exchanged messages; social-based semantic relations among the arguments; emotions, polarity, opinions detected from the text; emotions, physical state detected from sensors.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

9.5.1.1. Internships

Hatim Aouzal

Date: May – September

Institution: MIAGE UNS & EMSI Casablanca, Morocco

Title: Intelligent System for Mobile Robot Museum Visit.

Supervisor: Michel Buffa

Lautaro Petaccio

Date: July – December

Institution: Universidad de Buenos Aires (Argentina)

Title: Design and development of a Fact-Checking Framework Based on Argumentation Theory and Natural Language Processing Techniques.

Supervisors: Elena Cabrio, Serena Villata

Konstantina Poulida

Date: until January

Institution: University of Patras, Computer Engineering and Informatics Department

Title: Semantic Categorization of Segments of Ancient and Mediaeval Zoological Texts

Supervisors: Catherine Faron-Zucker, Andrea Tettamanzi

Avijit Shah

Date: September – December

Institution: NITK, National Institute of Technology Karnataka, Surathkal (India).

Title: Bootstrapping the Construction of a Knowledge Base of Objects

Supervisors: Valerio Basile and Elena Cabrio

9.5.2. Visits to International Teams

9.5.2.1. Research Stays Abroad

Tuan Anh Pham

Date: October 2016 to July 2017.

Erasmus Mundus Scholarship Exchange at University of Danang, Vietnam for 7 months to deploy the result of the PhD in a common project with UNS.

Serena Villata

Date: February-March.

Visit of the Nomotika startup in Turin, Italia, for two months as a secondment of the MIREL H2020 Project.

Topic: This secondment was in the context of WP2, and more specifically it addressed Task 2.2 (Develop NLP systems for mining named entities and concepts, in order to populate the ontology). Serena Villata worked in the past on the topic of ontology-based information extraction from licensing information applying machine learning techniques. The results of her work have been exploited to define the two tools called NLL2RDF [0] and Licentia [0].

During this secondment, she studied together with the Nomotika personnel how to generalize the approach proposed in NLL2RDF and Licentia in such a way that this kind of processing is applicable to legal texts in general, and not only to licenses. More precisely, the collaboration has been concentrated on the investigation of the following open issues: (i) find and refine (if needed) existing computational ontologies for normative reasoning, and (ii) mine legal texts to extract the main deontic components (i.e., obligations, permissions, and prohibitions) and returning a machine-readable semantic representation of such information extracted from the texts exploiting a distributional semantics approach where the meaning of a word is represented by the set of contexts in which it occurs in texts. The collaboration is still ongoing and results are expected soon (i.e., publications).

[0] http://www.airpedia.org/nll2rdf/
[0] http://licentia.inria.fr/

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

Valerio Basile: Area chair for Information Retrieval at CLiC-it 2016.

Elena Cabrio: Area chair (Semantics for applications). The Fifth Joint Conference on Lexical and Computational Semantics (*SEM 2016).

Scientific co-chair. Dagstuhl Seminar on Natural Language Argumentation: Mining, Processing, and Reasoning over Textual Arguments, 2016.

Fabien Gandon: co-chair and organizer of the Q4APS (Question Answering And Activity Analysis in Participatory Sites) Workshop at WWW [0].

Catherine Faron-Zucker: co-chair of the ESWC2016 workshop on Semantic Web for Scientific Heritage (SW4SH 2016),

co-chair of the first scientific day of the Inria Learning Lab, November 16th,

scientific chair of the Inria-Industry meeting (R2I) on Ed-Tech, December 1st.

Serena Villata: Chair together with Elena Cabrio, Graeme Hirst and Adam Wyner of the Dagstuhl Seminar on Mining, Processing, and Reasoning over Textual Arguments (Dagstuhl Seminar 16161), April 17-22, 2016. Local chair of the 29th International Conference on Legal Knowledge and Information Systems (JURIX 2016), December 14-16, 2016.

10.1.1.2. Member of the Organizing Committees

Valerio Basile: local organizer for JURIX 2016 and for the SENTIPOLC challenge at EVALITA 2016.

Elena Cabrio: 6th Open Challenge on Question Answering over Linked Data (QALD-6), ESWC 2016.

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

Catherine Faron-Zucker: PC co-chair of the 22th Int. Conference on Conceptual Structures (ICCS 2016).

10.1.2.2. Member of the Conference Program Committees

Valerio Basile: *SEM , PEOPLES workshop at COLING, EACL 2017, WebNLG workshop at INLG, ESWC, EKAW, ICRA, CLiC-it, MIREL workshop at JURIX, DSAA, AIC workshop at BICA.

Michel Buffa: Web Audio Conference (WAC), ESWC, ISWC, WWW demo W3C track, Semantic Web Collaborative Spaces (SWCS) workshop.

Elena Cabrio: Association for Computational Linguistics conference (ACL, EACL), the Computational Linguistics conference (COLING), and the Extended Semantic Web Conference (ESWC).

Olivier Corby: Arima, EKAW, GraphQ, IC, ICCS, MoreBI, Top-K Shortest Path in Large Typed RDF Graphs Challenge at ESWC.

Catherine Faron-Zucker: ESWC (European Semantic Web Conference), ISWC (Int. Semantic Web Conference, P&D), WebEd (WWW Workshop on Web Science and Technology for Education), Q4APS2016 (WWW Workshop on Question Answering And Activity Analysis in Participatory Sites), EKM (EKAW workshop on Educational Knowledge Management), ISW-LOD (Int. Workshop on Semantic Web and Linked Open Data), CNIA (Conf. Nationale d'Intelligence Artificielle), IC (Ingénierie des Connaissances), EGC 2017 (Extraction et Gestion des Connaissances).

[0] https://project.inria.fr/q4aps2016/

Fabien Gandon: IJCAI , ISWC (Senior PC), WWW , WebScience (Senior PC), ESWC, FOIS, IC, Semantics, SemWeb.Pro, CNIA (Conférence Nationale en Intelligence Artificielle), Diversity-Aware AI Workshop at ECAI, EGC, Journée Intelligence Artificielle et Big Data [0].

Alain Giboin is member of the steering committee of the COOP conference series (International Conferences on the Design of Cooperative Systems). He is also member of the program committee of: COOP, ESWC (In-use & Industrial Track), IC, SEMANTICS (Research Track), SEMANTICS (Posters and Demos), UBIMOB, WebSci.

Isabelle Mirbel: 27th International Conference on Advanced Information Systems Engineering (CAISE), IEEE Tenth International Conference on Research Challenges in Information Science.

Alexandre Monnin: WWW, ESWC, SWASH (ESWC workshop), WebSci, IC.

Oscar Rodríguez Rocha: KEOD, KSE

Andrea Tettamanzi: ECG 2017, ESWC, FLAIRS-29, FUZZ-IEEE, IC, LREC, MOD, PPSN, and SAC 2017 conferences, SW4SH workshop of ESWC.

Serena Villata: IJCAI, AAAI, JURIX.

10.1.2.3. Reviewer

Olivier Corby: ESWC, ISWC, WWW, EGC.

Isabelle Mirbel: ESWC.

Alain Giboin: ISWC, WWW, IHM.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

Catherine Faron-Zucker: Revue d'Intelligence Artificielle, special issue "Ingénierie des Connaissances".

Fabien Gandon:

- Editor of the special issue of the Semantic Web Journal for best papers at ESWC 2015.
- Special issue RIA, Revue d'intelligence artificielle, Analyse intelligente des réseaux sociaux, volume 30, n. 4/2016.

Nhan Le Thanh: Journal of Science and Technology, Da Nang University- Issue on Information and Communications Technology.

Isabelle Mirbel: Ingénierie des Systèmes d'Information (Hermès).

10.1.3.2. Reviewer - Reviewing Activities

Valerio Basile: Language and Cognition (published by Cambridge University Press), Computer Speech & Language, Interacting with Computers.

Olivier Corby: Semantic Web Journal.

Catherine Faron-Zucker: Semantic Web Journal (SWJ), Journal of Web Science, ACM's Transactions on Internet Technology (TOIT), International Journal of Web Information Systems (IJWIS), International Journal of Metadata, Semantics and Ontologies (IJMSO).

Nhan Le Thanh: Journal of Science and Technology, Da Nang University- Issue on Information and Communications Technology.

Isabelle Mirbel: Neurocomp journal.

Alexandre Monnin: Minds and Machines, Big Data and Society, Revue d'intelligence artificielle.

Andrea Tettamanzi: Evolutionary Intelligence, Soft COmputing (SOCO).

Serena Villata: Journal of Logic and Computation, Argument & Computation, Artificial Intelligence.

[0] http://bigia2016.irisa.fr/

10.1.4. Invited Talks

Valerio Basile: University of Turin, Building a default knowledge base of objects (and other stories of robots), November 16th.

Michel Buffa:

WWW 2016 W3C Track: HTML5 games, When your browser becomes a game console! Coding games for the Web + Demo of a HTML5 game developed by students in the first session of the W3Cx HTML5 Part 2 MOOC.

Discussion on the future of Web games development using HTML5, special off-conference HTML5 gaming meetup (chair and co-organizer), WWW 2016 Conference, April 13, Montreal, Canada.

AmpSim2, un simulateur d'amplificateur de guitare en Web Audio, Paris Audio #3, September 7, IRCAM.

Michel Buffa, Thierry Bergeron: "Le projet AZKAR : navigation d'un robot mobile temps réel à travers le Web en P2P avec l'API WebRTC", Conférence Blend WebMix 2016, November 2 & 3, Lyon, France.

Elena Cabrio: Bielefeld University, Germany, ”Argument mining: our story so far”, June 20th.

Catherine Faron-Zucker: Invited research Talk, at the Ministry of Economy and Finance (MEF- DGE), September 23rd.

Fabien Gandon:

- Keynote speaker for the conference Web Intelligence, Mining and Semantics (WIMS 2016) titled "One Web of pages, One Web of peoples, One Web of Services, One Web of Data, One Web of Things... and with the Semantic Web bind them.", June 14th;
- Joint keynote speaker for the International Conference on Conceptual Structures (ICCS 2016) and International Conference on Formal Ontology in Information Systems (FOIS 2016) titled "On the many graphs of the Web and the interest of adding their missing links.", July 7th;
- CafeLecture - Atelier de lecture transdisciplinaire - Learning Centre SophiaTech, Regards Croisés. "Dans l'esprit du Pagerank : regards croisés sur les algorithmes".

Alain Giboin (with Agnès Festré, GREDEG) gave a talk on ”Nudges, Affordances et conception d'artefacts” in ”Regards croisés” Seminar at Sophia Antipolis Campus.

Alexandre Monnin:

National interLabex symposium "Excellence in Smart Systems" (Besançon), November 17th.

Roundtable as part of the Economique numérique summer school - 3EN (Nice), May 31st.

Master Miage to deliver a talk entitled ”La philosophie à partir de l'architecture du Web” (Sophia Antipolis), March 9th.

Hypertopic seminar of Tech-Cico (UTT, Troyes, online presentation), March 21st.

Emilie Palagi:

A presentation in FORUM SPARKS seminar on the evaluation and design of the explanation features of the exploratory search system Discovery Hub, March 1st.

A presentation in Axis-2 of the ”Maison des Sciences Humaines et Sociales (MSHS) du Sud-Est (Nice)" : ”Exploratory search system and user centered evaluation method”, March 14th.

A presentation of Palagi's PhD Subject in a new cycle of seminars on Human Computer Interaction (HCI) and UX Design called ”les lundis de l'ergonomie”, October 10th.

”Journée rencontre Inria Industrie” in Lille: A demo of Discovery Hub and the presentation of an ongoing work on the design of a user centered evaluation method of exploratory search systems, November 25th.

10.1.5. Leadership within the Scientific Community

Alexandre Monnin organizes a seminar with Lise Arena (UNS, GREDEG) and Bernard Conein (UNS, GREDEG), between Inria and MSHS, entitled "Digital artifacts and materialities". International researchers such as Jérôme Denis [0] (Mines ParisTech), Paul Smart (Southampton) [0], Michael Wheeler (Stirling), David Kirsh (San Diego) [0], Yuk Hui (Lüneburg) [0] and Brian Cantwell Smith (Toronto) participated in the seminar this year.

Alexandre Monnin and Manuel Boutet (UNS, GREDEG) organize the "ateliers de lecture transdisciplinaires" of UCA, hosted by SophiaTech learning centre and later redubbed "Regards croisés" (5 sessions took place, all organized by Alexandre Monnin, with Lise Arena and Fabien Gandon, Alexandre Monnin et Bernard Conein, Ali Douai et Gabriel Plassat, Nathalie Oriol and François Bremond, Alain Giboin and Agnès Festré). The regards croisés have been chosen to be recorded and archived on a future UCA portal and YouTube channel.

Alexandre Monnin participated to the invitation of Brian Cantwell Smith to a Morgenstern colloquium at Inria Sophia Antipolis, December 8th. Alexandre Monnin is extending Brian Cantwell Smith's stay for the Morgenstern Colloquium thanks to fundings provided by the MSHS. Two workshops will be organized around him on Dec. 12th and 13th at the MSHS in Nice in addition to the PhiloWeb day on the 14th.

Alexandre Monnin organized a PhiloWeb conference with B.C. Smith and Harry Halpin,

Alexandre Monnin participated in two events as part of the $Transition^2$ initiative set up by Inria and FING. In January, he created the W3C Community Group "Web We Can Afford" whose goal is to discuss the future of the Web at the time of the Anthropocene [0].

”Les lundis de l'ergonomie” is a new cycle of seminars on Human Computer Interaction (HCI) and UX Design. Organized by Emilie Palagi and Louise Chaussade, this multidisciplinary series of talks may attract academic and professional profiles but also anyone interested in social science's approach to digital matters. Two presentations took place in October (with Emilie Palagi and Louise Chaussade) and December (Patrice Pena).

10.1.6. Scientific Expertise

Elena Cabrio was reviewer for French ANR projects.

Olivier Corby was reviewer for Atlanstic 2020 (Pays de la Loire) project submission.

Catherine Faron-Zucker is the scientific reference of the Inria Learning Lab.

Catherine Faron-Zucker reviewed project proposals for the Academic Research Community (ARC) 6 of Rhône Alpes Region.

10.1.7. Research Administration

Michel Buffa is director of the MIAGE of Nice Sophia Antipolis, composed of Licence, Master 1 and four Master 2 diplomas with about 350 students [0]. He is member of the OpenMiage committee that aims at proposing an online version of the whole MIAGE cursus.

Olivier Corby is member of the PostDoc Inria Sophia committee.

Catherine Faron-Zucker is General Treasurer of the French Society for Artificial Intelligence (AFIA).

She was member of the 2016 recruitment committee of Telecom Saint Etienne, University Jean Monnet.

She coordinates the Web option of the 5th year of Polytech Nice Sophia engineering school and is in charge of continuous training for the computer science department of Polytech Nice Sophia Antipolis.

[0] http://mshs.unice.fr/?p=6799
[0] http://mshs.unice.fr/?p=6725
[0] http://mshs.unice.fr/?p=6908
[0] http://mshs.unice.fr/?p=7644
[0] https://www.w3.org/community/wwca/
[0] http://miage.unice.fr

Fabien Gandon is:

- representative of Inria at W3C consortium.
- representative of Inria in the Web Science Trust Network.
- member of the Steering Committee of the Scientific Board of Inria Sophia Antipolis (Bureau CP).
- member of the scientific committee of the Labex UCN.
- member of the Scientific Committee academy 1 of IDEX.
- member of the Steering Committee academy 5 of IDEX.
- member of ESWC Steering committee.
- member of IW3C2 Steering committee for WWW conference series.

Alain Giboin serves as scientific correspondent for Inria Sophia of COERLE (Inria Comité Opérationnel d'Evaluation des Risques Légaux et Ethiques), in tandem with the legal correspondent Nadège Camelio-Laurent. Alain Giboin is member of the Commission "Médiation et Animation des MAthématiques, des Sciences et Techniques Informatiques et des Communications" (MASTIC) of Inria Sophia Antipolis – Méditerranée.

Nhan Le Thanh is Animator of a multidisciplinary Idex working group "Connected Healthcare and well Aging INnovative Services" (CHAINS) at UNS. He is animator of a multidisciplinary join working group (TRT eHealth), UNS and Da Nang University, on the themes of IoT services for eHealth and smart city. He is coordinator of the bilateral scientific cooperation program NiceCampus between UNS and Da Nang University. He is director of the computer science department, IUT, UNS.

Isabelle Mirbel is Vice Dean of Science Department at University Nice-Sophia Antipolis.

Andrea Tettamanzi is coordinator of the 3rd year of the *Licence* in Business Informatics (MIAGE) at the UFR Science of the Université Nice Sophia Antipolis (UNS). He is co-animator, together with Johan Montagnat (I3S), of the SPARKS team who hosts Wimmics at I3S.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence: Amel Ben Othmane, Oracle Database, 64h, L1, IUT Institute of Technology of Nice, France.

Licence: Elena Cabrio, Web Server Programming, 45h, L1, UNS, France.

Licence: Amosse Edouard, Object Oriented Design, 33h, L3, UNS, France.

Licence: Amosse Edouard, Introduction to Web Programming, 16h, L3, UNS, France.

Licence: Catherine Faron-Zucker, Web languages, 36h, Licence 3, Polytech UNS.

Licence: Catherine Faron-Zucker, Statistics, 36h, Licence 3, Polytech UNS.

Licence: Nhan Le Thanh, Databases, 150h, DUT Info S2 at IUT, UNS, France.

Licence: Nhan Le Thanh, Advanced Databases, 105h, DUT Info S3 at IUT, UNS, France.

Licence: Nhan Le Thanh, Logical Data Models and languages, 24h, L3 LPSIL at IUT, UNS, France.

Licence: Nhan Le Thanh, Design and Development of DBMS services, 24h, L3 LPSIL at IUT, UNS, France.

Licence: Isabelle Mirbel, Databases, 58h, L3 MIAGE, UNS, France.

Licence: Isabelle Mirbel, Web programming (Persistence), 54h, L3 MIAGE, UNS, France.

Licence: Alexandre Monnin, Analyse des controverses, 4h30, L1, Telecom ParisTech, France.

Licence: Alexandre Monnin, Analyse des controverses and climate change, 6h, ESC Clermont-Ferrand, France.

Licence: Andrea Tettamanzi, Algorithmique, Programmation Objet, Python, L2, 50h, UNS, France.

Licence: Andrea Tettamanzi, Programmation Web Avancée coté client, L2, 39h, UNS, France.

Licence: Andrea Tettamanzi, Web, 18h, L3 MIAGE, UNS, ETD;

Master: Valerio Basile, Knowledge Engineering, 7h, Master 2 IFI, UNS, France.

Master: Michel Buffa, Web technologies, 40h, M1, UNS, France.

Master: Michel Buffa, Server Side JavaScript, 20h, M2 UNS, France.

Master: Michel Buffa, Web 2.0/Web Services/HTML5, 40h, M2, UNS, France.

Master: Michel Buffa, Java Certification, 25h, M2, Polytech'Nice UNS, France.

Master: Michel Buffa, Programmable Web, 40h, M2, Polytech'Nice students, UNS, France.

Master: Michel Buffa, Distributed Web development, 40h, M2, UNS, France. This course is also given by video conference to M2 students in Marroco, Madagascar and Haïti, that gets the same diploma as students from the UNS, France.

Master: Elena Cabrio, Web Science, 5h, M2, UNS, France.

Master: Olivier Corby, Oscar Rodríguez Rocha, Catherine Faron-Zucker, Fabien Gandon, Semantic Web, 45h, M2, UNS, France.

Master: Olivier Corby, XML, 15H, M2, UNS, France.

Master: Olivier Corby, Semantic Web, 3H, M2, University of Toulouse, France.

Master: Olivier Corby, Semantic Web, 3H, M2, University of Montpellier, France.

Master: Amosse Edouard, Development on the Android platform, 38h, M2, UNS, France.

Master: Amosse Edouard, Web Services, 17h, M2, UNS, France.

Master: Amosse Edouard, Introduction to Near Field Communication, 20h, M2, EMSI, Morocco.

Master: Catherine Faron-Zucker, Web languages, 24h, M1, Polytech UNS.

Master: Catherine Faron-Zucker, Web Science, 4h, M1 IFI, UNS.

Master: Catherine Faron-Zucker, Network Programming, 12h, M1, Polytech UNS.

Master: Catherine Faron-Zucker, XML technologies, 24h, M2 IMAFA, UNS.

Master: Catherine Faron-Zucker, Semantic Web technologies, 28h, M2 IFI, Polytech, UNS.

Master: Catherine Faron-Zucker, Knowledge Engineering, 9h, M2 IFI, Polytech, UNS.

Master: Fabien Gandon, Web Science, 4h, M1 IFI, UNS.

Master: Fabien Gandon, Semantic Web technologies, 4h, M2 IFI, Polytech, UNS.

Master: Fabien Gandon, Semantic Web technologies, 25h, Data Science Technical Institute, Paris.

Master: Alain Giboin, Human-Computer-Interaction Design and Evaluation, 54h, M2, UNS.

Master: Alain Giboin, Interaction Techniques and Multimodality, 8h, 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, Economics and ICT: Ergonomics, 15h, M2 Economics and ICT, ISEM, UNS.

Master: Isabelle Mirbel, Requirement Engineering, 42h Master MIAGE 1, UNS, France.

Master: Isabelle Mirbel, Advanced databases, 48h Master MIAGE 1, UNS, France.

Master: Alexandre Monnin, Ingénierie des connaissances, 11h, M2, UNS, France.

Master: Oscar Rodríguez Rocha, Ingénierie des connaissances, 12h, M2, UNS, France.

Master: Andrea Tettamanzi, Systèmes Distribués, 18h, M1 MIAGE, UNS, France.

Master: Andrea Tettamanzi, Concurrency and Parallelism, 18h, M1 International, UNS, France.

Master: Andrea Tettamanzi, Fuzzy Description Logics and Ontology Learning, *in Ingénierie des connaissances*, 10h, M2, Polytech'Nice, UNS, France.

E-learning

MOOC: Fabien Gandon, Olivier Corby & Catherine Faron-Zucker, Introduction au Web Sémantique, 7 weeks, https://www.fun-mooc.fr/, Inria, France Université Numérique, Education for Adults, 4870 registered.

MOOC: Fabien Gandon, Olivier Corby & Catherine Faron-Zucker, Introduction to a Web of Linked Data, 4 weeks, https://www.fun-mooc.fr/, Inria, France Université Numérique, Education for Adults, 1703 registered.

MOOC: Michel Buffa, two MOOCs HTML5 for W3Cx / edX (MIT/Harvard). More than 300k registered students since 2015. Finalist for the first-ever edX Prize for Exceptional Contributions in Online Teaching and Learning (11 teachers have been selected among 2500 others and 1200 online courses).

10.2.1.1. Internships

Mihai-Alexandru Dusmanu

Date: June – August

Institution: ENS Paris

Title: Argument Detection on Twitter

Supervisors: Elena Cabrio, Serena Villata

Safaa Rziou

Date: April – September

Title: Semantic Categorization of Segments of Ancient and Mediaeval Zoological Texts

Institution: Université Nice Sophia Antipolis, Master 2 MIAGE

Supervisors: Catherine Faron-Zucker, Andrea Tettamanzi

10.2.2. Supervision

PhD: **Papa Fary Diallo**, *Co-Construction of Community Ontologies and Corpus in a Limited Technological Environment*, Inria, UNS, UGB, September 16th, Isabelle Mirbel, Olivier Corby, Moussa Lo.

PhD: **Zide Meng**, *Temporal and Semantic Analysis of Richly Typed Social Networks from User-Generated-Content Sites on the Web*, UNS, November 7th, Fabien Gandon, Catherine Faron-Zucker.

PhD in progress: **Amel Ben Othmane**, *Temporal and Semantic Analysis of Information Retrieved from Short and Spatio-Temporal Messages in Social Networks*, UNS, Nhan Le Than.

PhD in progress: **Chihabeddine Bouchenaki**, *Semantic Analysis of Activities in a Learning Environment*, UNS, September 2016, Fabien Gandon, Catherine Faron-Zucker.

PhD in progress: **Amosse Edouard**, *Studies of Spatial Semantic Aspect, Real Time Filtering Mechanisms and Semantic Enrichment of Short Messages on Dynamic Spatio-Temporal Social Networks*, UNS, Nhan Le Thanh and Elena Cabrio.

PhD in progress: **Raphaël Gazzotti**, *Conversational Agent Assistant Endowed with Natural Language and Intuition*, UNS & SynchroNext, Fabien Gandon, Catherine Faron-Zucker.

PhD in progress: **Franck Michel**, *Heterogeneous Databases Federation in Distributed Environment*, UNS, Johan Montagnat, Catherine Faron-Zucker.

PhD in progress: **Tran Duc Minh**, *Learning Ontologies from Linked Open Data*, Andrea Tettamanzi, UNS and Nguyen Thanh Binh, University of Danang.

PhD in progress: **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).

PhD in progress : **Tuan Anh Pham**, *Study and integration of the mechanism of workflow control in MVC (Model View Controler) architecture: design and implementation of an APM (Activity Process Management) platform for dynamic information systems on the networks*, UNS, Nhan Le Thanh.

10.2.3. Juries

Olivier Corby was jury member for the PhD Thesis of Géraud Fokou Pelap on *Conception d'un framework pour la relaxation des requêtes SPARQL*, November 21st, ENSMA, Poitiers.

Fabien Gandon was:

- President HDR Fabrice Huet entitled "From HPC to Big Data: Models and Tools for Large Scale Middleware", February 15th.
- Reviewer HDR Olivier Dameron entitled "Ontology-based methods for analyzing life science data", IRISA, Université de Rennes, January 11th.
- Reviewer PhD Thesis Andrei-Nicolae Ciortea entitled "Weaving a Social Web of Things: Enabling Autonomous and Flexible Interaction in the Internet of Things", École Nationale Supérieure des Mines de Saint-Étienne and University Politehnica of Bucarest, January 14th.
- Reviewer PhD Thesis Gabriela Montoya entitled "Answering SPARQL Queries using Views", LINA, Université de Nantes Angers Le Mans, March 3rd.
- Reviewer PhD Thesis Luis Redondo Garcia, "Semantically Capturing and Representing Contextualized News Stories on the Web", Eurecom, TELECOM ParisTech, March 4th.
- Jury member PhD Thesis Mazen Alsarem entitled "Semantic Snippets via Query-Biased Ranking of Linked Data Entities", Insa Lyon, University Lyon, Villeurbanne, May 5th.
- Jury member PhD Thesis Luis Galárraga entitled "Rule Mining in Knowledge Bases", TELECOM ParisTech, September 9th.

Nhan Le Thanh was jury member for the PhD of Nourhène Alaya, *Managing The Empirical Hardness of the Ontology*, Paris 8 University, October 13rd; Cheikh Hito Kacfah Emani, *Formalisation automatique et sémantique de règles métier*, Lyon 1 University, December 1st.

Andrea Tettamanzi was reviewer for the PhD Thesis of Regina Ticona Herrera, *Towards RDF Normalization*, Université de Pau et des Pays de l'Adour, Anglet, July 6th.

He was President of the jury for the PhD Thesis of

Papa Fary Diallo, UNS, September 16th (see above); Romaric Pighetti, *Une méthode hybride pour la classification d'images à grain fin*, UNS, November 28th; Atheer Al-Najdi, *Une approche basée sur les motifs fermés pour résoudre le problème de clustering par consensus*, UNS, November 30th.

Alexandre Monnin was president of the jury of 11 Master thesis of graphic design students of ESAD Valence (Ecole supérieure d'art et de design), May. He was president of the "diplôme de fin d'études" of the same students of ESAD Valence, June.

10.3. Popularization

Catherine Faron-Zucker: Article on the Web of Data in the Interstices online journal of scientific culture [0].

Fabien Gandon:

- Les Révolutions de la Planète Web, Lycée Calmette, – Nice – April 26th.
- Retour d'expérience sur le Mooc Web Sémantique, Journée Pédagogie innovante June 6th.
- SPARKS Day: How to supervise your supervisor?
- Meeting "Alumni" with students from Insa Rouen.

[0] https://interstices.info/jcms/d_80071/le-web-de-donnees

Alexandre Monnin: Café-in (June 2) : *Transition numérique et effondrement écologique : quel monde d'après ?* Stage Maths C2+ (June 16) : same presentation as above. Invitation by the FING to address the issues of "Small Science".

11. Bibliography

Major publications by the team in recent years

[1] S. BENLAMINE, M. CHAOUACHI, S. VILLATA, E. CABRIO, C. FRASSON, F. GANDON.*Emotions in Argumentation: an Empirical Evaluation*, in "International Joint Conference on Artificial Intelligence, IJCAI 2015", Buenos Aires, Argentina, Proceedings of the Twenty-Fourth International Joint Conference on Artificial Intelligence, IJCAI 2015, July 2015, p. 156-163, https://hal.inria.fr/hal-01152966.

[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.

[3] E. CABRIO, S. VILLATA, F. GANDON.*A Support Framework for Argumentative Discussions Management in the Web*, in "ESWC - 10th International Conference on The Semantic Web: Semantics and Big Data", Montpellier, France, Lecture Notes in Computer Science, Springer, May 2013, vol. 7882, p. 412-426, Best Paper Award, https://hal.inria.fr/hal-00907877.

[4] O. CORBY, R. DIENG-KUNTZ, C. HEBERT.*A Conceptual Graph Model for W3C Resource Description Framework*, in "Conceptual Structures: Theory, Tools and Applications, Proc. of the 8th Int. Conference on Conceptual Structures (ICCS'2000)", Darmstadt, Allemagne, B. GANTER, G. W. MINEAU (editors), Springer-Verlag, LNAI n. 1867, August 13 -17 2000, p. 468-482.

[5] O. CORBY, C. FARON-ZUCKER, F. GANDON.*A Generic RDF Transformation Software and its Application to an Online Translation Service for Common Languages of Linked Data*, in "Proc. 14th International Semantic Web Conference, ISWC", Bethlehem, Pennsylvania, USA, October 2015.

[6] L. COSTABELLO, S. VILLATA, F. GANDON.*Context-Aware Access Control for RDF Graph Stores*, in "ECAI - 20th European Conference on Artificial Intelligence - 2012", Montpellier, France, August 2012, https://hal.inria.fr/hal-00724041.

[7] C. DA COSTA PEREIRA, A. G. B. TETTAMANZI.*A Syntactic Possibilistic Belief Change Operator: Theory and empirical study*, in "Web Intelligence and Agent Systems: An International Journal", 2014, vol. 12, n^{o} 2, p. 155-169 [*DOI :* 10.3233/WIA-140290], https://hal.archives-ouvertes.fr/hal-00983200.

[8] F. GANDON, C. FARON-ZUCKER, O. CORBY.*Web sémantique: comment lier données et schémas sur le Web ?*, Dunod, May 2012, ISBN: 978-2-10-057294-6.

[9] G. GOVERNATORI, A. ROTOLO, S. VILLATA, F. GANDON.*One License to Compose Them All - A Deontic Logic Approach to Data Licensing on the Web of Data*, in "ISWC - 12th International Semantic Web Conference - 2013", Sydney, Australia, Lecture Notes in Computer Science, Springer, October 2013, vol. 8218, p. 151-166, https://hal.inria.fr/hal-00907883.

[10] S. VILLATA, L. COSTABELLO, N. DELAFORGE, F. GANDON.*A Social Semantic Web Access Control Model*, in "Journal on Data Semantics", March 2013, vol. 2, n^{o} 1, p. 21-36, https://hal.inria.fr/hal-00907866.

Publications of the year

Doctoral Dissertations and Habilitation Theses

[11] P. F. DIALLO.*Sociocultural and Temporal Aspects in Ontologies for Virtual Communities*, Université Nice Sophia Antipolis [UNS] ; Université Gaston Berger - Saint-Louis, September 2016, https://hal.inria.fr/tel-01402394.

[12] Z. MENG.*Temporal and semantic analysis of richly typed social networks from user-generated content sites on the Web*, Université Nice Sophia Antipolis [UNS], November 2016, https://hal.inria.fr/tel-01402612.

Articles in International Peer-Reviewed Journal

[13] E. CABRIO, S. VILLATA, A. PALMERO APROSIO.*A RADAR for Information Reconciliation in Question Answering Systems over Linked Data*, in "Semantic Web – Interoperability, Usability, Applicability", 2016, https://hal.inria.fr/hal-01332595.

[14] P. F. DIALLO, O. CORBY, I. MIRBEL, M. LO, S. M. NDIAYE.*Ontologies-Based Platform for Sociocultural Knowledge Management*, in "Journal on Data Semantics", June 2016, 23 [*DOI :* 10.1007/s13740-016-0065-4], https://hal.inria.fr/hal-01342912.

[15] H. HALPIN, A. MONNIN.*The Decentralization of Knowledge: How Carnap and Heidegger influenced the Web*, in "First Monday", December 2016, vol. 21, n^o 12, https://hal.archives-ouvertes.fr/hal-01397931.

[16] D. LANDIVAR, A. MONNIN, E. RAMILLIEN.*Cartographier l'ontologie d'un territoire sur le web : Le cas de la Bolivie*, in "NETCOM : Réseaux, communication et territoires", May 2016, vol. 29, n^o 3/4, p. 297-324, https://hal.archives-ouvertes.fr/hal-01327060.

[17] M. THIMM, S. VILLATA, F. CERUTTI, N. OREN, H. STRASS, M. VALLATI.*Summary Report of The First International Competition on Computational Models of Argumentation*, in "AI magazine", 2016, vol. 37, n^o 1, p. 102-104, https://hal.inria.fr/hal-01332194.

Articles in National Peer-Reviewed Journal

[18] O. CORBY, C. FARON-ZUCKER.*Un language et un serveur de transformation de graphes pour le Web de données*, in "Revue des Sciences et Technologies de l'Information - Série RIA : Revue d'Intelligence Artificielle", 2016, https://hal.inria.fr/hal-01330124.

[19] F. GANDON, R. BOYER, A. MONNIN.*DBpédia.fr : retour sur la publication de données de la culture française*, in "I2D – Information, données & documents", July 2016, vol. 53, n^o 2016/2, 84, https://hal.inria.fr/hal-01342757.

[20] A. MONNIN, J. DENIS, N. DELAFORGE.*Re-Source, une archive en temps réel pour la publication et la production*, in "I2D – Information, données & documents", July 2016, vol. 53, n^o 2, 84, https://hal.inria.fr/hal-01342747.

International Conferences with Proceedings

[21] F. BARBIERI, V. BASILE, D. CROCE, M. NISSIM, N. NOVIELLI, V. PATTI.*Overview of the Evalita 2016 SENTIment POLarity Classification Task*, in "Proceedings of Third Italian Conference on Computational

Linguistics (CLiC-it 2016) & Fifth Evaluation Campaign of Natural Language Processing and Speech Tools for Italian. Final Workshop (EVALITA 2016)", Naples, Italy, December 2016, https://hal.inria.fr/hal-01414731.

[22] V. BASILE.*A Repository of Frame Instance Lexicalizations for Generation*, in "Proceedings of the 2nd International Workshop on Natural Language Generation and the Semantic Web", Edinburgh, United Kingdom, September 2016, https://hal.inria.fr/hal-01389398.

[23] P. BASILE, V. BASILE, E. CABRIO, S. VILLATA.*Argument Mining on Italian News Blogs*, in "Third Italian Conference on Computational Linguistics (CLiC-it 2016) & Fifth Evaluation Campaign of Natural Language Processing and Speech Tools for Italian. Final Workshop (EVALITA 2016)", Naples, Italy, December 2016, https://hal.inria.fr/hal-01414698.

[24] V. BASILE, E. CABRIO, F. GANDON.*Building a General Knowledge Base of Physical Objects for Robots*, in "13th International Conference, ESWC 2016", Helaklion, Greece, The Semantic Web. Latest Advances and New Domains, May 2016, Poster paper, https://hal.inria.fr/hal-01330142.

[25] V. BASILE, E. CABRIO, C. SCHON.*KNEWS: Using Logical and Lexical Semantics to Extract Knowledge from Natural Language*, in "Proceedings of the European Conference on Artificial Intelligence (ECAI) 2016 conference", The Hague, Netherlands, August 2016, https://hal.inria.fr/hal-01389390.

[26] V. BASILE, E. CABRIO, S. VILLATA, C. FRASSON, F. GANDON.*A Pragma-Semantic Analysis of the Emotion/Sentiment Relation in Debates*, in "4th International Workshop on Artificial Intelligence and Cognition", New York, United States, Proceedings of the 4th International Workshop on Artificial Intelligence and Cognition, July 2016, https://hal.inria.fr/hal-01342438.

[27] V. BASILE, S. JEBBARA, E. CABRIO, P. CIMIANO.*Populating a Knowledge Base with Object-Location Relations Using Distributional Semantics*, in "20th International Conference on Knowledge Engineering and Knowledge Management (EKAW 2016)", Bologna, Italy, November 2016, p. 34 - 50 [*DOI :* 10.1007/978-3-319-49004-5_3], https://hal.inria.fr/hal-01403909.

[28] A. BEN OTHMANE, A. G. B. TETTAMANZI, S. VILLATA, M. BUFFA, N. LE THANH.*A Multi-context Framework for Modeling an Agent-Based Recommender System*, in "8th International Conference on Agents and Artificial Intelligence (ICAART2016)", Rome, Italy, Proceedings of the 8th International Conference on Agents and Artificial Intelligence (ICAART2016), February 2016, https://hal.inria.fr/hal-01239884.

[29] A. BEN OTHMANE, A. G. B. TETTAMANZI, S. VILLATA, N. LE THANH.*A Multi-context BDI Recommender System: from Theory to Simulation*, in "Web Intelligence", Omaha, United States, 2016 IEEE/WIC/ACM International Conference on Web Intelligence, October 2016, https://hal.archives-ouvertes.fr/hal-01400997.

[30] T. BOSC, E. CABRIO, S. VILLATA.*DART: a Dataset of Arguments and their Relations on Twitter*, in "Proceedings of the 10th edition of the Language Resources and Evaluation Conference", Portoroz, Slovenia, May 2016, p. 1258-1263, https://hal.inria.fr/hal-01332336.

[31] T. BOSC, E. CABRIO, S. VILLATA.*Tweeties Squabbling: Positive and Negative Results in Applying Argument Mining on Social Media*, in "Proceedings of the 6th International Conference on Computational Models of Argument", Potsdam, Germany, September 2016, https://hal.inria.fr/hal-01332617.

[32] M. BUFFA, C. FARON ZUCKER, T. BERGERON, H. AOUZAL.*Semantic Web Technologies for improving remote visits of museums, using a mobile robot*, in "Proceedings of the ISWC 2016 Posters & Demonstrations Track co-located with 15th International Semantic Web Conference (ISWC2016)", Kobé, Japan, CEUR, October 2016, https://hal.inria.fr/hal-01400924.

[33] E. CABRIO, S. VILLATA.*Abstract Dialectical Frameworks for Text Exploration*, in "Proceedings of the 8th International Conference on Agents and Artificial Intelligence (ICAART-2016)", Rome, Italy, February 2016, https://hal.inria.fr/hal-01333347.

[34] O. CORBY, C. FARON ZUCKER, R. GAZZOTTI.*Validating Ontologies against OWL 2 Profiles with the SPARQL Template Transformation Language*, in "10th International Conference on Web Reasoning and Rule Systems (RR 2016)", Aberdeen, United Kingdom, Lecture Notes in Computer Science, Springer, September 2016, vol. 9898, https://hal.archives-ouvertes.fr/hal-01349382.

[35] M. DRAGONI, C. DA COSTA PEREIRA, A. G. B. TETTAMANZI, S. VILLATA.*SMACk: An Argumentation Framework for Opinion Mining*, in "International Joint Conference on Artificial Intelligence (IJCAI)", New York, NY, United States, S. KAMBHAMPATI (editor), Proceedings of the Twenty-Fifth International Joint Conference on Artificial Intelligence, IJCAI 2016, New York, NY, USA, 9–15 July 2016, IJCAI/AAAI Press, July 2016, p. 4242-4243, https://hal.archives-ouvertes.fr/hal-01353931.

[36] M. DRAGONI, A. G. B. TETTAMANZI, C. DA COSTA PEREIRA.*DRANZIERA: An Evaluation Protocol For Multi-Domain Opinion Mining*, in "Tenth International Conference on Language Resources and Evaluation (LREC 2016)", Portorož, Slovenia, N. CALZOLARI, K. CHOUKRI, T. DECLERCK, M. GROBELNIK, B. MAEGAARD, J. MARIANI, A. MORENO, J. ODIJK, S. PIPERIDIS (editors), Proceedings of the Tenth International Conference on Language Resources and Evaluation (LREC 2016), European Language Resources Association (ELRA), May 2016, p. 267-272, https://hal.archives-ouvertes.fr/hal-01322949.

[37] M. DRAGONI, S. VILLATA, S. TONELLI, E. CABRIO.*Enriching a Small Artwork Collection through Semantic Linking*, in "The Semantic Web. Latest Advances and New Domains - 13th International Conference ESWC 2016", Heraklion, Crete, Greece, May 2016, https://hal.inria.fr/hal-01332513.

[38] C. FARON-ZUCKER, I. PAJÓN LEYRA, K. POULIDA, A. G. B. TETTAMANZI.*Semantic Categorization of Segments of Ancient and Mediaeval Zoological Texts*, in "Second International Workshop on Semantic Web for Scientific Heritage (SW4SH 2016)", Heraklion, Greece, I. DRAELANTS, C. FARON-ZUCKER, A. MONNIN, A. ZUCKER (editors), SWASH 2016. Semantic Web for Scientific Heritage. Proceedings of the Second International Workshop on Semantic Web for Scientific Heritage, co-located with 13th Extended Semantic Web Conference (ESWC 2016), Heraklion, Greece, May 30th, 2016, Sun SITE Central Europe (CEUR), May 2016, vol. 1595, p. 59-68, https://hal.archives-ouvertes.fr/hal-01322950.

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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

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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:

1. - Architectures, systems and networks
1.1. - Architectures
1.1.6. - Cloud
1.1.7. - Peer to peer
3.1. - Data
3.3. - Data and knowledge analysis
3.5. - Social networks
3.5.2. - Recommendation systems
4. - Security and privacy
4.8. - Privacy-enhancing technologies
5. - Interaction, multimedia and robotics
5.4. - Computer vision
5.4.3. - Content retrieval

Other Research Topics and Application Domains:

1. - Life sciences
1.1. - Biology
1.1.9. - Bioinformatics
1.2. - Ecology
1.2.1. - Biodiversity
6. - IT and telecom
6.5. - 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. However, constant progress in scientific observational instruments (e.g. satellites, sensors, large hadron collider) and simulation tools (that foster in silico experimentation) creates 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 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 and statistics for 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;
- Data search, including machine learning and content-based image retrieval.

3. Research Program

3.1. 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.).

The fundamental principle behind data management is *data independence*, which enables applications and users to deal with the data at a high conceptual level while ignoring implementation details. The relational model, by resting on a strong theory (set theory and first-order logic) to provide data independence, has revolutionized data management. The major innovation of relational DBMS has been to allow data manipulation through queries expressed in a high-level (declarative) language such as SQL. Queries can then be automatically translated into optimized query plans that take advantage of underlying access methods and indices. Many other advanced capabilities have been made possible by data independence : data and metadata modeling, schema management, consistency through integrity rules and triggers, transaction support, etc.

This data independence principle has also enabled DBMS to continuously integrate new advanced capabilities such as object and XML support and to adapt to all kinds of hardware/software platforms from very small smart devices (smart phone, PDA, smart card, etc.) to very large computers (multiprocessor, cluster, etc.) in distributed environments. For a long time, the research focus was on providing advanced database capabilities with good performance, for both transaction processing and decision support applications. And the main objective was to support all these capabilities within a single DBMS.

The problems of scientific data management (massive scale, complexity and heterogeneity) go well beyond the traditional context of DBMS. To address them, we capitalize on scientific foundations in closely related domains: distributed data management, cloud data management, big data, big data integration, scientific workflows, data analytics and search.

3.2. Distributed Data Management

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) [12]. 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 [8] 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. Popular examples of P2P systems such as Gnutella and BitTorrent 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.

3.3. Cloud Data Management

Cloud computing encompasses on demand, reliable services provided over the Internet (typically represented as a cloud) with easy access to virtually infinite computing, storage and networking resources. Through very simple Web interfaces and at small incremental cost, users can outsource complex tasks, such as data storage, system administration, or application deployment, to very large data centers operated by cloud providers. However, cloud computing has some drawbacks and not all applications are good candidates for being "cloudified". The major concern is w.r.t. data security and privacy, and trust in the provider (which may use no so trustful providers to operate). One earlier criticism of cloud computing was that customers get locked in proprietary clouds. It is true that most clouds are proprietary and there are no standards for cloud interoperability.

There is much more variety in cloud data than in scientific data since there are many different kinds of customers (individuals, samll companies, large corporations, etc.). However, we can identify common features. Cloud data can be very large, unstructured (e.g. text-based) or semi-structured, and typically append-only (with rare updates). And cloud users and application developers may be in high numbers, but not DBMS experts.

3.4. 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.

3.5. 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.

3.6. 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.

3.7. Data Search

Technologies for searching information in scientific data have relied on relational DBMS or text-based indexing methods. However, content-based information retrieval has progressed much in the last decade, with much impact on search engines. Rather than restricting the search to the use of metadata, content-based methods index, search and browse digital objects by means of signatures that describe their content. Such methods have been intensively studied in the multimedia community to allow searching massive amounts of multimedia documents that are created every day (e.g. 99% of web data are audio-visual content with very sparse metadata). Scalable content-based methods have been proposed for searching objects in large image collections or detecting copies in huge video archives. Besides multimedia contents, content-based information retrieval methods have expanded their scope to deal with more diverse data such as medical images, 3D models or even molecular data. Potential applications in scientific data management are numerous. First, to allow searching within huge collections of scientific images (earth observation, medical images, botanical images, biology images, etc.) or browsing large datasets of experimental data (e.g. multisensor data, molecular data or instrumental data). However, scalability remains a major issue, involving complex algorithms (such as similarity search, clustering or supervised retrieval), in high dimensional spaces (up to millions of dimensions) with complex metrics (Lp, Kernels, sets intersections, edit distances, etc.). Most of these algorithms have linear, quadratic or even cubic complexities so that their use at large scale is not affordable without major breakthroughs. In Zenith, we investigate the following challenges:

- **High-dimensional similarity search**. Whereas many indexing methods were designed in the last 20 years to efficiently retrieve multidimensional data with relatively small dimensions, high-dimensional data are challenged by the well-known curse of dimensionality . Only recently have some methods appeared that allow approximate Nearest Neighbors queries in sub-linear time, in particular, Locality Sensitive Hashing methods that offer new theoretical insights in high-dimensional Euclidean spaces and random projections. But there are still challenging issues such as efficient similarity search in any kernel or metric spaces, efficient construction of k-nearest neighbor graphs (k-NNG) or relational similarity queries.
- **Large-scale supervised retrieval**. Supervised retrieval aims at retrieving relevant objects in a dataset by providing some positive and/or negative training samples. Toward this goal, Support Vector Machines (SVM) offer the possibility to construct generalized, non-linear predictors in high-dimensional spaces using small training sets. The prediction time complexity of these methods is usually linear in dataset size. Allowing hyperplane similarity queries in sub-linear time is for example a challenging research issue. A symmetric problem in supervised retrieval consists in retrieving the most relevant object categories that might contain a given query object, providing huge labeled datasets (up to millions of classes and billions of objects) and very few objects per category (from 1 to 100 objects). SVM methods that are formulated as quadratic programming with cubic training time complexity and quadratic space complexity are clearly not usable. Promising solutions include hybrid supervised-unsupervised methods and supervised hashing methods.
- **Distributed content-based retrieval**. Distributed content-based retrieval methods appear as a promising solution to manage masses of data distributed over large networks, in particular when the data cannot be centralized for privacy or cost reasons, which is often the case in scientific social networks. However, current methods are limited to very simple similarity search paradigms. In Zenith, we consider more advanced distributed content-based retrieval and mining methods such as k-NNG construction, large-scale supervised retrieval or multi-source clustering.

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) through our international collaborations (e.g. in Brazil).

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 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.
- **Biology 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 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 days), at different sites and at different scales ranging from small tissue samples until the entire plant. Analyzing such big data creates new challenges for data management and data integration.

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

- The Pl@ntNet application, developed by Zenith and its partners, is enjoying a huge success: more than 2.7M downloads as in November 2016 in 150 countries; the number of users doubles every 6 months; tens of thousands of users each day, 12% being professionnals in agriculture or education.
- Alexis Joly and his collaborators of the Pl@ntNet project have been awarded the prize “La Recherche 2016” organized by the French magazine La Recherche for the article [2].

6. New Software and Platforms

6.1. Pl@ntNet

Participants: Antoine Affouard, Jean-Christophe Lombardo, Hervé Goëau, Alexis Joly [contact].

Pl@ntNet is an image sharing and retrieval application for the identification of plants. It is developed in the context of the Floris'tic project that involves Inria, CIRAD, INRA, IRD and Tela Botanica. The key feature of the iOS and Android front ends is to help identifying plant species from photographs, through a server-side visual search engine. Since its first release in march 2013 on the apple store, the application has been downloaded by 3M users in more than 170 countries, with between 15,000 and 50,000 active users daily. The collaborative training set that allows the content-based identification is continuously enriched by the users of the application and the members of Tela Botanica social network. At the time of writing, it includes about 300K images covering more than 10K species in the world (and about 60% of the West European flora).

6.2. The Plant Game: crowdsourced plants identification

Participants: Maximilien Servajean, Alexis Joly [contact], Antoine Affouard.

URL: http://theplantgame.com/

The Plant Game is a participatory game whose purpose is the production of large masses of taxonomic data to improve our knowledge of biodiversity. The objective is to learn botany with fun and participate to a large citizen sciences project in biodiversity. The game relies on consistent research contributions in scalable crowdsourcing models and algorithms that can deal with thousands of complex classes such as plant species. 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. The first public version of the game was released in july 2015. As of today, about 22K players are registered and produce hundreds of new validated plant observations per day. The accuracy of the produced taxonomic tags is about 94%, which is quite impressive considering the fact that a majority of users are beginners when they start playing.

6.3. Smart'Flore

Participants: Antoine Affouard [contact], Alexis Joly, Hervé Goëau.

URL: http://otmedia.lirmm.fr/

Smart'Flore is an Android mobile application for the discovery of the surrounding vegetal biodiversity. It has three main features: (i) the geo-based exploration of the world's largest repository of biodiversity occurrences (GBIF, http://www.gbif.org/), (ii) the exploration of virtual botanical trails (created offline through a dedicated web application hosted by TelaBotanica NGO) and (iii) the access to a variety of information about the plants. Smart'Flore is the first mobile app in the world making use of the GBIF web services which makes it a remarkable and possibly highly visible realization. The first public version of the application was released in may 2016. Since then, it has been downloaded by more than 22K users and the daily number of sessions is about 250.

6.4. Snoop & SnoopIm

Participants: Alexis Joly, Julien Champ, Jean-Christophe Lombardo.

URL: http://otmedia.lirmm.fr/

Snoop is a generalist C++ library dedicated to high-dimensional data management and efficient similarity search. Its main features are dimension reduction, high-dimensional feature vector hashing, approximate k-nearest neighbors search and Hamming embedding. Snoop is a refactoring of a previous library called PMH developed jointly with INA. SnoopIm is a content-based image search engine built on top of Snoop that allows retrieving small visual patterns or objects in large collections of pictures. The software is used as the visual search engine of the Pl@ntNet applications and it is used in several other contexts, including a logo retrieval application in collaboration with INA, a whale's individuals matching application in collaboration with the CetaMada NGO, and a hieroglyph recognition application in collaboration with the Egyptology department of University Montpellier 3.

6.5. MultiSite-Rec

Participants: Mohamed Reda Bouadjenek, Florent Masseglia, Esther Pacitti.

Recommender systems are used as a mean to supply users with content that may be of interest to them. They have become a popular research topic, where many aspects and dimensions have been studied to make them more accurate and effective. In practice, recommender systems suffer from cold-start problems. However, users use many online services, which can provide information about their interest and the content of items (e.g. Google search engine, Facebook, Twitter, etc.). These services may be valuable data sources, which supply information to help a recommender system in modeling users and items' preferences, and thus, make the recommender system more precise. Moreover, these data sources are distributed, and geographically distant from each other, which raise many research problems and challenges to design a distributed recommendation algorithm. MultiSite-Rec is a distributed collaborative filtering algorithm, which exploits and combine these multiple and heterogeneous data sources to improve the recommendation quality.

6.6. Chiaroscuro

Participants: Tristan Allard, Florent Masseglia, Esther Pacitti.

URL: http://people.irisa.fr/Tristan.Allard/chiaroscuro/

Chiaroscuro is a software developped in the context of a research contract with EDF. It aims at clustering time series with privacy preserving guarantees. It is a distributed system, working in a P2P environment. It is used by the team for experiments and by EDF as a proof-of-concept. Chiaroscuro is the first software for that purpose. It is written in Java. The distributed algorithm implemented in Chiaroscuro has been filed by EDF in a patent (with Inria and University of Montpellier)

6.7. LogMagnet

Participant: Florent Masseglia.

URL: https://team.inria.fr/zenith/software/LogMagnet

LogMagnet is a software for analyzing streaming data, and in particular log data. Log data usually arrive in the form of lines containing activities of human or machines. In the case of human activities, it may be the behavior on a Web site or the usage of an application. In the case of machines, such log may contain the activities of software and hardware components (say, for each node of a computing cluster, the calls to system functions or some hardware alerts). Analyzing such data is often difficult and crucial in the meanwhile. LogMagnet allows to summarize this data, and to provide a first analysis as a clustering. This summary may also be exploited as easily as the original data.

6.8. FP-Hadoop

Participants: Reza Akbarinia, Patrick Valduriez.

https://gforge.inria.fr/plugins/mediawiki/wiki/fp-hadoop

FP-Hadoop is an extension of Hadoop that efficiently deals with the problem of data skew in MapReduce jobs. 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, by using a scheduling strategy.

6.9. CloudMdsQL Compiler

Participants: Carlyna Bondiombouy, Boyan Kolev, Oleksandra Levchenko, Patrick Valduriez.

URL: http://cloudmdsql.gforge.inria.fr

The CloudMdsQL (Cloud Multi-datastore Query Language) compiler 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, as well as Spark/HDF in the context of the CoherentPaaS European project.

6.10. AgroLD

Participants: Pierre Larmande, Patrick Valduriez.

URL: http://www.agrold.org

Agronomic Linked Data (AgroLD) is a portal to help bioinformatics and domain experts exploiting the homogenized data models towards efficiently generating research hypotheses. AgroLD is an RDF knowledge base that is designed to integrate data from various publicly available plant centric data sources and ontologies, using Web Ontology Language (OWL) and the SPARQL Query Language (SPARQL).

6.11. SciFloware

Participants: Benjamin Billet, Didier Parigot.

URL: http://www-sop.inria.fr/members/Didier.Parigot/pmwiki/Scifloware

SciFloware is an action of technology development (ADT Inria) with the goal of developing a middleware for the execution of scientific workflows in a distributed and parallel way. It capitalizes on our experience with SON 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.

7. New Results

7.1. Data Integration

7.1.1. CloudMdsQL, a query language for heterogeneous data stores

Participants: Carlyna Bondiombouy, Boyan Kolev, Oleksandra Levchenko, Patrick Valduriez.

In the context of the CoherentPaaS European project, we have developped the Cloud Multi-datastore Query Language (CloudMdsQL), and its query engine. CloudMdsQL is a functional SQL-like language, capable of querying multiple heterogeneous data stores, e.g. relational, NoSQL or HDFS) [21]. The major innovation is that a CloudMdsQL query can exploit the full power of the local data stores, by simply allowing some local data store native queries to be called as functions, and at the same time be optimized. In [42], we demonstrate CloudMdsQL on two use cases each involving four diverse data stores (graph, document, relational, and key-value) with its corresponding CloudMdsQL queries. The query execution flows are visualized by an embedded real-time monitoring subsystem. In [17], we extend CloudMdsQL to allowing the ad-hoc usage of user defined map/filter/reduce operators in combination with traditional SQL statements, to integrate relational data and big data stored in HDFS and accessed by a data processing framework like Spark. Our experimental validation with several different data stores and representative queries [43] demonstrates the usability of the query language and the benefits from query optimization.

7.1.2. Agronomic Linked Data

Participant: Pierre Larmande.

Agronomic Linked Data (AgroLD) [30], [55], [54] is a knowledge system that exploits Semantic Web technology to integrate information on plant species widely studied by the agronomic research community. The objective is to provide the community with a platform for domain specific knowledge, capable of answering complex biological questions and thus facilitating the formulation of new hypotheses. The conceptual framework is based on well-established ontologies in plant sciences such as Gene Ontology, Sequence Ontology, Plant Ontology and Plant Environment Ontology. AgroLD version 1 consists of 50 million knowledge statements (i.e. RDF triples), which will grow in the subsequent versions to provide the required critical mass for hypotheses generation.

AgroLD relyes on AgroPortal [40], a reference ontology repository for the agronomi domain that features ontology hosting and search visualization with services for semantically annotating data with the ontologies. We used the AgroPortal Annotator web service to annotate more than 50 datasets and produced 22% additional triples validated manually. We also developed a dedicated AgroLD vocabulary that bridges the gap between these references ontologies and formalizes their mappings.

7.2. Data Management

7.2.1. Scalable Query Processing with Big Data

Participants: Reza Akbarinia, Patrick Valduriez.

In [22], we extend the popular Hadoop framework to deal efficiently with skewed MapReduce jobs. We extend the MapReduce programming model to allow the collaboration of reduce workers on processing the values of an intermediate key, without affecting the correctness of the final results. In FP-Hadoop, the reduce function is replaced by two functions: intermediate reduce and final reduce. There are three phases, each phase corresponding to one of the functions: map, intermediate reduce and final reduce phases. In the intermediate reduce phase, the function, which usually includes the main load of reducing in MapReduce jobs, is executed by reduce workers in a collaborative way, even if all values belong to only one intermediate key. This allows performing a big part of the reducing work by using the computing resources of all workers, even in case of highly skewed data. We implemented a prototype of FP-Hadoop by modifying Hadoop's code, and conducted extensive experiments over synthetic and real datasets. The results show that FP-Hadoop makes MapReduce job processing much faster and more parallel, and can efficiently deal with skewed data. We achieve excellent performance gains compared to native Hadoop, e.g. more than 10 times in reduce time and 5 times in total execution time.

7.2.2. Management of Simulation Data

Participant: Patrick Valduriez.

Supported by increasingly efficient HPC infrastructures , numerical simulations are rapidly expanding to fields such as oil and gas, medicine and meteorology. As simulations become more precise and cover longer periods of time, they may produce files with terabytes of data that need to be efficiently analyzed. In [24], we investigate techniques for managing such data using an array DBMS. We take advantage of multidimensional arrays that nicely models the dimensions and variables used in numerical simulations.We propose efficient techniques to map coordinate values in numerical simulations to evenly distributed cells in array chunks with the use of equi-depth histograms and space-filling curves. We implemented our techniques in SciDB and, through experiments over real-world data, compared them with two other approaches: row-store and column-store DBMS. The results indicate that multidimensional arrays and column-stores are much faster than a traditional row-store system for queries over a larger amount of simulation data. They also help identifying the scenarios where array DBMSs are most efficient, and those where they are outperformed by column-stores.

7.3. Scientific Workflows

7.3.1. A Scientific Workflow Infrastructure for Plant Phenomics

Participants: Didier Parigot, Patrick Valduriez.

Plant phenotyping consists in the observation of physical and biochemical traits of plant genotypes in response to environmental conditions. There are many challenges, in particular in the context of climate change and food security. High-throughput platforms have been introduced to observe the dynamic growth of a large number of plants in different environmental conditions. Instead of considering a few genotypes at a time (as it is the case when phenomic traits are measured manually), such platforms make it possible to use completely new kinds of approaches. However, the datasets produced by such widely instrumented platforms are huge, constantly augmenting and produced by increasingly complex experiments, reaching a point where distributed computation is mandatory to extract knowledge from data.

In[25], we introduce InfraPhenoGrid,an infrastructure to efficiently manage datasets produced by the PhenoArch plant phenomics platform in the context of the French Phenome Project. Our solution consists in deploying scientific workflows on a grid using a middle-ware to pilot workflow executions. Our approach is user-friendly in the sense that despite the intrinsic complexity of the infrastructure, running scientific workflows and understanding results obtained (using provenance information) is kept as simple as possible for end-users.

7.3.2. Managing Scientific Workflows in Multisite Cloud

Participants: Ji Liu, Esther Pacitti, Patrick Valduriez.

A cloud is typically made of several sites (or data centers), each with its own resources and data. Thus, it becomes important to be able to execute big scientific workflows at multiple cloud sites because of geographical distribution of data or available resources. Therefore, a major problem is how to execute a SWf in a multisite cloud, while reducing execution time and monetary cost. In [23], we propose a general solution based on multi-objective scheduling in order to execute SWfs in a multisite cloud. The solution includes a multi-objective cost model with execution time and monetary cost, a Single Site Virtual Machine (VM) Provisioning approach (SSVP) and ActGreedy, a multisite scheduling approach. We present an experimental evaluation, based on the execution of the SciEvol workflow in Microsoft Azure cloud. The results reveal that our scheduling approach significantly outperforms two adapted baseline algorithms and the scheduling time is reasonable compared with genetic and brute-force algorithms.

In [46], we present a hybrid decentralized/distributed model for handling frequently accessed metadata in a multisite cloud. We couple our model with a scientific workflow management system (SWfMS) to validate and tune its applicability to different real-life scientific scenarios. We show that efficient management of hot metadata improves the performance of SWfMS, reducing the workflow execution time up to 50% for highly parallel jobs and avoiding unnecessary cold metadata operations.

7.3.3. Online Input Data Reduction in Scientific Workflows

Participant: Patrick Valduriez.

Many scientific workflows are data-intensive and must be iteratively executed for large input sets of data elements. Reducing input data is a powerful way to reduce overall execution time in such workflows. When this is accomplished online (i.e., without requiring users to stop execution to reduce the data and resume execution), it can save much time and user interactions can integrate within workflow execution. Then, a major problem is to determine which subset of the input data should be removed. Other related problems include guaranteeing that the workflow system will maintain execution and data consistent after reduction, and keeping track of how users interacted with execution. In [48], we adopt the approach “human-in-the-loop” for scientific workflows by enabling users to steer the workflow execution and reduce input elements from datasets at runtime. We propose an adaptive monitoring approach that combines workflow provenance monitoring and computational steering to support users in analyzing the evolution of key parameters and determining which subset of the data should be removed. We also extend a provenance data model to keep track of user interactions when users reduce data at runtime. In our experimental validation, we develop a test case from the oil and gas industry, using a 936-cores cluster. The results on our parameter sweep test case show that the user interactions for online data reduction yield a 37% reduction of execution time.

7.4. Data Analytics

7.4.1. Parallel Mining of Maximally Informative k-Itemsets

Participants: Saber Salah, 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 [26], [52], we address the problem of parallel mining of maximally informative k-itemsets (miki) based on joint entropy. We propose PHIKS (Parallel Highly Informative K-itemSets) a highly scalable, parallel mining algorithm. PHIKS renders the mining process of large scale databases (up to terabytes of data) succinct and effective. Its mining process is made up of only two compact, yet efficient parallel jobs. PHIKS uses a clever heuristic approach to efficiently estimate the joint entropies of miki having different sizes with very low upper bound error rate, which dramatically reduces the runtime process. PHIKS has been extensively evaluated using massive, real-world datasets. Our experimental results confirm the effectiveness of our approach by the significant scale-up obtained with high featuresets length and hundreds of millions of objects.

7.4.2. Chiaroscuro

Participants: Tristan Allard, Florent Masseglia, Esther Pacitti.

New personal data fields are currently emerging due to the proliferation of on-body/at-home sensors connected to personal devices. However, strong privacy concerns prevent individuals to benefit from large-scale analytics that could be performed on this fine-grain highly sensitive wealth of data. In [32] we propose a demonstration of Chiaroscuro, a complete solution for clustering massively-distributed sensitive personal data while guaranteeing their privacy. The demonstration scenario highlights the affordability of the *privacy vs. quality* and *privacy vs. performance* tradeoffs by dissecting the inner working of Chiaroscuro, exposing the results obtained by the individuals participating in the clustering process, and illustrating possible uses.

7.5. Data Search

7.5.1. Spatially Localized Visual Dictionary Learning

Participants: Valentin Leveau, Alexis Joly, Patrick Valduriez.

In [44], we devise new representation learning algorithms that overcome the lack of interpretability of classical visual models. We introduce a new recursive visual patch selection technique built on top of a Shared Nearest Neighbors embedding method. The main contribution is to drastically reduce the high-dimensionality of such over-complete representation using a recursive feature elimination method. We show that the number of spatial atoms of the representation can be reduced by up to two orders of magnitude without degrading much the encoded information. The resulting representations are shown to provide competitive image classification performance with the state-of-the-art while enabling to learn highly interpretable visual models. This contribution was the last one in Valentin Leveau's PhD on Nearest Neighbor Representations [13].

7.5.2. Crowdsourcing Biodiversity Monitoring

Participants: Alexis Joly, Julien Champ, Herve Goeau, Jean-Christophe Lombardo.

Large scale biodiversity monitoring is essential for sustainable development (earth stewardship). With the recent advances in computer vision, we see the emergence of more and more effective identification tools, thus allowing large-scale data collection platforms such as the popular Pl@ntNet initiative to reuse interaction data. Although it covers only a fraction of the world flora, this platform has been used by more than 300K people who produce tens of thousands of validated plant observations each year. This explicitly shared and validated data is only the tip of the iceberg. The real potential relies on the millions of raw image queries submitted by the users of the mobile application for which there is no human validation. People make such requests to get information on a plant along a hike or something they find in their garden but do not know anything about. Allowing the exploitation of such contents in a fully automatic way could scale up the world-wide collection of implicit plant observations by several orders of magnitude, thus complementing the explicit monitoring efforts.

In [37], we first survey existing automated plant identification systems through a five-year synthesis of the PlantCLEF benchmark and an impact study of the Pl@ntNet platform. We then focus on the implicit monitoring scenario and discuss related research challenges at the frontier of computer science and biodiversity studies. Finally, we discuss the results of a preliminary study focused on implicit monitoring of invasive species in mobile search logs. We show that the results are promising while there is room for improvement before being able to automatically share implicit observations within international platforms.

7.5.3. Unsupervised Individual Whales Identification

Participants: Alexis Joly, Jean-Christophe Lombardo.

Identifying organisms is critical in accessing information related to the ecology of species. Unfortunately, this is difficult to achieve due to the level of expertise necessary to correctly identify and record living organisms. To bridge this gap, a lot of work has been done on the development of automated species identification tools such as image-based plant identification or audio recordings-based bird identification. Yet, for some groups, it is preferable to monitor the organisms at the individual level rather than at the species level. The automation of this problem has received much less attention than species identification.

In [39], we address the specific scenario of discovering humpack whale individuals in a large collection of pictures collected by nature observers. The process is initiated from scratch, without any knowledge on the number of individuals and without any training samples of these individuals. Thus, the problem is entirely unsupervised. To address it, we set up and experimented a scalable fine-grained matching system, which allows discovering small rigid visual patterns in highly cluttered backgrounds. The evaluation was conducted in blind in the context of the LifeCLEF evaluation campaign. Results show that the proposed system provides very promising results with regard to the difficulty of the task but that there is still room for improvements to reach higher recall and precision in the future. This work was done in collaboration with the Cetamada NGO.

7.5.4. Evaluation of Biodiversity Identification and Search Techniques

Participants: Alexis Joly, Herve Goeau, Jean-Christophe Lombardo.

We ran a new edition of the LifeCLEF evaluation campaign in the context of the CLEF international research forum. We did share a new subset of the data produced by the Pl@ntNet platform and set up three new challenges: one related to the identification of plant images in open-world data streams, one related to bird sounds identification in soundscapes and one related to the visual-based identification of fish species and whales individuals. More than 150 research groups registered to at least one of the challenges and about 15 of them crossed the finish lines by running their system on the final test data. A synthesis of the results is published in the LifeCLEF 2016 overview paper [38] and more detailed analyses are provided in research reports for the plant task [35] and the bird task [36].

7.5.5. Crowdsourcing Thousands of Specialized Labels using a Bayesian Approach

Participants: Maximilien Servajean, Alexis Joly, Dennis Shasha, Julien Champ, Esther Pacitti.

Large-scale annotated corpora are often at the basis of huge performance gaps in machine learning based content analysis. However, the availability of such datasets has only been made possible thanks to the great amount of human labeling efforts leveraged by popular crowdsourcing and social media platforms. When the labels correspond to well known concepts, it is straightforward to train the annotators by giving a few examples with known answers. It is also straightforward to judge the quality of their labels. But neither is true with thousands of complex domain specific labels. Training on all labels is infeasible and the quality of an annotator's judgements may be vastly different for some subsets of labels than for others. This paper proposes a set of data-driven algorithms to (i) train annotators on how to disambiguate automatically labelled images, (ii) evaluate the quality of annotators' answers on new test items and (iii) weight predictions. The algorithms adapt to the skills of each annotator both in the questions asked and the weights given to their answers. The underlying judgements are Bayesian, based on adaptive priors. We measure the benefits of these algorithms by a live user experiment related to image-based plant identification involving around 1,000 people [47] (at the origin of ThePlantGame, see Software section). The proposed methods yield huge gains in annotation accuracy. While a standard user could correctly label around 2% of our data, this goes up to 80% with machine learning assisted training and almost 90% when doing a weighted combination of several annotators' labels.

8. Bilateral Contracts and Grants with Industry

8.1. Microsoft ZcloudFlow (2013-2017)

Participants: Jalexis Joly, Ji Liu, Esther Pacitti, Patrick Valduriez.

ZcloudFlow is a project in collaboration with the Kerdata team in the context of the Joint Inria–Microsoft Research Centre. It addresses the problem of advanced data storage and processing for supporting scientific workflows in the cloud. The goal is to design and implement a framework for the efficient processing of scientific workflows in clouds. The validation is performed using synthetic benchmarks and real-life applications from bioinformatics on the Microsoft Azure cloud with multiple sites.

8.2. Triton I-lab (2014-2016)

Participants: Benjamin Billet, Didier Parigot.

Triton is a common Inria lab (i-lab) between Zenith and Beepeers (http://beepeers.com/) to work on a scalable platform for developing social networks in mobile/Web environments. The main objective of this project is to design and implement a new architecture for Beepeers applications to scale up to high numbers of participants. The new platform relyes on our SON middleware and NoSQL graph databases.

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. Florent Masseglia co-heads the theme on scientific data.

9.1.2. Institute of Computational Biology (IBC), Montpellier

URL: http://www.ibc-montpellier.fr

IBC is a 5 year project (2012-2017) 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. PIA (Projets Investissements d'Avenir

9.2.1.1. PIA Floris'Tic (2015-2018), 430Keuro.

Participants: Julien Champ, 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.

9.2.2. Others

9.2.2.1. CIFRE INA/Inria (2013-2016), 100Keuros

Participants: Alexis Joly, Valentin Leveau, Patrick Valduriez.

This contract with INA allows funding a 3-years PhD (Valentin Leveau). This PhD addresses research challenges related to large-scale supervised content-based retrieval in distributed environments.

9.2.2.2. 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 Projects

9.3.1.1. CoherentPaaS

Participants: Carlyna Bondiombouy, Boyan Kolev, Oleksandra Levchenko, Patrick Valduriez.

Project title: A Coherent and Rich Platform as a Service with a Common Programming Model
Instrument: Integrated Project
Duration: 2013 - 2016
Total funding: 5 Meuros (Zenith: 500Keuros)
Coordinator: U. Madrid, Spain
Partner: FORTH (Greece), ICCS (Greece), INESC (Portugal) and the companies MonetDB (Netherlands), QuartetFS (France), Sparsity (Spain), Neurocom (Greece), Portugal Telecom (Portugal).
Inria contact: Patrick Valduriez

CoherentPaaS has been developing a PaaS that incorporates a rich and diverse set of cloud data management technologies, including NoSQL data stores, such as key-value data stores and graph databases, SQL data stores, such as in-memory and column-oriented databases, hybrid systems, such as SQL engines on top on key-value data stores, and complex event processing data management systems. It uses a common query language to unify the programming models of all systems under a single paradigm and provides holistic coherence across data stores using a scalable, transactional management system. CoherentPaaS will dramatically reduce the effort required to build and the quality of the resulting cloud applications using multiple cloud data management technologies via a single query language, a uniform programming model, and ACID-based global transactional semantics. CoherentPaaS will design and build a working prototype and will validate the proposed technology with real-life use cases. In this project, Zenith is in charge of designing the CloudMdsQL language and implementing its compiler/optimizer and query engine.

9.3.1.2. HPC4E

Participants: Reza Akbarinia, Florent Masseglia, Esther Pacitti, Patrick Valduriez.

Project title: High Performance Computing for Energy
Instrument: H2020
Duration: 2015 - 2017
Total funding: 2 Meuros
Coordinator: Barcelona Supercomputing Center (BSC), Spain
Partner: Europe: Inria, Lancaster University, Centro de Investigaciones Energéticas Medioambientales y Tecnológicas, Repsol S.A., Iberdrola Renovables Energía S.A., Total S.A. Brazil: COPPE/Universidade Federal de Rio de Janeiro, LNCC, Instituto Tecnológico de Aeronáutica (ITA), Universidade Federal do Rio Grande do Sul, Universidade Federal de Pernambuco, Petrobras.
Inria contact: Patrick Valduriez

The main objective is to develop high performance simulation tools that can help the energy industry to respond future energy demands and also to carbon-related environmental issues using HPC systems. The project also aims at improving the usage of energy using HPC tools by acting at many levels of the energy chain for different energy sources. Another objective is to improve the cooperation between energy industries from EU and Brazil. The project includes relevant energy industral partners from Brazil (Petrobras) and EU (Repsol and Total as O&G industries), which benefit from the project's results. A last objective is to improve the cooperation between the leading research centres in EU and Brazil in HPC applied to energy. This includes sharing supercomputing infrastructures between Brazil and EU. In this project, Zenith is working on Big Data management and analysis of numerical simulations.

9.3.1.3. 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: (1) 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; (2) 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; (3) 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. MUSIC

Title: MUltiSite Cloud (MUSIC) data management
Inria principal investigator: Esther Pacitti
International Partner):

Laboratorio Nacional de Computaçao Cientifica, Petropolis (Brazil) - Fabio Porto

Universidade Federal do Rio de Janeiro (Brazil) - Alvaro Coutinho and Marta Mattoso

Universidade Federal Fluminense, Niteroi (Brazil) - Daniel Oliveira

Centro Federal de Educa cao Tecnologica, Rio de Janeiro (Brazil) - Eduardo Ogasawara

Duration: 2014 - 2016
See also: https://team.inria.fr/zenith/projects/international-projects/music/

By centralizing all data in a large-scale data center, the cloud significantly simplifies the task of system administration. But for scientific data, where different organizations may have their own data centers, a distributed (multisite) cloud model where each site is visible from outside, is needed. The main objective of this research and scientific collaboration is to develop a multisite cloud architecture for managing and analyzing scientific data, including support for heterogeneous data; distributed scientific workflows, and complex big data analysis. The resulting architecture will enable scalable data management infrastructures that can be used to host a variety of scientific applications that benefit from computing, storage, and networking resources that span multiple data centers.

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)
- Asia: National Univ. of Singapore (Beng Chin Ooi, Stéphane Bressan), Wonkwang University, Korea (Kwangjin Park)
- Europe: Univ. of Madrid (Ricardo Jiménez-Periz), UPC Barcelona (Josep Lluis Larriba Pey), HES-SO (Henning Müller), University of Catania (Concetto Spampinatto), The Open University (Stefan Rüger)
- North Africa: Univ. of Tunis (Sadok Ben-Yahia)
- 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

We are involved in LifeCLEF lab, a self-organized research platform whose main mission is to promote research, innovation, and development of computer-assisted identification of living organisms. It was initiated by Alexis Joly in 2014 in collaboration with several European colleagues: Henning Müller (CH), Robert B Fisher (UK), Andreas Rauber (AU), Concetto Spampinato (IT), Hervé Glotin (FR). Each year, LifeCLEF releases large-scale experimental data covering tens of thousands of species (plants images, birds audio recordings and fish sub-marine videos). About 100-150 research groups register each year to get access to it and tens of them submit reports describing their conducted research (published in CEUR-WS proceedings). Results are then synthesized and further analyzed in joint research papers.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

Marta Mattoso (UFRJ, Brazil) gave a seminar on "“Exploratory Analysis of Raw Data Files through Dataflows” in march.

Jose Mario Carranza Rojas (PhD student, Technologico de Costa-Rica) spent two days per week in the team in the context of a 4 months internship at the Montpellier research lab AMAP in the context of the Floris'Tic project).

10. Dissemination

10.1. Scientific Animation

Editorial board of scientific journals:

- VLDB Journal: P. Valduriez.
- Journal of Transactions on Large Scale Data and Knowledge Centered Systems: R. Akbarinia and E. Pacitti are guest editors of a special issue on data management in internet of things (IoT).
- Distributed and Parallel Databases, Kluwer Academic Publishers: E. Pacitti, P. Valduriez.
- Internet and Databases: Web Information Systems, Kluwer Academic Publishers: P. Valduriez.
- Journal of Information and Data Management, Brazilian Computer Society Special Interest Group on Databases: P. Valduriez.
- Book series "Data Centric Systems and Applications" (Springer): P. Valduriez.
- Multimedia Tools and Applications: A. Joly.

Organization of conferences and workshops:

- Alexis Joly was the chair of the LifeCLEF 2016 international workshop [0] dedicated to multimedia biodiversity data management, Evora, sept. 2016
- Alexis Joly was in the organizing committee of the Floris'tic national workshop held in Montpellier, nov. 2016 (http://floristic.org/8-nov-2016)

[0] http://www.imageclef.org/lifeclef/2016

Conference program committees :

- ACM SIGMOD Conf. 2016: R. Akbarinia, 2017: F. Masseglia
- IEEE Int. Conf. on Data Engineering (ICDE) 2016: R. Akbarinia, E. Pacitti, P. Valduriez (area chair)
- VLDB Joint Workshop on Big Data Open-Source Systems (BOSS) / Polyglot: P. Valduriez (co-chair)
- DataDiversityConvergence workshop, 6th International Conference on Cloud Computing and Services Science (CLOSER 2016): P. Valduriez (co-chair)
- Int. Conf. on Extending DataBase Technologies (EDBT), 2017: E. Pacitti
- 2nd Workshop on Big Data and Data Mining Challenges on IoT and Pervasive Systems (BigD2M), 2016: E. Pacitti
- International Conference and Labs of the Evaluation Forum (CLEF), 2016: A. Joly
- ACM International Conference on Multimedia Retrieval (ICMR), 2016: A. Joly
- IEEE International Conference on Image Processing (ICIP), 2016: A. Joly
- ACM Multimedia conference (ACMMM), 2016: A. Joly
- Int. work.Multimedia Analysis and Retrieval for Multimodal Interactions (MARMI): A. Joly
- Int. Conf. on Scientific and Statistical Database Management (SSDBM), 2016: A. Joly
- European Conf. on Computer Vision (ECCV), 2016: A. Joly
- VLDB 2017: F. Masseglia
- IEEE Int. Conf. on Data Mining, 2016: F. Masseglia
- ACM Symposium on Applied Computing 2017: F. Masseglia
- Pacific-Asia Conf. on Knowledge Discovery and Data Mining (PAKDD) 2017: F. Masseglia
- IEEE Int. Conf. on Data Science and Advanced Analytics (DSAA), 2016: F. Masseglia
- Int. Symposium on Information Management and Big Data (SimBig), 2016: F. Masseglia
- Int. Conf. on Data Science, Technology and Applications (DATA), 2016: F. Masseglia

Reviewing in international journals :

- Distributed and Parallel Databases: R. Akbarinia
- ACM Transactions on Database Systems (TODS): A. Joly
- IEEE Transactions on Pattern Analysis and Machine Intelligence (PAMI): A. Joly
- IEEE Transactions on Knowledge and Data Engineering: R. Akbarinia
- 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 Transactions on Knowledge and Data Engineering (TKDE): F. Masseglia

Other activities (national):

- Alexis Joly gave invited talks in national events: Inria scientific days (https://journees-scientifiques2016.inria.fr/), INRA-Inria days (https://journees.inra.fr/maths-info2016), Award ceremony of « La Recherche 2016 » (http://www.leprixlarecherche.com/).
- P. Valduriez is the scientific manager for the Latin America zone at Inria Direction des Relations Internationales (DRI), Member of the Scientific Committee at Agence Nationale de la Recherche (ANR) - Défi 7 Information and communication society and Member of the Scientific Committee of the BDA conference.
- F. Masseglia gave an invited talk at the CNRS national seminar on IST about "Publication Data Analytics" (Meudon, 10 November), and an invited talk to the DSI service of IRD on "Scientific Data Mining" (Montpellier, 18 September). Florent also participates in the Class'Code PIA project dedicated to teaching computational thinking for professionals of education (head of the working group on the definition of fundamental notions).
- P. Valduriez gave invited talks at: "La Science des données à l'IRIT", Toulouse, april 2016, the Junior Conference on Data Science and Engineering, Paris Saclay, sept. 2016, the Orange Summer University "Innovate in IT", sept. 2016.

Other activities (international):

- Alexis Joly was a member of the scientific advisory board of the EU REVEAL project (http://revealproject.eu). He was invited by the ATC innovation lab in Athens to participate in a workshop on social media verification (http://revealproject.eu/reveal-workshop-on-16-sept-2016).
- E. Pacitti gave an invited talk at the 6th workshop on big data and analytics (WOS6), co-organized by Technicolor and Inria (http://www.bretagne-networking.org/wos6) on Experiences on Data Management Techniques for Scientific Application in Rennes, nov. 2016, and a talk at Fundação Getulio Vargas on Experiences on Data Management Techniques for Big Data in Rio de Janeiro, dec. 2016.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Most permanent members of Zenith teach at the Licence and Master degree levels at UM2.

Reza Akbarinia:

Master Research: New approaches for data storage, 9h, level M2, Faculty of Science, UM

Florent Masseglia:

Science Popularization: 4 Ph.D students, from 3 different doctoral schools are having a 30h doctoral module under Florent Masseglia's supervision.

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

Professional: XML, 10h, level M2, Orsys Formation

Alexis Joly:

Master Research: Large-scale Content-based Visual Information Retrieval, 3h, level M2, Faculty of Science, UM

10.2.2. Supervision

- PhD: Ji Liu, Multisite Management of Scientific Worflows in the Cloud, Univ. Montpellier, 3 Nov 2016, Advisors: Esther Pacitti and Patrick Valduriez
- PhD: Valentin Leveau, Spatially Consistent Nearest Neighbor Representations for Fine-Grained Classification, Univ. Montpellier, 9 Nov 2016, Advisor: Patrick Valduriez, co-advisor: Alexis Joly and Olivier Buisson
- PhD : Saber Salah, Optimizing a Cloud for Data Mining Primitives, Univ. Montpellier, 20 Apr 2016 Advisor: Florent Masseglia, co-advisor: Reza Akbarinia
- PhD in progress: Christophe Botella, Lareg-scale Species Distribution Modelling based on crowd-srouced image streams, started Oct 2016, Univ. Montpellier, 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: Mehdi Zitouni Closed Pattern Mining in a Massively Distributed Environment started sept. 2014, Univ. Tunis, Advisor: Florent Masseglia, co-advisor: Reza Akbarinia
- PhD in progress : Djamel-Edine Yagoubi, Indexing Time Series in a Massively Distributed Environment, started oct. 2014, Univ. Montpellier, Advisors: Florent Masseglia and Patrick Valduriez, co-advisor: Reza Akbarinia
- PhD in progress : Sakina Mahboubi, Privacy Preserving Query Processing in Clouds, started oct. 2015, Univ. Montpellier, Advisor: Patrick Valduriez, co-advisor: Reza Akbarinia
- PhD in progress: Khadidja Meguelati, Massively Distributed Clustering, started Oct 2016, Univ. Montpellier, Advisor: Florent Masseglia, co-advisor : Nadine Hilgert (INRA)

10.2.3. Juries

Members of the team participated to the following PhD committees:

- A. Joly: Zongyuan Ge (Queensland University of Technology), Amel Tuama Alhussainy (Univ. of Montpellier)
- E. Pacitti: Saliha Lallali (UVSQ), Nupur Mittal (Univ. Rennes 1)
- P. Valduriez: Damien Graux (Univ. Grenoble)
- F. Masseglia: Hadi Hashem (Telecom SudParis), Manuel Pozo (CNAM), Martin Kirchgessner (Univ. Grenoble)

10.3. Popularization

F. Masseglia is now “Chargé de mission pour la médiation scientifique Inria” and heads Inria’s national network of colleagues involved in science popularization.

Zenith has major contributions to science popularization, as follows.

10.3.1. Code Teaching for Kids

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).

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.

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, 12 people have been trained. He is also a member of the management board of "Les Petits Débrouillards" in Languedoc-Roussillon and the scientific responsible for school visits in the LIRMM laboratory.

10.3.2. Science Outreach

In the context of the Floris'tic project, A. Joly participates regularly to the set up of popularization, educational and citizen science actions in France (with schools, cities, parks, 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 planned to be used in a large-scale program in the Czech republic that is being finalized (in 40 classrooms). 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. The Inria movie “Pl@ntNet, the application that helps people identify plants” enjoyed about 350 thousand views on Youtube.

10.3.3. Events

Zenith participated to the following events:

- F. Masseglia co-organized and co-animated the Inria's stand at “La fête de la science”, Montpellier, held by Genopolys (a science village).
- F. Masseglia is member of the project selection committee for “La fête de la science” in Montpellier.
- M. Servajean and A. Joly animated a stand at “La fête de la science”, Montpellier, held by the LIRMM laboratory.
- A. Joly and J. Champ participated to the set-up of a Pl@ntNet demo within the French pavillon at the Universal Exposition hold in Milan (about 2M visitors on the French pavillon).
- As a member of the organizing committee of the Floris'tic project, A. Joly participated to several popularization and educational actions in collaboration with Tela Botanica NGO (cities, parks, schools, etc.).
- P. Valduriez published an article in Interstices on “the data in question” [58].

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