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Sophia Antipolis - Méditerranée

FIELD

Activity Report 2016

Section New Results

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AOSTE Project-Team

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recursive expressivity of CCSL, by encoding the dynamics of Petri Nets with inhibitor arcs in our framework (still unpublished).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].

AROMATH Project-Team

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).

DATASHAPE Team

7. New Results

7.1. Algorithmic aspects of topological and geometric data analysis

7.1.1. An Efficient Representation for Filtrations of Simplicial Complexes

Participant: Jean-Daniel Boissonnat.

In collaboration with Karthik C.S. (Department of Computer Science and Applied Mathematics, Weizmann Institute of Science, Israel)

A filtration over a simplicial complex K is an ordering of the simplices of K such that all prefixes in the ordering are subcomplexes of K. Filtrations are at the core of Persistent Homology, a major tool in Topological Data Analysis. In order to represent the filtration of a simplicial complex, the entire filtration can be appended to any data structure that explicitly stores all the simplices of the complex such as the Hasse diagram or the recently introduced Simplex Tree by Boissonnat and Maria [Algorithmica '14]. However, with the popularity of various computational methods that need to handle simplicial complexes, and with the rapidly increasing size of the complexes, the task of finding a compact data structure that can still support efficient queries is of great interest.

This direction has been recently pursued for the case of maintaining simplicial complexes. For instance, Boissonnat et al. [SoCG '15] considered storing the simplices that are maximal for the inclusion and Attali et al. [IJCGA '12] considered storing the simplices that block the expansion of the complex. Nevertheless, so far there has been no data structure that compactly stores the *filtration* of a simplicial complex, while also allowing the efficient implementation of basic operations on the complex.

In this work [22], we propose a new data structure called the Critical Simplex Diagram (CSD) which is a variant of our work on the Simplex Array List (SAL) introduced in [SoCG '15]. Our data structure allows to store in a compact way the filtration of a simplicial complex, and allows for the efficient implementation of a large range of basic operations. Moreover, we prove that our data structure is essentially optimal with respect to the requisite storage space. Next, we show that the CSD representation admits the following construction algorithms.

- A new *edge-deletion* algorithm for the fast construction of Flag complexes, which only depends on the number of critical simplices and the number of vertices.
- A new *matrix-parsing* algorithm to quickly construct the relaxed strong Delaunay complexes, depending only on the number of witnesses and the dimension of the complex.

7.1.2. Discretized Riemannian Delaunay triangulations

Participants: Mael Rouxel-Labbé, Mathijs Wintraecken, Jean-Daniel Boissonnat.

Anisotropic meshes are desirable for various applications, such as the numerical solving of partial differential equations and graphics. In [27], we introduce an algorithm to compute discrete approximations of Riemannian Voronoi diagrams on 2-manifolds. This is not straightforward because geodesics, shortest paths between points, and therefore distances cannot in general be computed exactly. Our implementation employs recent developments in the numerical computation of geodesic distances and is accelerated through the use of an underlying anisotropic graph structure. We give conditions that guarantee that our discrete Riemannian Voronoi diagram is combinatorially equivalent to the Riemannian Voronoi diagram and that its dual is an embedded triangulation, using both approximate geodesics and straight edges. Both the theoretical guarantees on the approximation of the Voronoi diagram and the implementation are new and provide a step towards the practical application of Riemannian Delaunay triangulations.

7.1.3. Efficient and Robust Persistent Homology for Measures

Participants: Frédéric Chazal, Steve Oudot.

In collaboration with M. Buchet (Tohoku University), D. Sheehy (Univ. Connecticut).

A new paradigm for point cloud data analysis has emerged recently, where point clouds are no longer treated as mere compact sets but rather as empirical measures. A notion of distance to such measures has been defined and shown to be stable with respect to perturbations of the measure. This distance can easily be computed pointwise in the case of a point cloud, but its sublevel-sets, which carry the geometric information about the measure, remain hard to compute or approximate. This makes it challenging to adapt many powerful techniques based on the Euclidean distance to a point cloud to the more general setting of the distance to a measure on a metric space. We propose an efficient and reliable scheme to approximate the topological structure of the family of sublevel-sets of the distance to a measure. We obtain an algorithm for approximating the persistent homology of the distance to an empirical measure that works in arbitrary metric spaces. Precise quality and complexity guarantees are given with a discussion on the behavior of our approach in practice [17].

7.1.4. Shallow Packings in Geometry

Participants: Kunal Dutta, Arijit Ghosh.

A merged paper with Ezra, Esther (School of Mathematics, Georgia Institute of Technology, Atlanta, U.S.A.)

We refine the bound on the packing number, originally shown by Haussler, for shallow geometric set systems. Specifically, let V be a finite set system defined over an n-point set X; we view V as a set of indicator vectors over the n-dimensional unit cube. A $delta$-separated set of V is a subcollection W, such that the Hamming distance between each pair $u, v \in W$ is greater than δ, where $\delta > 0$ is an integer parameter. The δ-packing number is then defined as the cardinality of the largest δ-separated subcollection of V. Haussler showed an asymptotically tight bound of $\Theta((n/delta)^d)$ on the δ-packing number if V has VC-dimension (or primal shatter dimension) d. We refine this bound for the scenario where, for any subset, $X' \subset X$ of size $m \leq n$ and for any parameter $1 \leq k \leq m$, the number of vectors of length at most k in the restriction of V to X' is only $O(m^{d_1} k^{d-d_1})$, for a fixed integer $d > 0$ and a real parameter $1 \leq d_1 \leq d$ (this generalizes the standard notion of bounded primal shatter dimension when $d_1 = d$). In this case when V is "k-shallow" (all vector lengths are at most k), we show that its δ-packing number is $O(n^{d_1} k^{d-d_1} / \delta^d)$, matching Haussler's bound for the special cases where $d_1 = d$ or $k = n$. We present two proofs, the first is an extension of Haussler's approach, and the second extends the proof of Chazelle, originally presented as a simplification for Haussler's proof. [21]

- A new *tight upper bound* for shallow-packings in δ-separated set systems of bounded primal shatter dimension.

7.1.5. On Subgraphs of Bounded Degeneracy in Hypergraphs

Participants: Kunal Dutta, Arijit Ghosh.

A k-uniform hypergraph has degeneracy bounded by d if every induced subgraph has a vertex of degree at most d. Given a k-uniform hypergraph $H = (V(H), E(H))$, we show there exists an induced subgraph of size at least

$$\sum_{v \in V(H)} \min 1, ck \left(\frac{d+1}{d_H(v)+1} \right)^{1/(k-1)},$$

where $c_k = 2^{-(1+\frac{1}{k-1})}\left(1-\frac{1}{k}\right)$ and $d_H(v)$ denotes the degree of vertex v in the hypergraph H. This extends and generalizes a result of Alon-Kahn-Seymour (Graphs and Combinatorics, 1987) for graphs, as well as a result of Dutta-Mubayi-Subramanian (SIAM Journal on Discrete Mathematics, 2012) for linear hypergraphs, to general k-uniform hypergraphs. We also generalize the results of Srinivasan and Shachnai (SIAM Journal on Discrete Mathematics, 2004) from independent sets (0-degenerate subgraphs) to d-degenerate subgraphs. We further give a simple non-probabilistic proof of the Dutta-Mubayi-Subramanian bound for linear k-uniform hypergraphs, which extends the Alon-Kahn-Seymour proof technique to hypergraphs. Our proof combines the random permutation technique of Bopanna-Caro-Wei (see e.g. The Probabilistic Method, N. Alon and J. H. Spencer; Dutta-Mubayi-Subramanian) and also Beame-Luby (SODA, 1990) together with a new local density argument which may be of independent interest. We also provide some applications in discrete geometry, and address some natural algorithmic questions. [28]

- A new algorithmic *lower bound* for largest d-degenerate subgraphs in k-uniform hypergraphs.

7.1.6. A Simple Proof of Optimal Epsilon Nets

Participants: Kunal Dutta, Arijit Ghosh.

In collaboration with Nabil Mustafa (Université Paris-Est, Laboratoire d'Informatique Gaspard-Monge, ESIEE Paris, France.)

Showing the existence of ε-nets of small size has been the subject of investigation for almost 30 years, starting from the initial breakthrough of Haussler and Welzl (1987). Following a long line of successive improvements, recent results have settled the question of the size of the smallest ε-nets for set systems as a function of their so-called shallow-cell complexity.

In this paper we give a short proof of this theorem in the space of a few elementary paragraphs, showing that it follows by combining the ε-net bound of Haussler and Welzl (1987) with a variant of Haussler's packing lemma (1991).

This implies all known cases of results on unweighted ε-nets studied for the past 30 years, starting from the result of Matoušek, Seidel and Welzl (1990) to that of Clarkson and Varadajan (2007) to that of Varadarajan (2010) and Chan, Grant, Könemann and Sharpe (2012) for the unweighted case, as well as the technical and intricate paper of Aronov, Ezra and Sharir (2010). [40]

- A new *unified proof* for all known bounds on unweighted ε-nets studied in the last 30 years.

7.1.7. Combinatorics of Set Systems with Small Shallow Cell Complexity: Optimal Bounds via Packings

Participants: Kunal Dutta, Arijit Ghosh.

In collaboration with Bruno Jartoux and Nabil Mustafa (Université Paris-Est Marne-la-Vallée, Laboratoire d'Informatique Gaspard-Monge, ESIEE Paris, France.)

The packing lemma of Haussler states that given a set system (X, R) with bounded VC dimension, if every pair of sets in R are 'far apart' (i.e., have large symmetric difference), then R cannot contain too many sets. This has turned out to be the technical foundation for many results in geometric discrepancy using the entropy method as well as recent work on set systems with bounded VC dimension. Recently it was generalized to the shallow packing lemma [Dutta-Ezra-Ghosh SoCG 2015, Mustafa DCG 2016], applying to set systems as a function of their shallow cell complexity. In this paper we present several new results and applications related to packings:

1. an optimal lower bound for shallow packings, thus settling the open question in Ezra (SODA 2014) and Dutta et al. (SoCG 2015),
2. improved bounds on Mnets, providing a combinatorial analogue to Macbeath regions in convex geometry (Annals of Mathematics, 1952),
3. simplifying and generalizing the main technical tool in Fox et al. (J. of the EMS, 2016).

Besides using the packing lemma and a combinatorial construction, our proofs combine tools from polynomial partitioning and the probabilistic method. [37]

- A new *optimal lower bound* for shallow packings.
- New *improved bounds* for M-nets - combinatorial analogs of Macbeath regions in convex geometry.

7.1.8. A new asymmetric correlation inequality for Gaussian measure

Participants: Kunal Dutta, Arijit Ghosh.

In collaboration with Nabil Mustafa (Université Paris-Est Marne-la-Vallée, Laboratoire d'Informatique Gaspard-Monge, ESIEE Paris, France.)

The Khatri-Šidák lemma says that for any Gaussian measure μ over $\mathbb{R}^n$, given a convex set K and a slab L, both symmetric about the origin, one has $\mu(K \cap L) \geq \mu(K)\mu(L)$. We state and prove a new asymmetric version of the Khatri-Šidák lemma when K is a symmetric convex body and L is a slab (not necessarily symmetric about the barycenter of K). Our result also extends that of Szarek and Werner (1999), in a special case.

- A new *asymmetric* inequality for gaussian measure. [38].

7.2. Statistical aspects of topological and geometric data analysis

7.2.1. Stability and Minimax Optimality of Tangential Delaunay Complexes for Manifold Reconstruction

Participant: Eddie Aamari.

In collaboration with C. Levrard (Univ. Paris Diderot).

we consider the problem of optimality in manifold reconstruction. A random sample $\mathbb{X}_n = \{X_1, \ldots, X_n\} \subset \mathbb{R}^D$ composed of points lying on a d-dimensional submanifold M, with or without outliers drawn in the ambient space, is observed. Based on the tangential Delaunay complex, we construct an estimator$\widehat{M}$ that is ambient isotopic and Hausdorff-close to M with high probability. $\widehat{M}$ is built from existing algorithms. In a model without outliers, we show that this estimator is asymptotically minimax optimal for the Hausdorff distance over a class of submanifolds with reach condition. Therefore, even with no a priori information on the tangent spaces of M, our estimator based on tangential Delaunay complexes is optimal. This shows that the optimal rate of convergence can be achieved through existing algorithms. A similar result is also derived in a model with outliers. A geometric interpolation result is derived, showing that the tangential Delaunay complex is stable with respect to noise and perturbations of the tangent spaces. In the process, a denoising procedure and a tangent space estimator both based on local principal component analysis (PCA) are studied [32].

7.2.2. Rates in the Central Limit Theorem and diffusion approximation via Stein's Method

Participant: Thomas Bonis.

We present a way to apply Stein's method in order to bound the Wasserstein distance between a, possibly discrete, measure and another measure assumed to be the invariant measure of a diffusion operator. We apply this construction to obtain convergence rates, in terms of p-Wasserstein distance for $p \geq 2$, in the Central Limit Theorem in dimension 1 under precise moment conditions. We also establish a similar result for the Wasserstein distance of order 2 in the multidimensional setting. In a second time, we study the convergence of stationary distributions of Markov chains in the context of diffusion approximation, with applications to density estimation from geometric random graphs and to sampling using the Langevin Monte Carlo algorithm [33].

7.2.3. Rates of Convergence for Robust Geometric Inference

Participants: Frédéric Chazal, Bertrand Michel.

In collaboration with P. Massart (Univ. Paris Sud et Inria Select team).

Distances to compact sets are widely used in the field of Topological Data Analysis for inferring geometric and topological features from point clouds. In this context, the distance to a probability measure (DTM) has been introduced by Chazal et al. as a robust alternative to the distance a compact set. In practice, the DTM can be estimated by its empirical counterpart, that is the distance to the empirical measure (DTEM). In this paper we give a tight control of the deviation of the DTEM. Our analysis relies on a local analysis of empirical processes. In particular, we show that the rate of convergence of the DTEM directly depends on the regularity at zero of a particular quantile function which contains some local information about the geometry of the support. This quantile function is the relevant quantity to describe precisely how difficult is a geometric inference problem. Several numerical experiments illustrate the convergence of the DTEM and also confirm that our bounds are tight [19].

7.2.4. Data driven estimation of Laplace-Beltrami operator

Participants: Frédéric Chazal, Bertrand Michel, Ilaria Giulini.

Approximations of Laplace-Beltrami operators on manifolds through graph Laplacians have become popular tools in data analysis and machine learning. These discretized operators usually depend on bandwidth parameters whose tuning remains a theoretical and practical problem. In this paper, we address this problem for the unnormalized graph Laplacian by establishing an oracle inequality that opens the door to a well-founded data-driven procedure for the bandwidth selection. Our approach relies on recent results by Lacour and Massart on the so-called Lepski's method [26].

7.3. Topological approach for multimodal data processing

7.3.1. Persistence-based Pooling for Shape Pose Recognition

Participants: Thomas Bonis, Frédéric Chazal, Steve Oudot, Maksim Ovsjanikov.

We propose a novel pooling approach for shape classification and recognition using the bag-of-words pipeline, based on topological persistence, a recent tool from Topological Data Analysis. Our technique extends the standard max-pooling, which summarizes the distribution of a visual feature with a single number, thereby losing any notion of spatiality. Instead, we propose to use topological persistence, and the derived persistence diagrams, to provide significantly more informative and spatially sensitive characterizations of the feature functions, which can lead to better recognition performance. Unfortunately, despite their conceptual appeal, persistence diagrams are difficult to handle, since they are not naturally represented as vectors in Euclidean space and even the standard metric, the bottleneck distance is not easy to compute. Furthermore, classical distances between diagrams, such as the bottleneck and Wasserstein distances, do not allow to build positive definite kernels that can be used for learning. To handle this issue, we provide a novel way to transform persistence diagrams into vectors, in which comparisons are trivial. Finally, we demonstrate the performance of our construction on the Non-Rigid 3D Human Models SHREC 2014 dataset, where we show that topological pooling can provide significant improvements over the standard pooling methods for the shape pose recognition within the bag-of-words pipeline [23].

7.3.2. Structure and Stability of the 1-Dimensional Mapper

Participants: Steve Oudot, Mathieu Carrière.

Given a continuous function $f : X \to \mathbb{R}$ and a cover $\mathcal{I}$ of its image by intervals, the Mapper is the nerve of a refinement of the pullback cover $f^{-1}(\mathcal{I})$. Despite its success in applications, little is known about the structure and stability of this construction from a theoretical point of view. As a pixelized version of the Reeb graph of f, it is expected to capture a subset of its features (branches, holes), depending on how the interval cover is positioned with respect to the critical values of the function. Its stability should also depend on this positioning. We propose a theoretical framework that relates the structure of the Mapper to the one of the Reeb graph, making it possible to predict which features will be present and which will be absent in the Mapper given the function and the cover, and for each feature, to quantify its degree of (in-)stability. Using this framework, we can derive guarantees on the structure of the Mapper, on its stability, and on its convergence to the Reeb graph as the granularity of the cover $\mathcal{I}$ goes to zero [25].

7.3.3. Decomposition of exact pfd persistence bimodules

Participants: Steve Oudot, Jérémy Cochoy.

We characterize the class of persistence modules indexed over $\mathbb{R}^2$ that are decomposable into summands whose support have the shape of a *block*—i.e. a horizontal band, a vertical band, an upper-right quadrant, or a lower-left quadrant. Assuming the modules are *pointwise finite-dimensional* (pfd), we show that they are decomposable into block summands if and only if they satisfy a certain local property called *exactness*. Our proof follows the same scheme as the proof of decomposition for pfd persistence modules indexed over $\mathbb{R}$, yet it departs from it at key stages due to the product order not being a total order on $\mathbb{R}^2$, which leaves some important gaps open. These gaps are filled in using more direct arguments. Our work is motivated primarily by the stability theory for zigzags and interlevel-sets persistence modules, in which block-decomposable bimodules play a key part. Our results allow us to drop some of the conditions under which that theory holds, in particular the Morse-type conditions [39].

7.4. Experimental research and software development

7.4.1. Topological Microstructure Analysis Using Persistence Landscapes

Participant: Paweł Dłotko.

In collaboration with T. Wanner (George Mason University).

Phase separation mechanisms can produce a variety of complicated and intricate microstructures, which often can be difficult to characterize in a quantitative way. In recent years, a number of novel topological metrics for microstructures have been proposed, which measure essential connectivity information and are based on techniques from algebraic topology. Such metrics are inherently computable using computational homology, provided the microstructures are discretized using a thresholding process. However, while in many cases the thresholding is straightforward, noise and measurement errors can lead to misleading metric values. In such situations, persistence landscapes have been proposed as a natural topology metric. Common to all of these approaches is the enormous data reduction, which passes from complicated patterns to discrete information. It is therefore natural to wonder what type of information is actually retained by the topology. In the present paper, we demonstrate that averaged persistence landscapes can be used to recover central system information in the Cahn-Hilliard theory of phase separation. More precisely, we show that topological information of evolving microstructures alone suffices to accurately detect both concentration information and the actual decomposition stage of a data snapshot. Considering that persistent homology only measures discrete connectivity information, regardless of the size of the topological features, these results indicate that the system parameters in a phase separation process affect the topology considerably more than anticipated. We believe that the methods discussed in this paper could provide a valuable tool for relating experimental data to model simulations [36].

7.4.2. Topological analysis of the connectome of digital reconstructions of neural microcircuits

Participant: Paweł Dłotko.

In collaboration with K. Hess, L. Ran, H. Markram, E. Muller, M. Nolte, M. Reimann, M. Scolamiero, K. Turner (Univ. of Aberden, EPFL, Brain and Mind Institute).

A first draft digital reconstruction and simulation of a microcircuit of neurons in the neocortex of a two-week-old rat was recently published. Since graph-theoretical methods may not be sufficient to understand the immense complexity of the network formed by the neurons and their connections, we explored whether application of methods from algebraic topology can provide a novel and useful perspective on the structural and functional organization of the microcircuit. Structural topological analysis revealed that directed graphs representing the connectivity between neurons are significantly different from random graphs and that there exist an enormous number of simplicial complexes of different dimensions representing all-to-all connections within different sets of neurons, the most extreme motif of neuronal clustering reported so far in the brain. Functional topological analysis based on data from simulations confirmed the interest of a new approach to studying the relationship between the structure of the connectome and its emergent functions. In particular, functional responses to different stimuli can readily be distinguished by topological methods. This study represents the first algebraic topological analysis of connectomics data from neural microcircuits and shows promise for general applications in network science.

7.4.3. A persistence landscapes toolbox for topological statistics

Participant: Paweł Dłotko.

In collaboration with P. Bubenik (University of Florida).

Topological data analysis provides a multiscale description of the geometry and topology of quantitative data. The persistence landscape is a topological summary that can be easily combined with tools from statistics and machine learning. We give efficient algorithms for calculating persistence landscapes, their averages, and distances between such averages. We discuss an implementation of these algorithms and some related procedures. These are intended to facilitate the combination of statistics and machine learning with topological data analysis. We present an experiment showing that the low-dimensional persistence landscapes of points sampled from spheres (and boxes) of varying dimensions differ.

7.5. Miscellaneous

7.5.1. Monotone Simultaneous Paths Embeddings in $\mathbb{R}^d$

Participant: Marc Glisse.

In collaboration with O. Devillers and S. Lazard (Inria Nancy), David Bremner (University of New Brunswick, Canada), Giuseppe Liotta (University of Perugia, Italy), Tamara Mchedlidze (KIT, Germany), Sue Whitesides (University of Victoria, Canada), Stephen Wismath (University of Lethbridge, Canada).

We study[24] the following problem: Given k paths that share the same vertex set, is there a simultaneous geometric embedding of these paths such that each individual drawing is monotone in some direction? We prove that for any dimension $d \geq 2$, there is a set of $d+1$ paths that does not admit a monotone simultaneous geometric embedding.

MARELLE Project-Team

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.

ACUMES Project-Team

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.

APICS Project-Team

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 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.

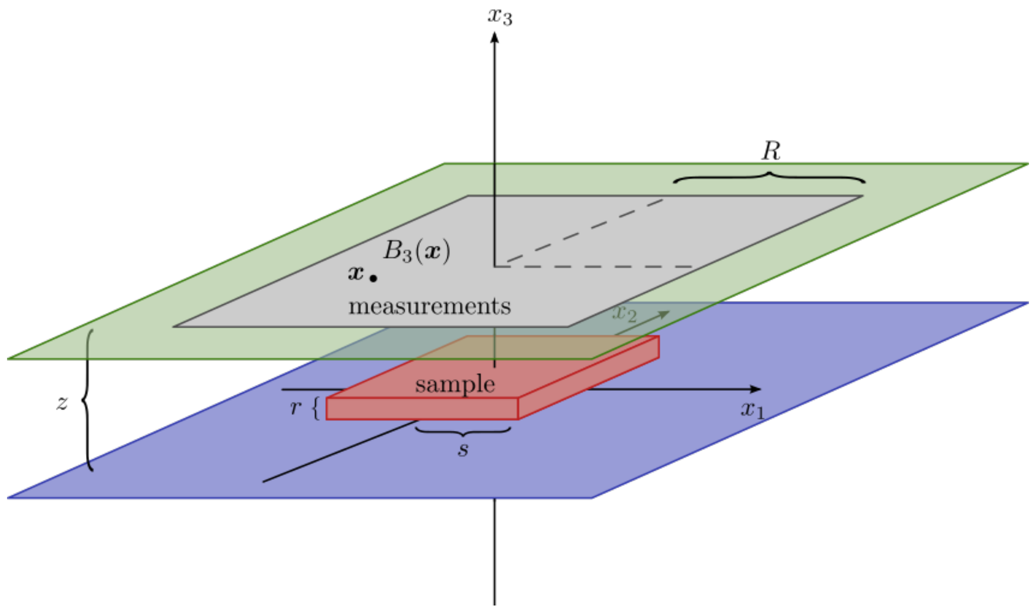


Figure 3. Schematic view of the experimental setup

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 $\|\nabla\phi_\epsilon\|_2 \le M$. 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.

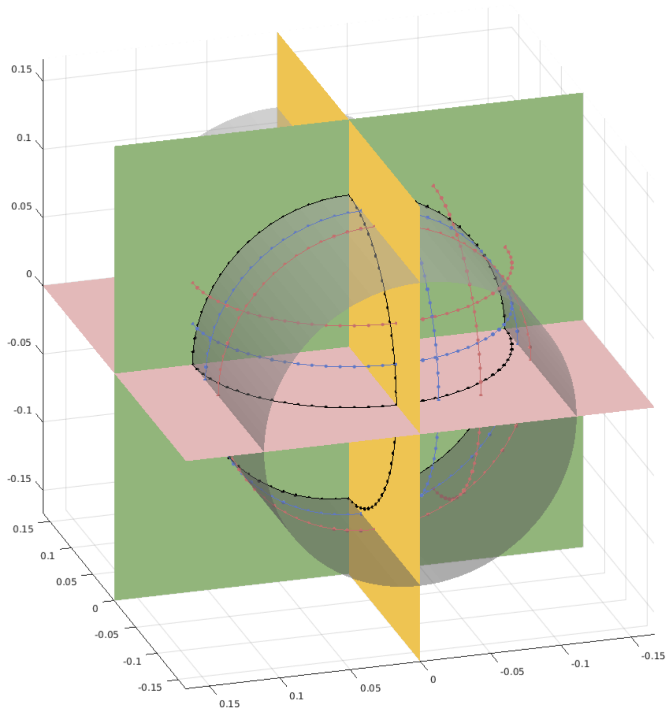


Figure 4. Typical measurements obtained with the instrument of Cerege. Measurements of the field are performed on nine circles, given as sections of three cylinders. On each circle, only one component of the field is measured: the component B_h along the axis of the corresponding cylinder (blue points),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

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

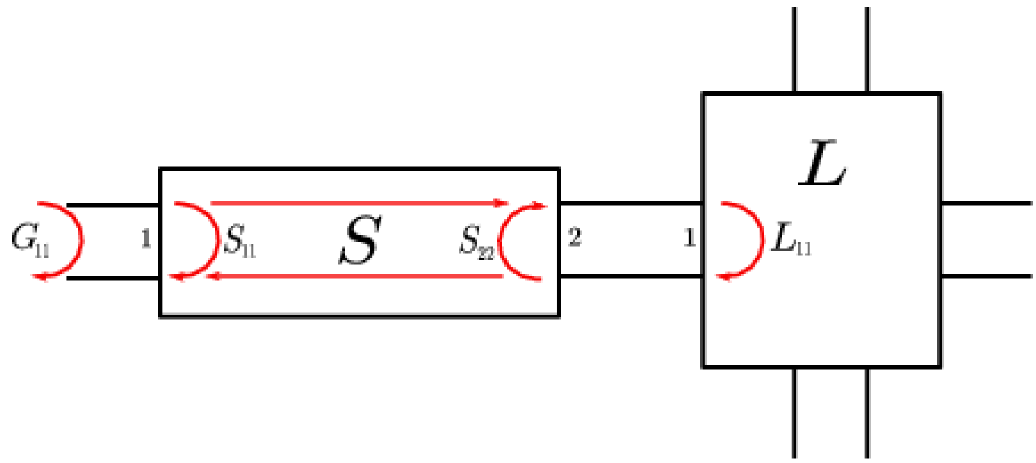


Figure 5. Filter plugged on a system with reflexion coefficient L_{11}

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.

ECUADOR Project-Team

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.

MCTAO Project-Team

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.

NACHOS Project-Team

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.

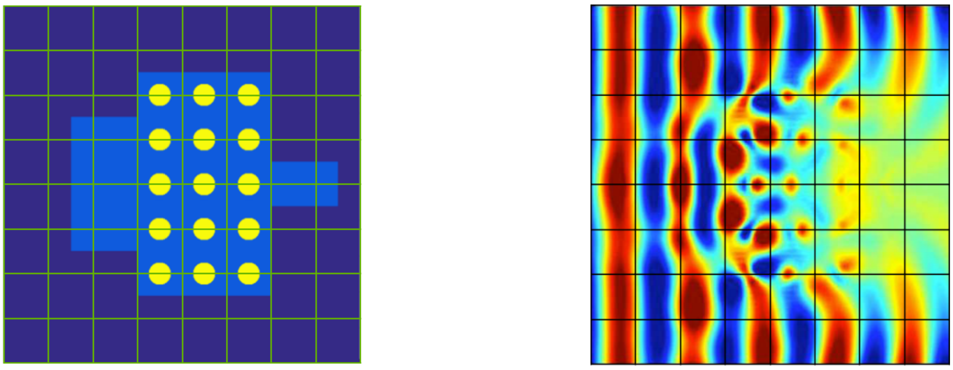


Figure 4. Light propagation in a photonic crystal structure using a MHM-DGTD method for solving the 2D Maxwell's equations. Left: quadrangular mesh. Right: contour lines of the amplitude of the electric field.

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.

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

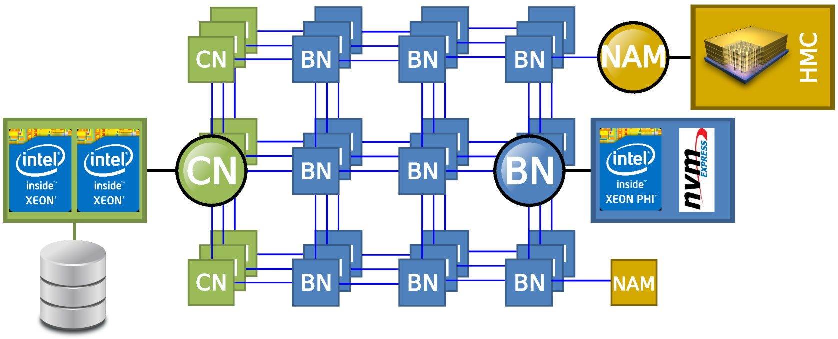


Figure 5. DEEP-ER hardware architecture sketch.

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.

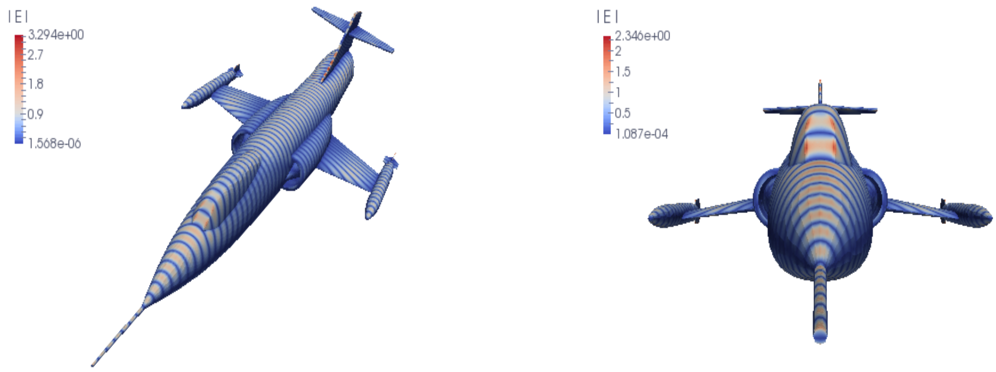


Figure 6. Scattering of a plane wave by a Lockheed F-104 Starfighter. Contour lines of the amplitude of the electric field. Simulations are performed with a HDG scheme based on a cubic interpolation of the electric and magnetic field unknowns, combined with a PDE-based domain decomposition solver.

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.

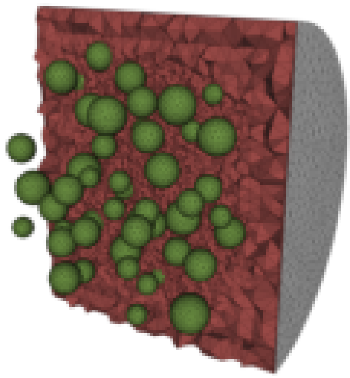


Figure 7. Unstructured tetrahdral mesh of a nanostructured optical fiber core.

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).

6.4.3. Dielectric reflectarrays

Participants: Maciej Klemm [Centre for Communications Research, University of Bristol], Stéphane Lanteri, Claire Scheid, Jonathan Viquerat.

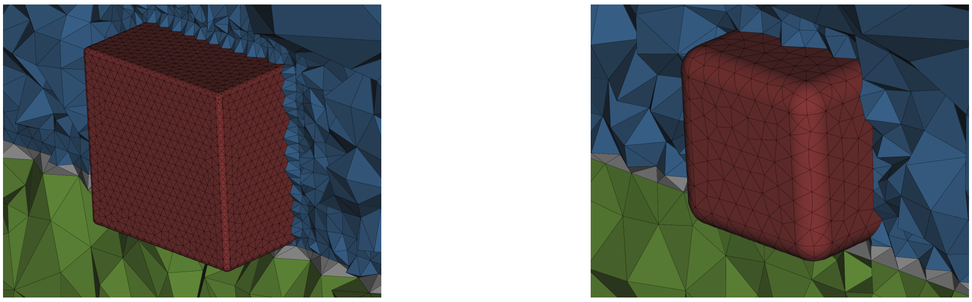
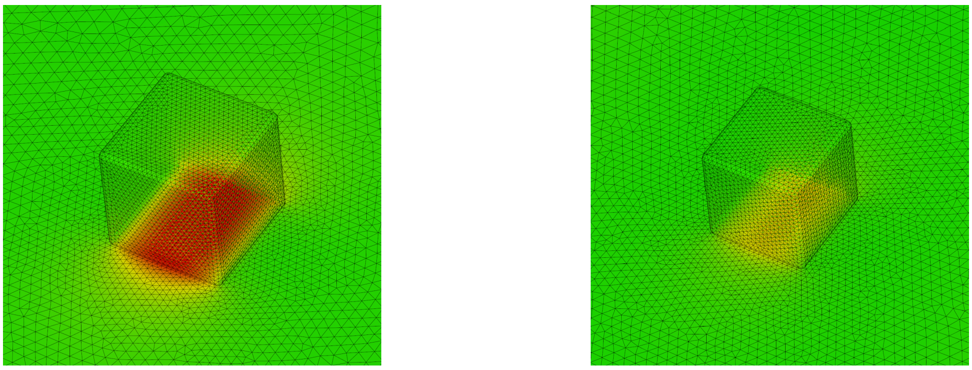


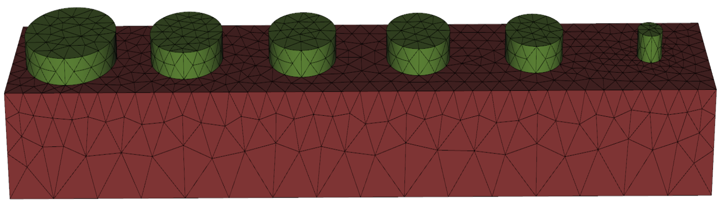
Figure 8. Meshes of rounded nanocubes with rounding radii ranging from 2 to 10 nm. Red cells correspond to the cube. The latter lies on the dielectric spacer (gray cells) and the metallic plate (green). Blue cells represent the air surrounding the device.



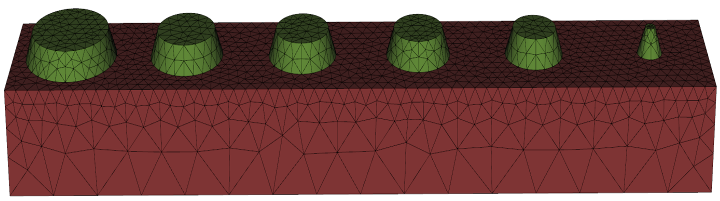
$c = 70$ nm, $\delta = 12$ nm $\qquad$ $c = 60$ nm, $\delta = 18$ nm

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.

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 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.

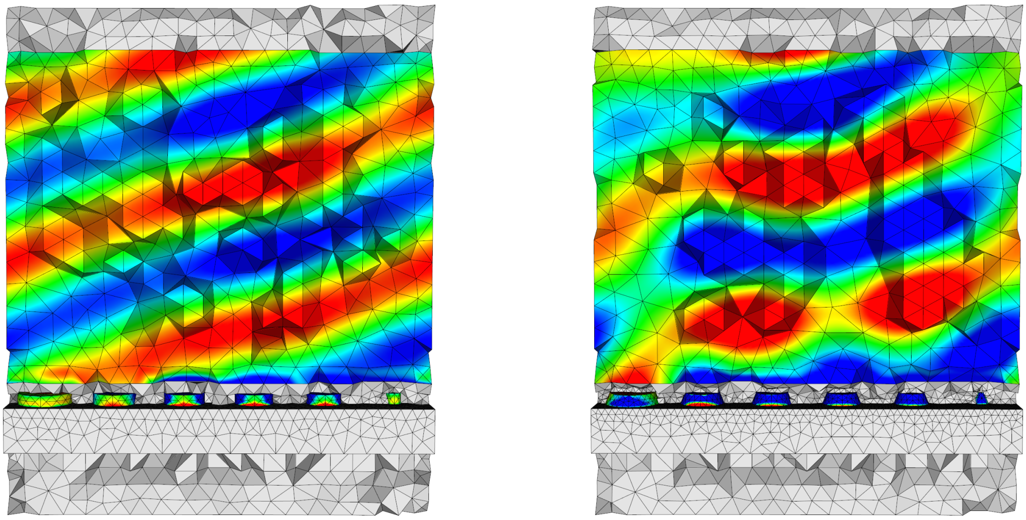


Ideal reflectarray



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 $[-1, 1]$.

TOSCA Project-Team

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.

ABS Project-Team

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.

ASCLEPIOS Project-Team

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].

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

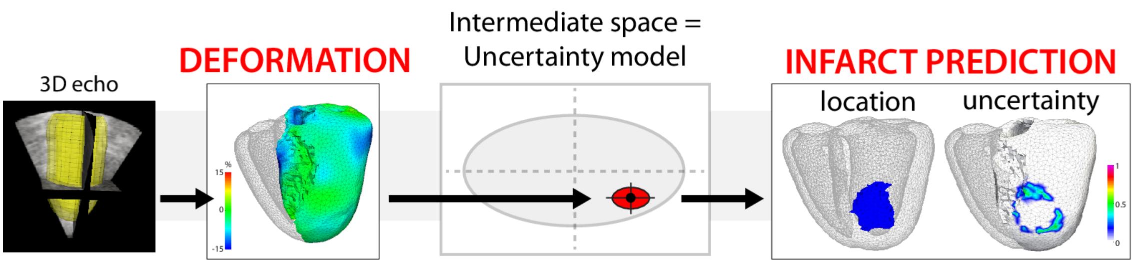


Figure 2. Overview of the proposed localization of myocardial infarct and uncertainty quantification from local wall deformation, extracted from 3D echocardiographic sequences.

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

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.

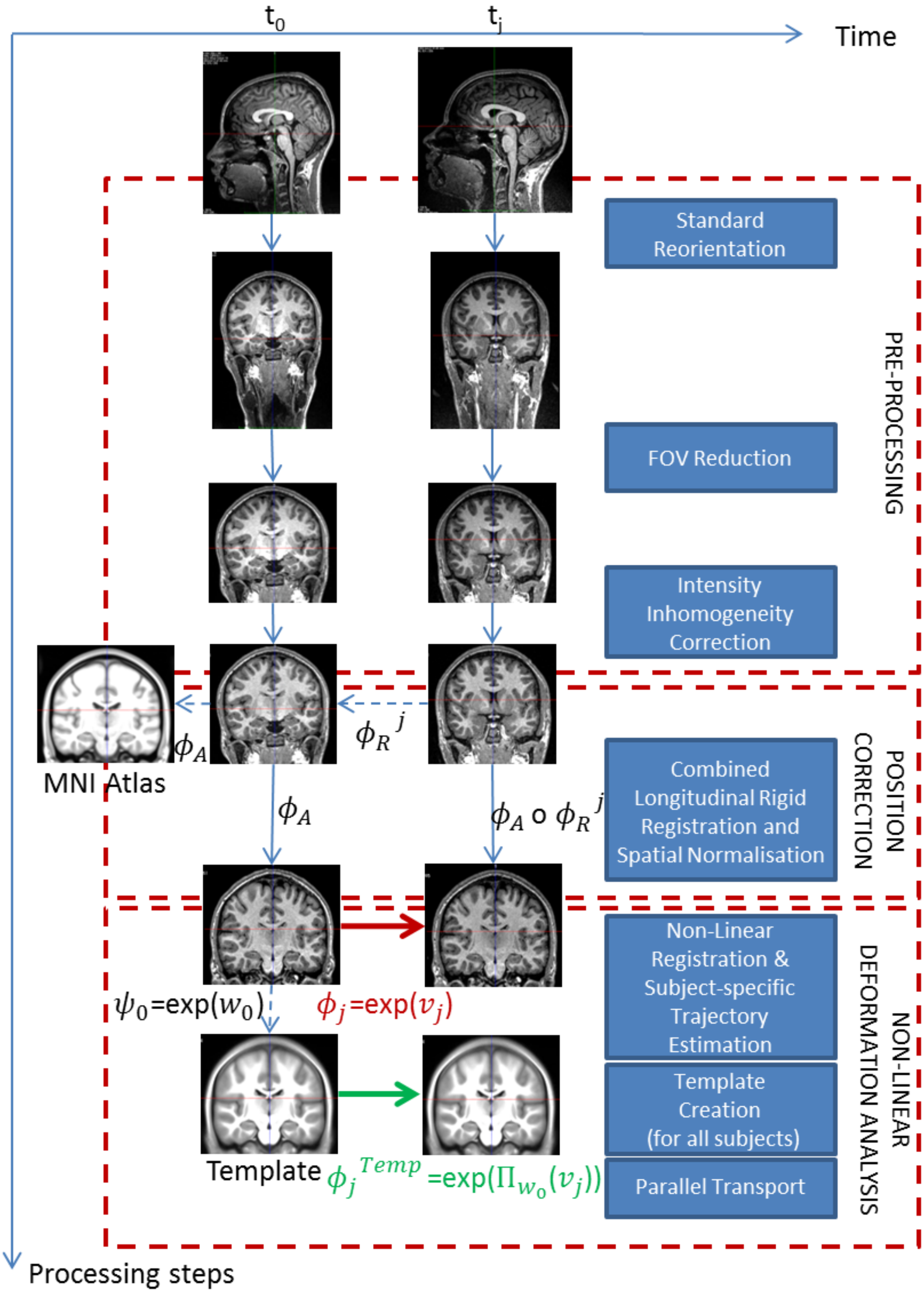


Figure 3. Processing pipeline for longitudinal analysis.

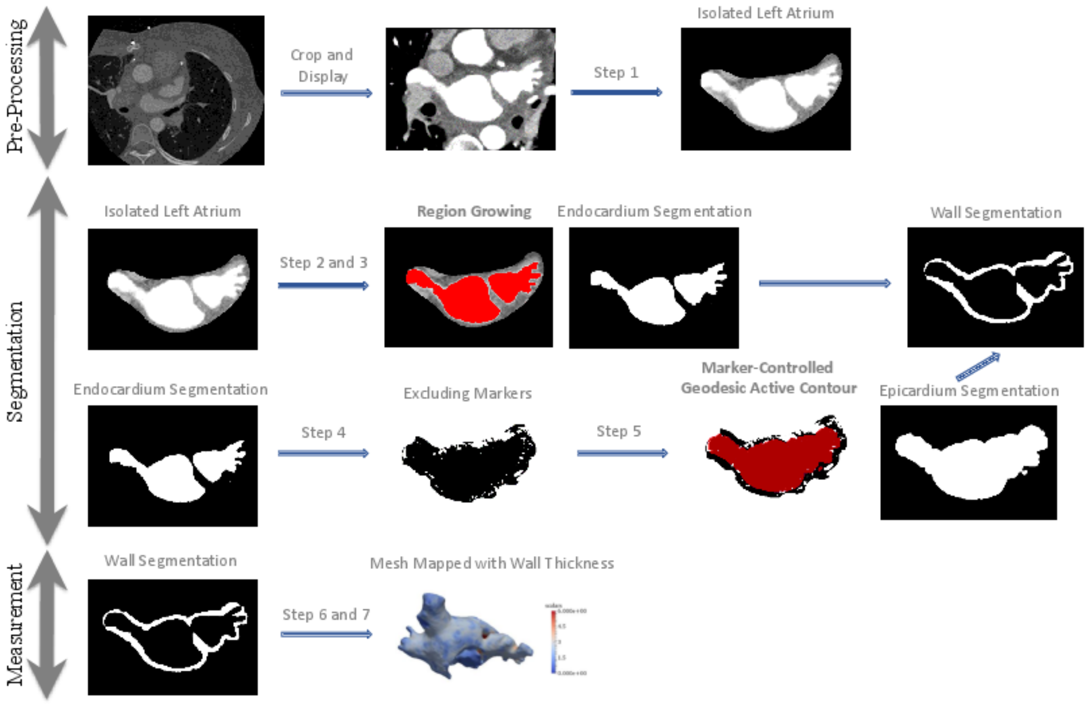


Figure 4. Flowchart of the method.

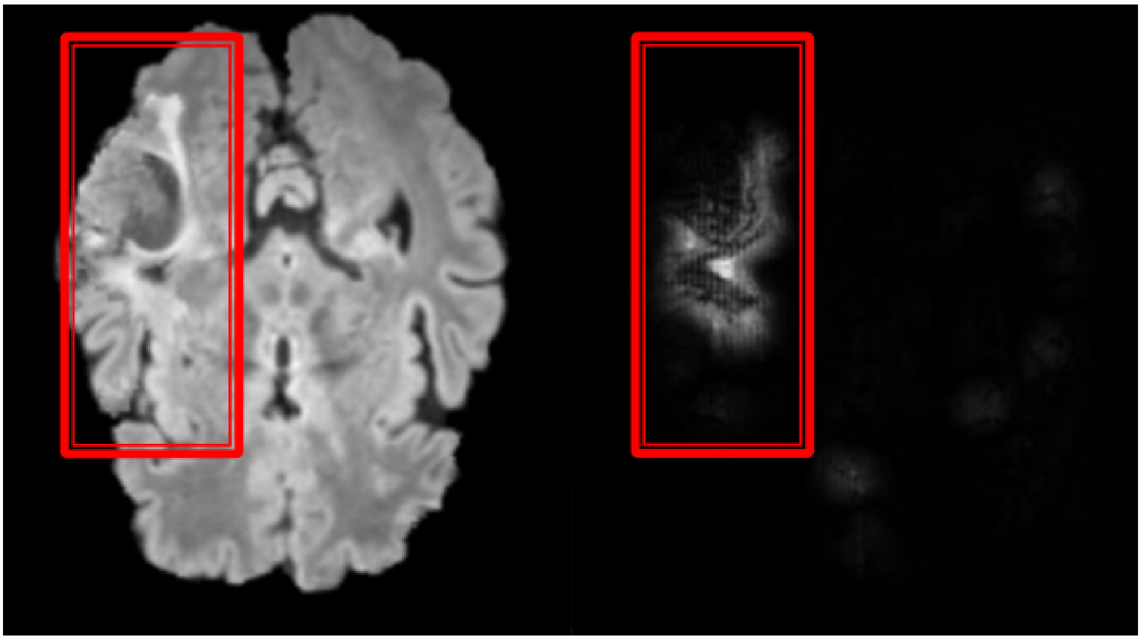


Figure 5. Left: axial slice of a brain MR image containing a tumor. Right: test of a weakly supervised (no ground truth provided during the training) Deep Learning method for an approximate localization of the tumor.

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.

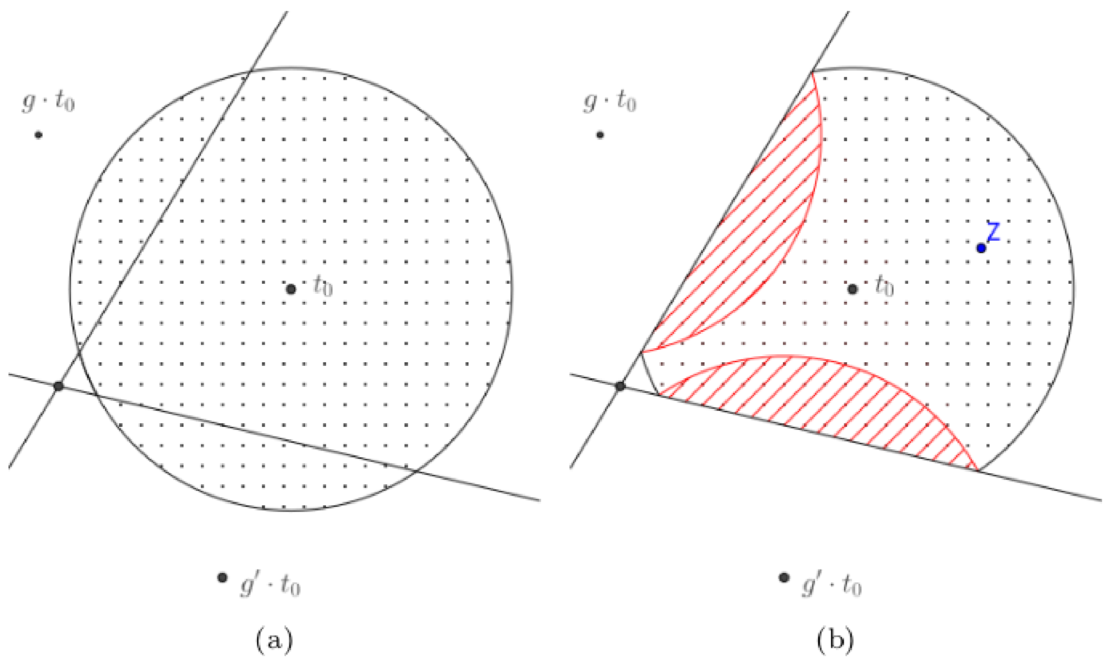


Figure 6. Geometric origin of the inconsistency: the distribution in the ambient space (panel (a)) is folded by the quotient (symmetries around the two lines, panel (b)), which biases the distribution in the quotient space.

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.

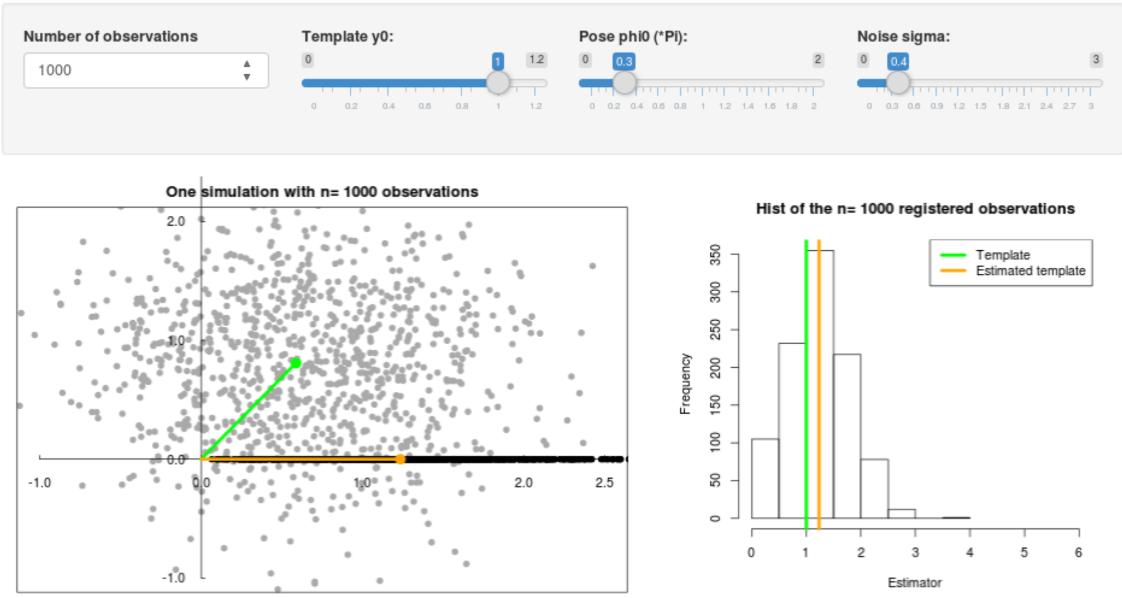


Figure 7. In this toy example, the template estimate (in orange) is biased with respect to the parameter (in green).

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.

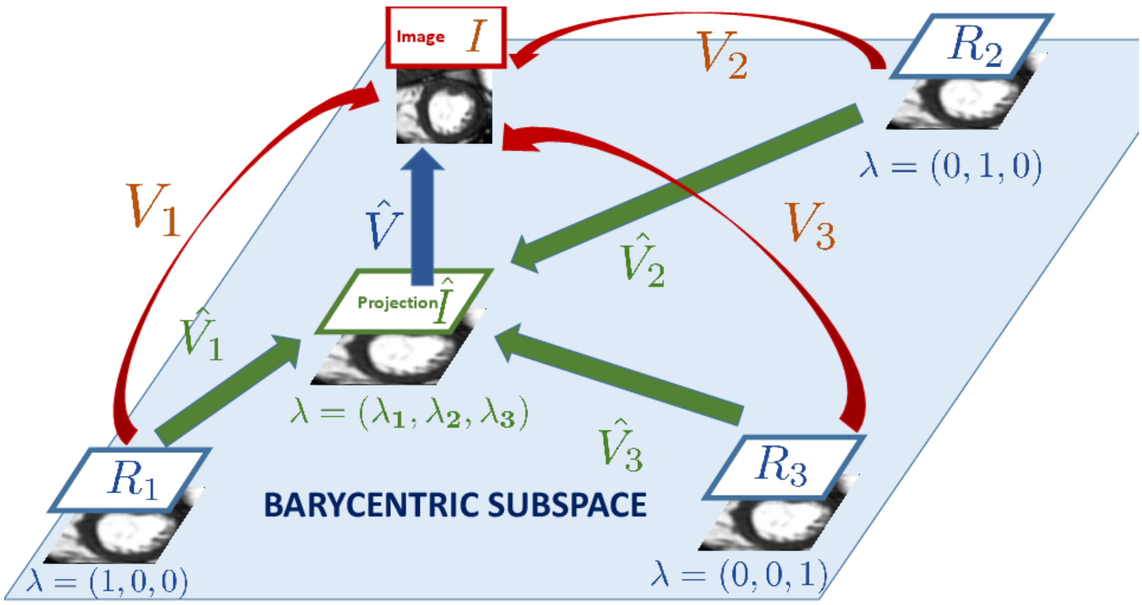


Figure 8.

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.

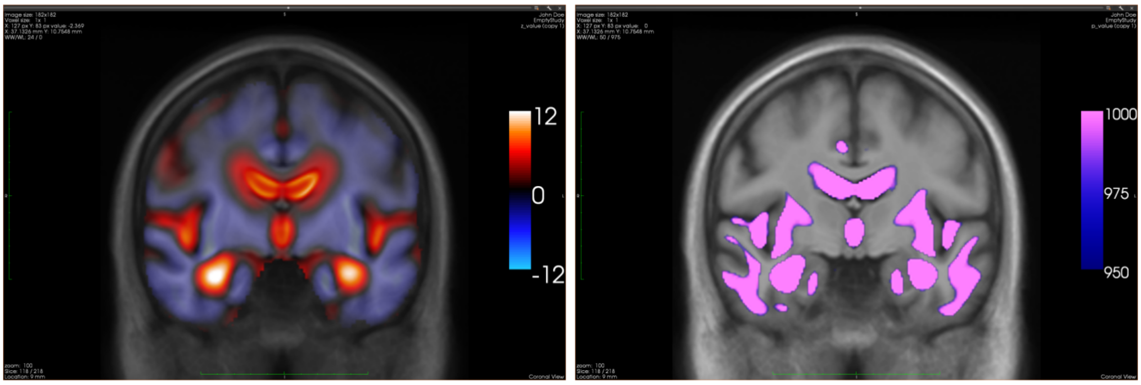


Figure 9. Left: z-values associated with group-wise differences between controls and Alzheimer-diagnosed subjects. Right: Areas of statistically significant differences.

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].

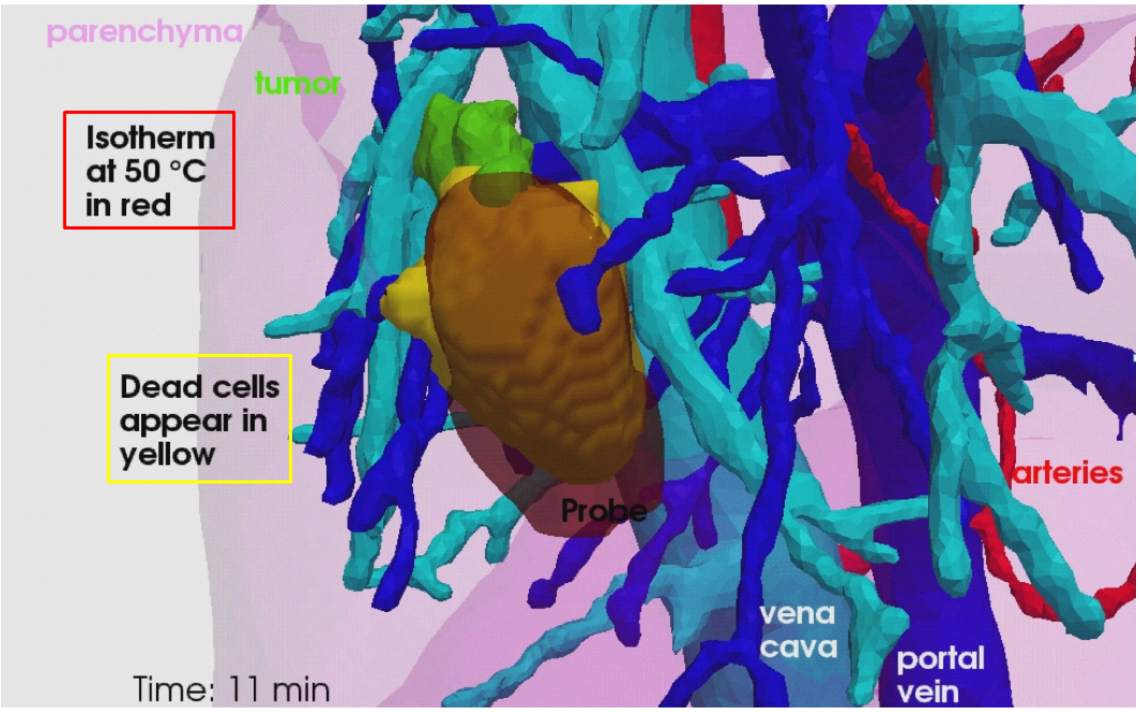


Figure 10. Computed isotherm at 50°C and computed necrosis appears in a subject-specific geometry.

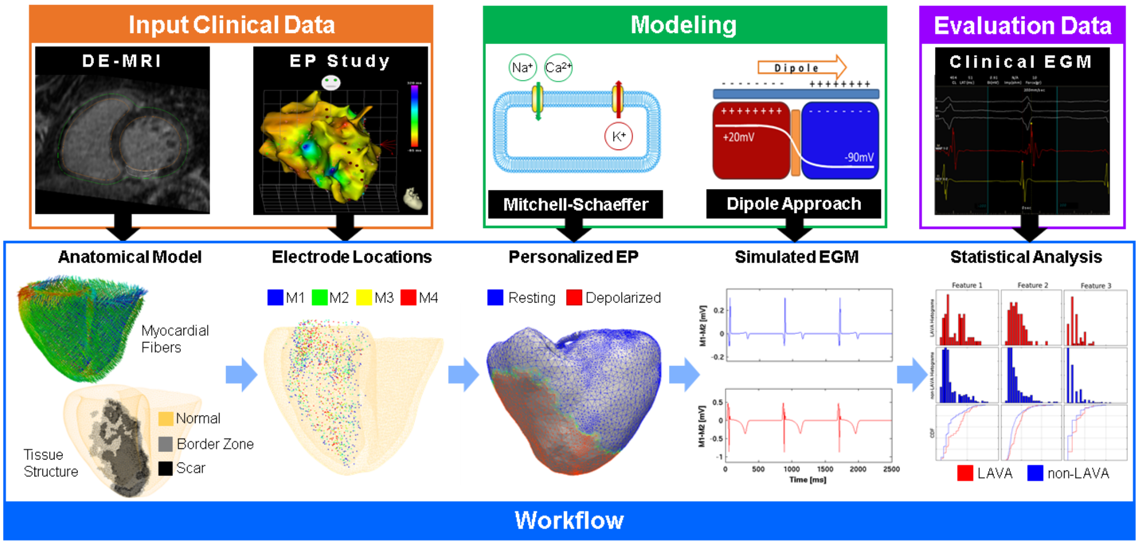


Figure 11. Pipeline developed to simulate intracardiac electrogram using patient-specific models.

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.

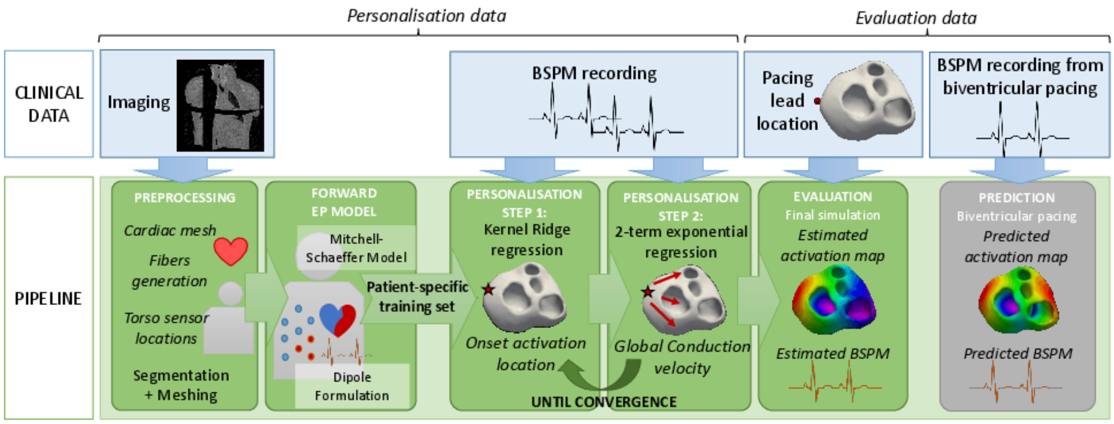


Figure 12. Personalisation framework.

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/.

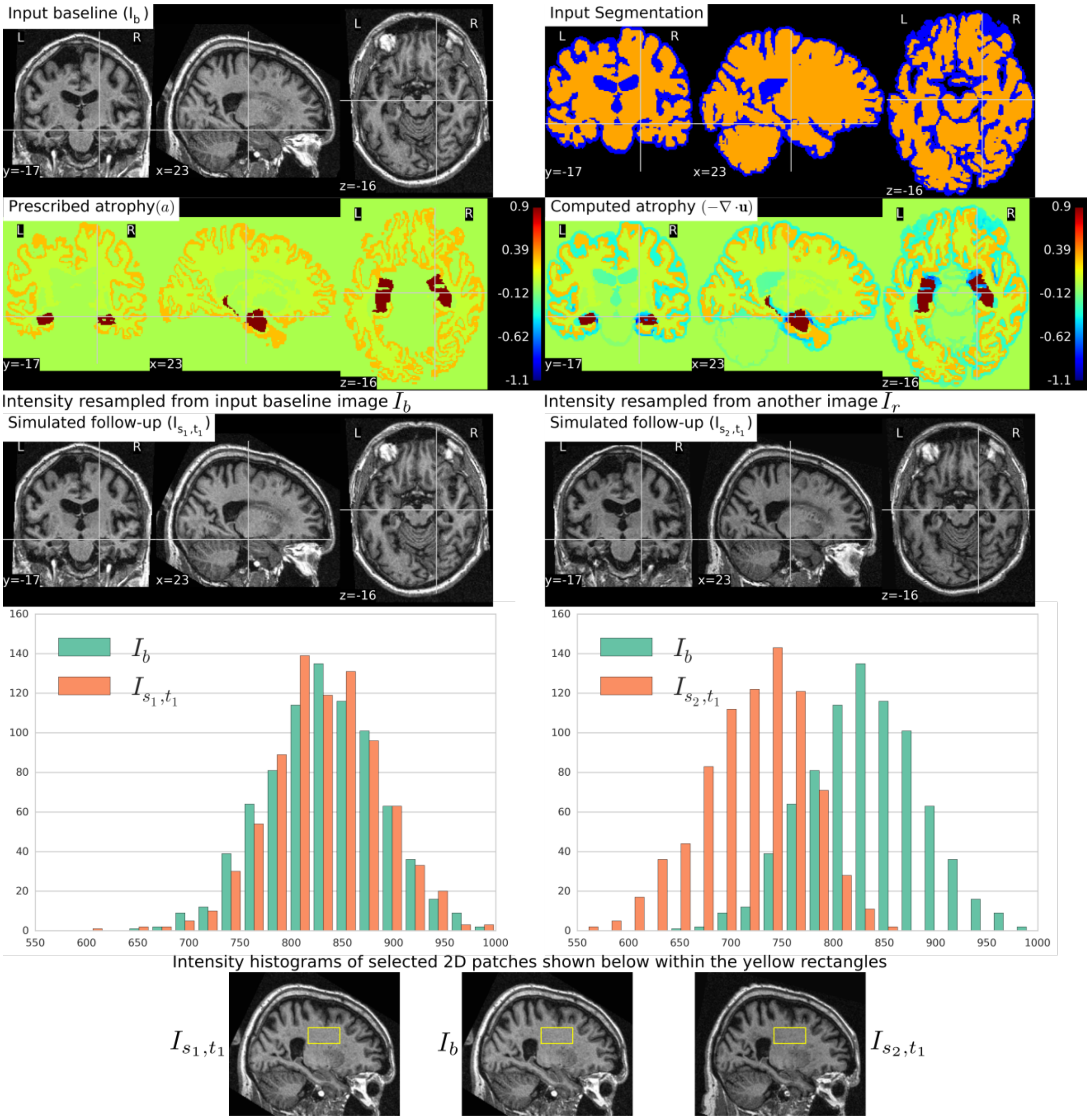


*Figure 13. **1st row:** (left) input baseline image I_b; (right) its input segmentation image. **2nd row:** (left) prescribed atrophy; (right) the atrophy computed from the simulated deformation. **3rd row:** (left) first time-point simulated follow-up image I_{s_1,t_1} where the intensity is resampled 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.

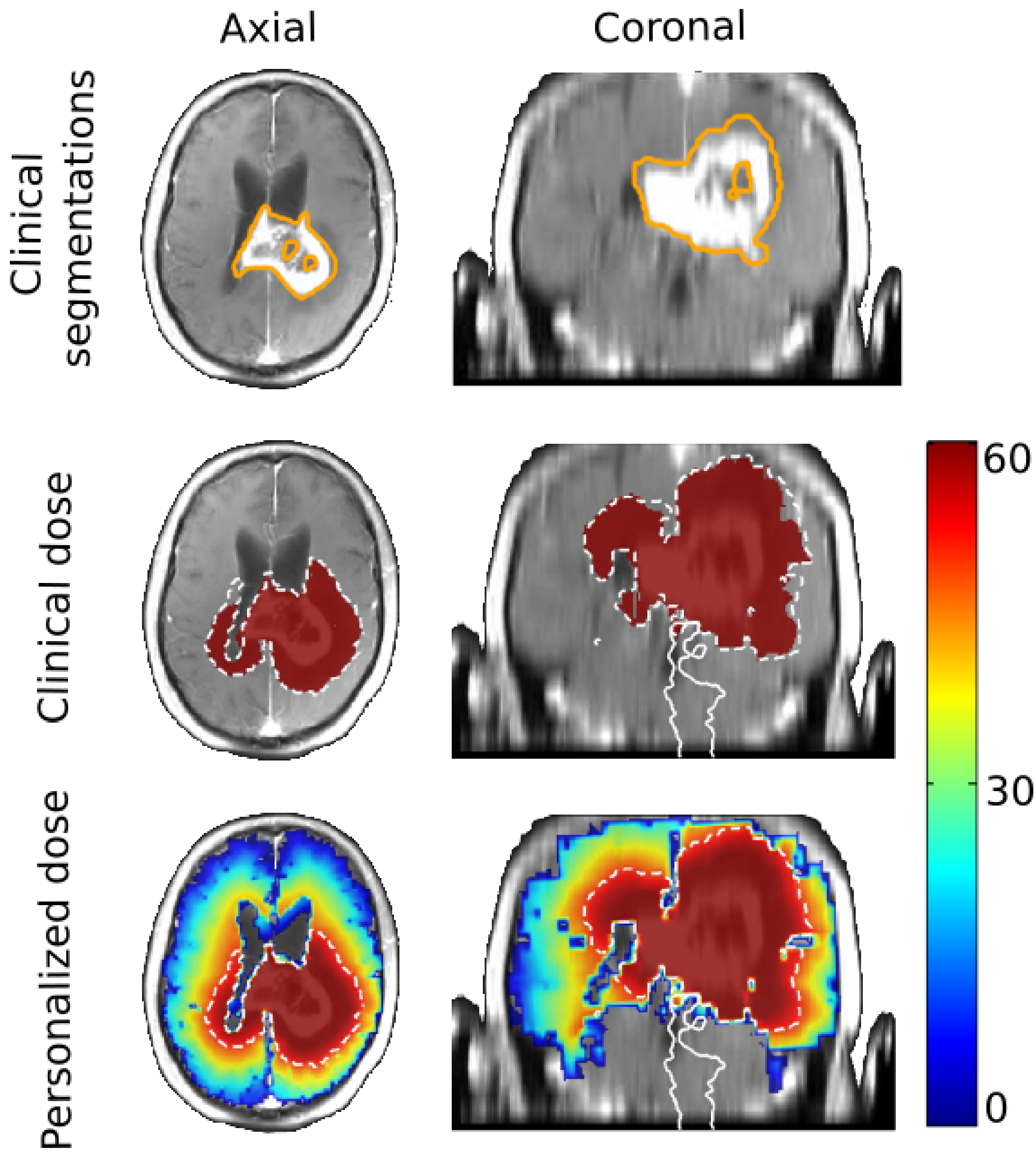


Figure 14. The clinical segmentation of the T1Gd abnormality (top, orange line) is used to define the clinical target volume (CTV, white dashed line) as a 2 cm expansion of the segmentation. In clinical settings, 60 Gy is prescribed to the CTV. We propose to personalize the prescription dose (bottom) to account for tumor infiltration and segmentation uncertainty.

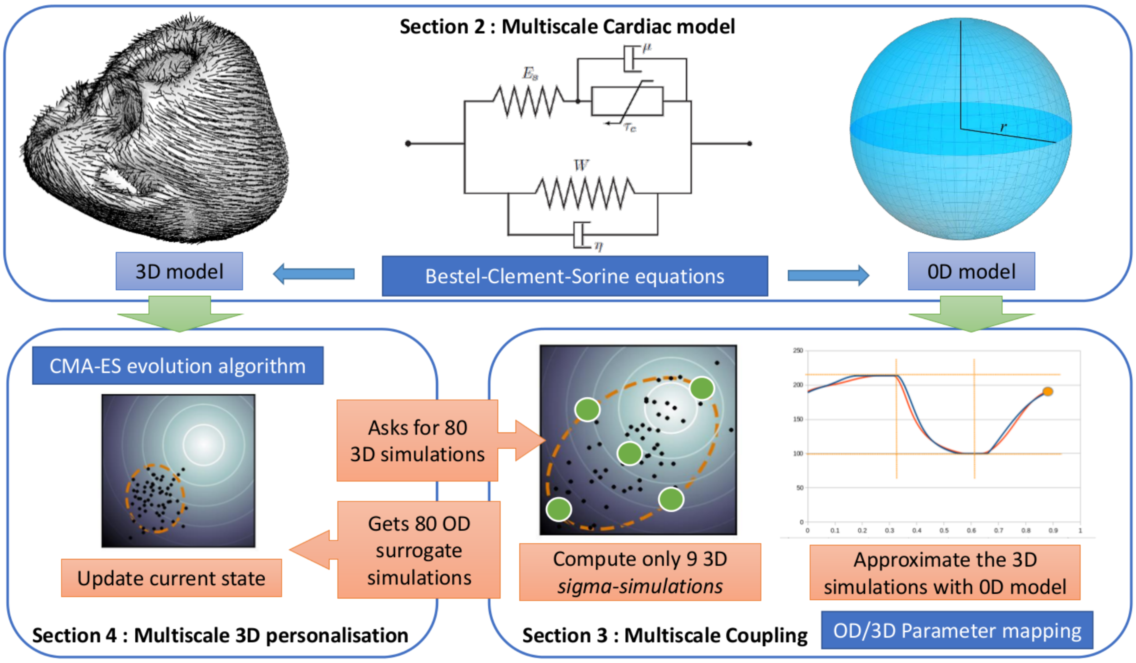


Figure 15. Multi-fidelity model and personalisation pipeline.

ATHENA Project-Team

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].

BIOCORE Project-Team

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].

BIOVISION Team

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 - NeuroEngineering & 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.

CAMIN Team

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

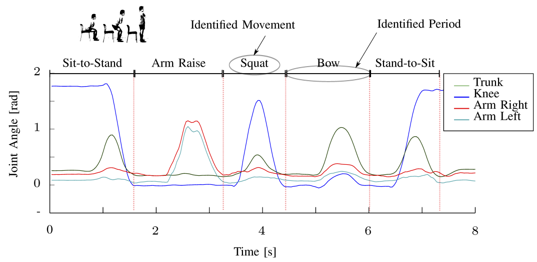
Participants: Baptista Roberto [Universidade de Brasilia, Brasil], Bo Antonio P.l. [Universidade de Brasilia, Brasil], Mitsuhiro Hayashibe.

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.

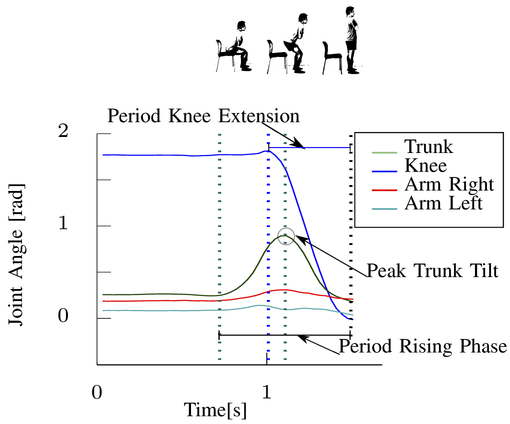
This work presents a novel framework for automatic human movement assessment that executes segmentation and motor performance parameter extraction in time-series of measurements from a sequence of human movements. We use the elements of a Switching Linear Dynamic System model as building blocks to translate 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

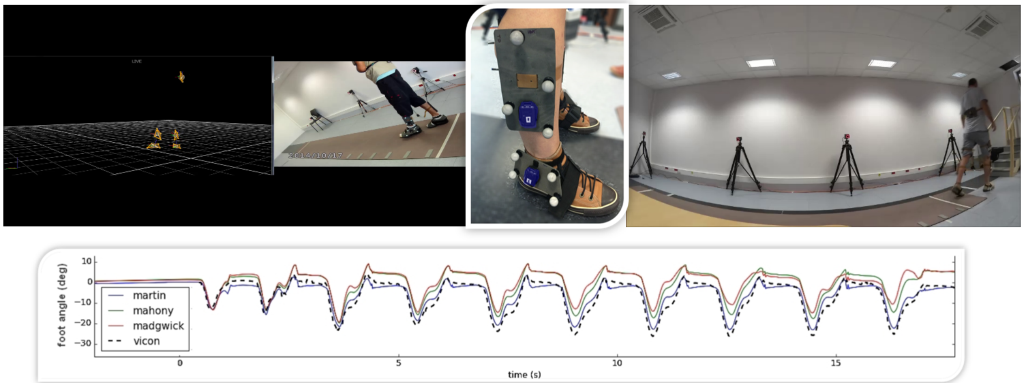


Figure 11. Gait analysis after stroke

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).

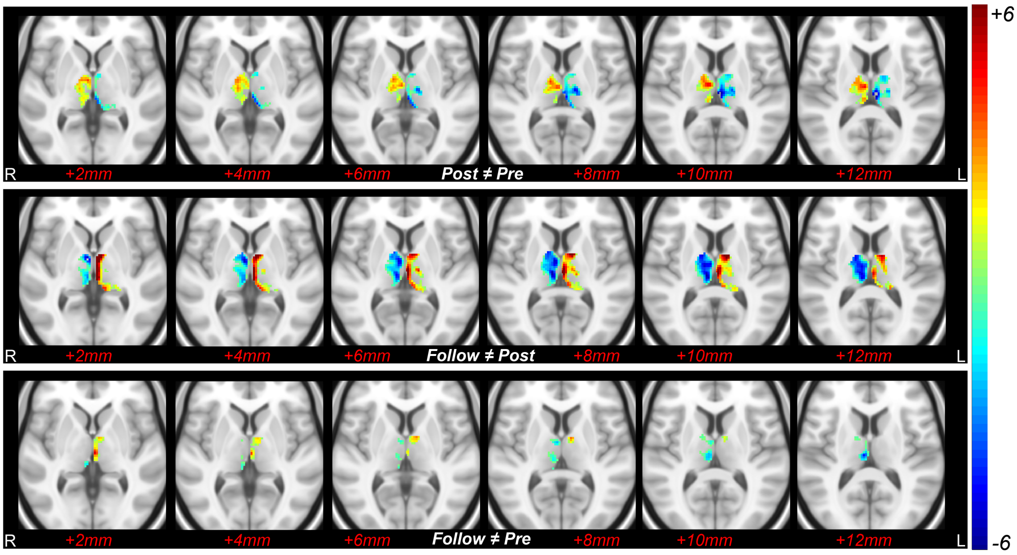


Figure 12. Voxelwise differences in ALFF score over time: ALFF maps were grouped depending on the acquisition date 1_Pre (-48h), 2_Post (+24h), 3_Follow (+3 months) and between-groups contrasts were generated as voxel-wise two-sample t-tests in order to highlight significant differences in scores over 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.

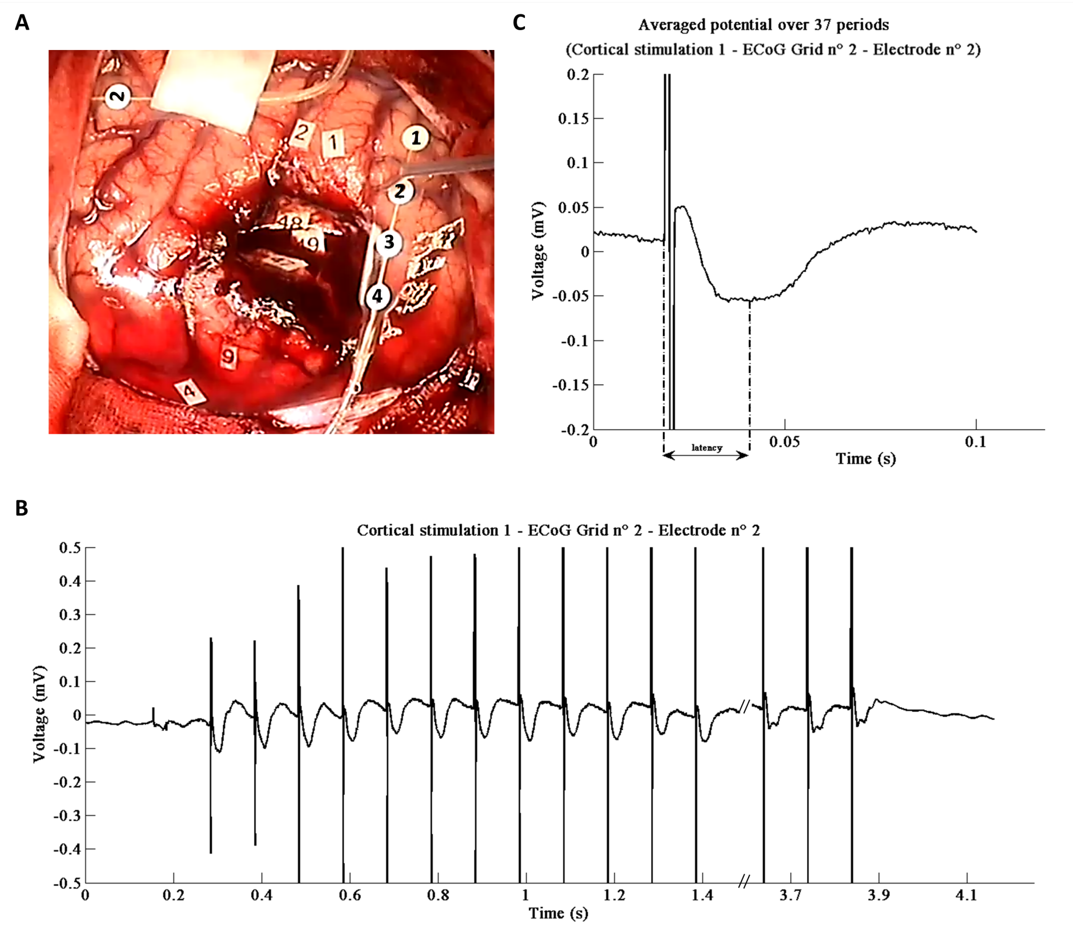


Figure 13. A: DES is applied cortically near the second electrode of the ECoG strip 2 during 3.7 s. B: Magnified view of the ECoG signal corresponding to the stimulation (with the 104 gain). CCEPs can be observed after each stimulation artefact. The last CCEPs are distorted due to the amplifier response. 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

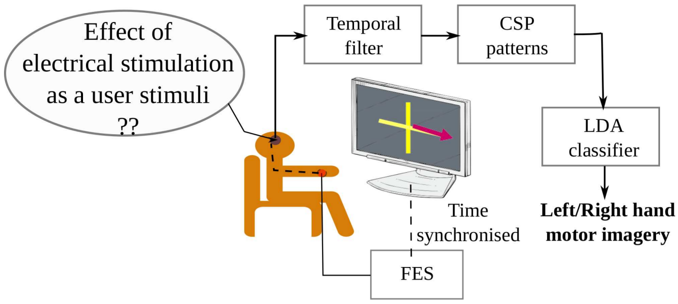


Figure 14. Block diagram of our experimental setup during motor imagery sessions where user stimuli is with conventional visual stimuli, electrical stimulation stimuli or the combined, respectively.

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.

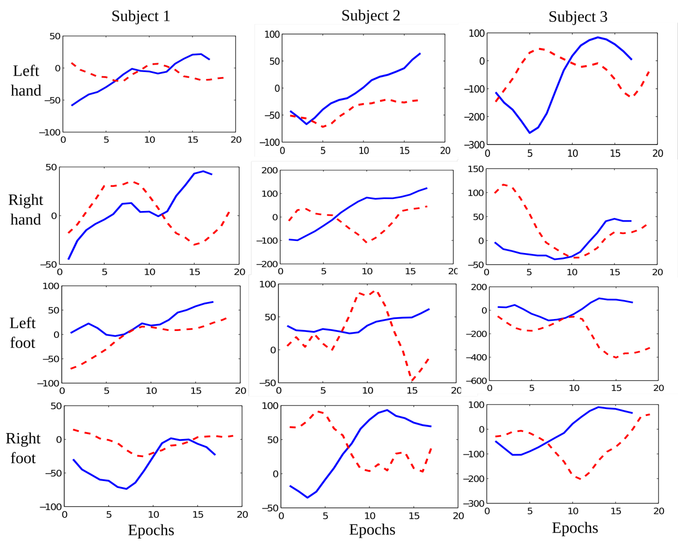


Figure 15. The learning curve of the 3 subjects for the motor imagery correctly classified tasks during FES sessions (in blue –) and VIS sessions (in red –) based on the average hyperplane distance.

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).

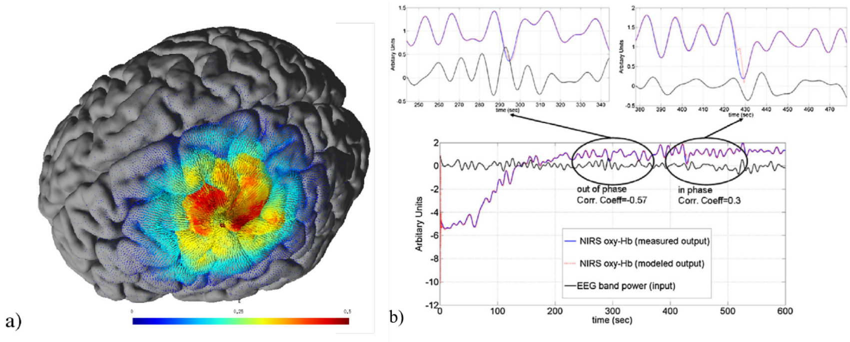


Figure 16. a) Electric field (V/m) estimated at the gray matter surface due to 2 mA anodal HD-tDCS. b) An illustrative example showing the NIRS oxy-Hb signal that was measured (in blue) as well as the predicted NIRS oxy-Hb signal using the ARX online tracking method (in dotted red).

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

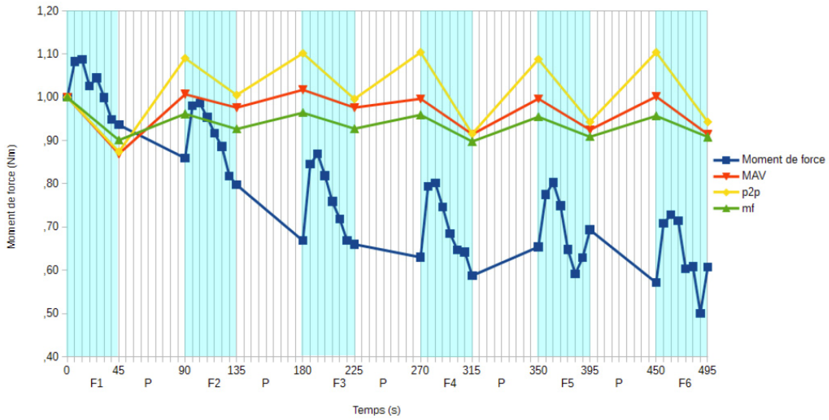


Figure 17. Correlation of different EMG features and torque during (Fn phases) and between (P phases) train of stimulations. Fatigue can be oberved and followed by EMG parameters.

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).

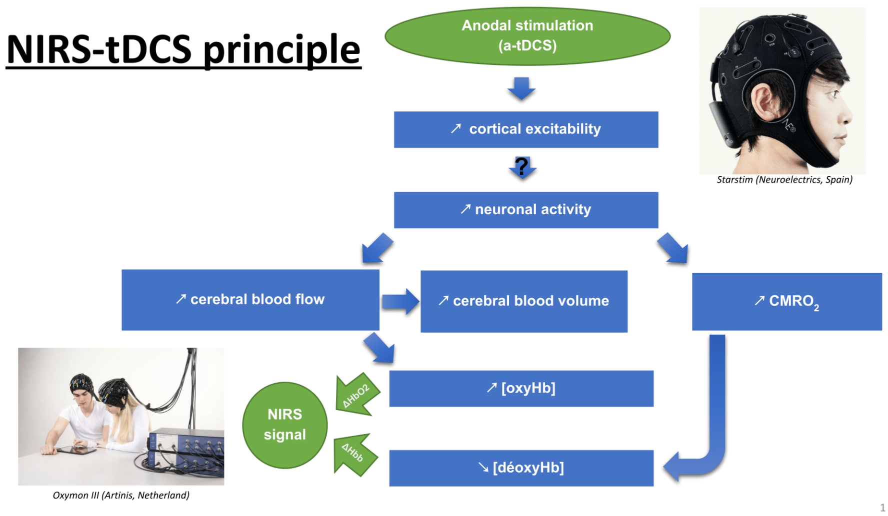


Figure 18.

In parallel, within CACAO associate team context, our Brazilian partner has trained several pilots using a similar training protocol [24], [22].

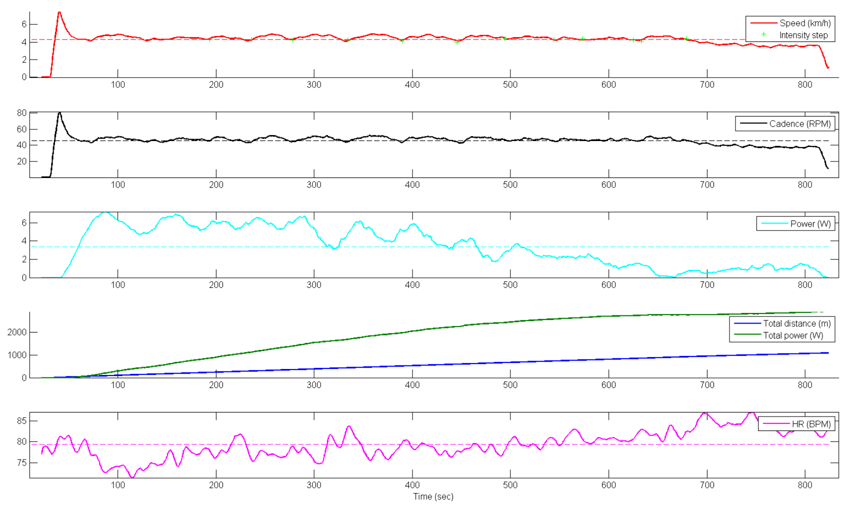


Figure 19. Best cycling performance. From top to bottom: speed (km/h), cadence (RPM), power (W), total distance (m) vs power (W), heart rate (BPM).

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.

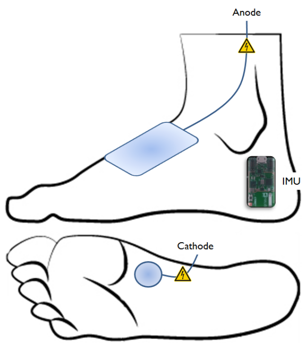


Figure 20. New cueing modality for Parkinson Disease. Electrodes and inertial sensor localization.

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].

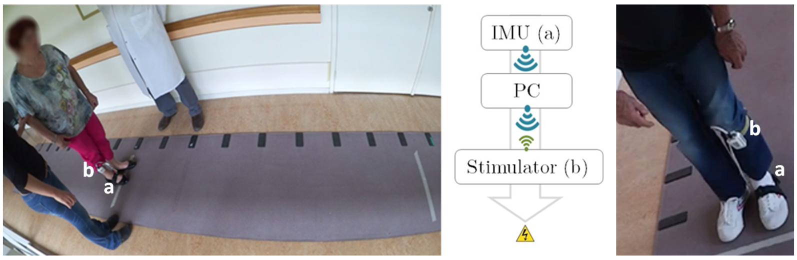


Figure 21. New cueing modality for Parkinson Disease. Experimental setup description.

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).

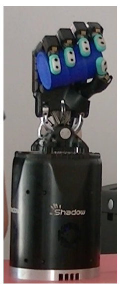


Figure 22. Closure posture of the Shadow robotic hand in the palmar grasp situation.

7.3.5. Spinal cord stimulation investigation

Participants: Christine Azevedo Coste, David Guiraud, Thomas Guiho, Charles Fattal, Luc Bauchet [CHU Montpellier].

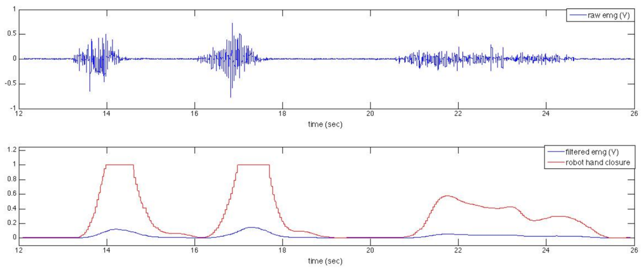


Figure 23. Robot hand trajectories generated from EMG recording for proportional mode. Top: raw EMG, bottom filtered EMG (blue) and hand trajectory (red). 0: hand is open, 1: hand is closed.

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.

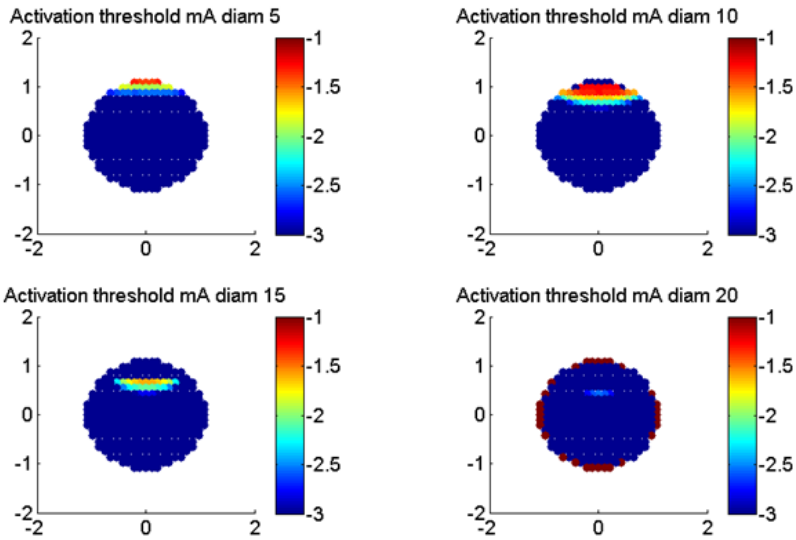


Figure 24. Spatially reverse recruitment order for fiber from 5µm to 20µm diameter obtained by multipolar configuration and prepulse technique

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 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.

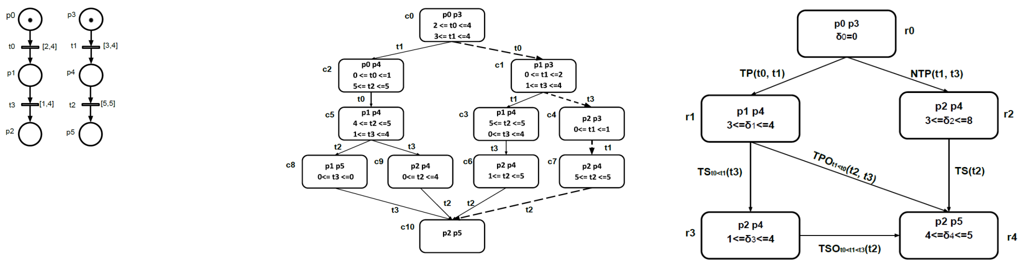


Figure 25. a Time Petri net, its classical State Class Graph and our Reduced Graph

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.

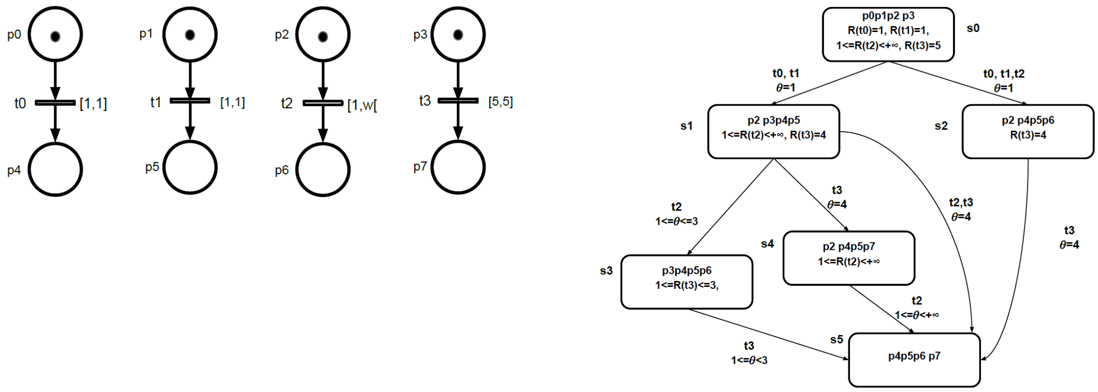


Figure 26. a Time Petri net and its Synchronous Behaviour Graph.

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].

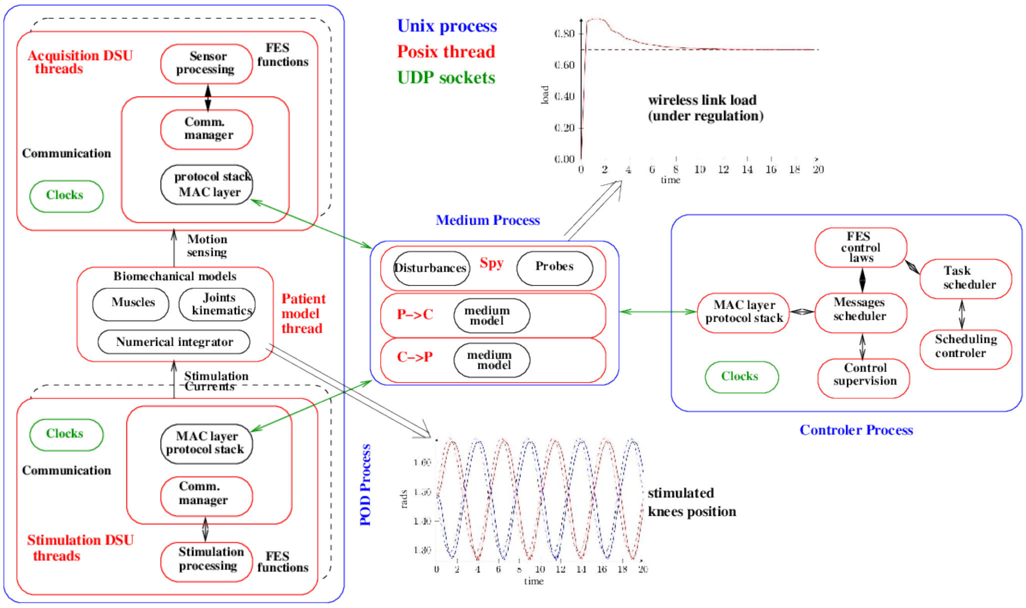


Figure 27. Real-time hybrid simulation architecture

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.

CASTOR Project-Team

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.

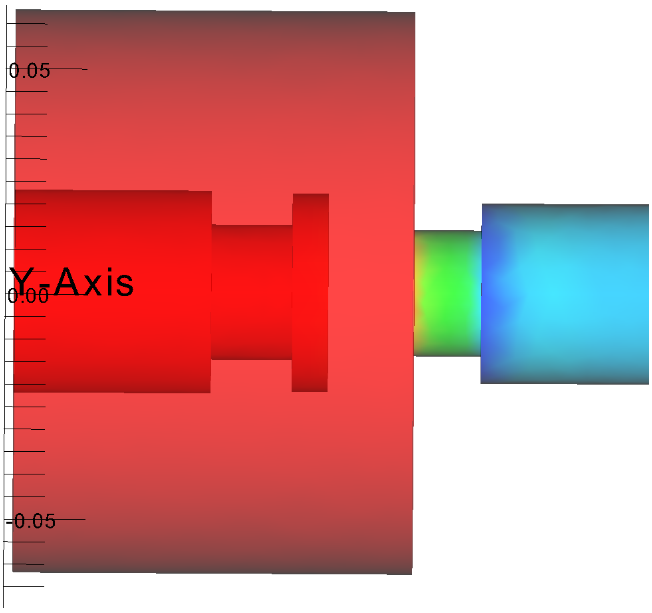


Figure 1. DMV resevoir of the JET Tokamak

5.18. A Multidimensional Analogue of the HLLI Riemann Solver for Conservative Hyperbolic Systems

Participants: Boniface Nkonga, Dinshaw Balsara.

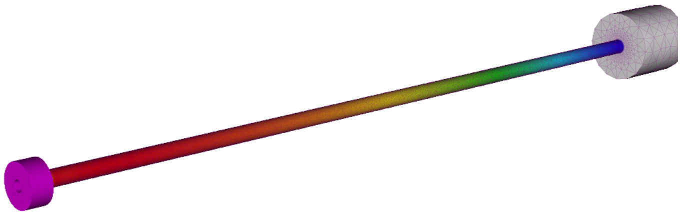


Figure 2. Reservoir, tube and plasma front of the Injection system of JET.

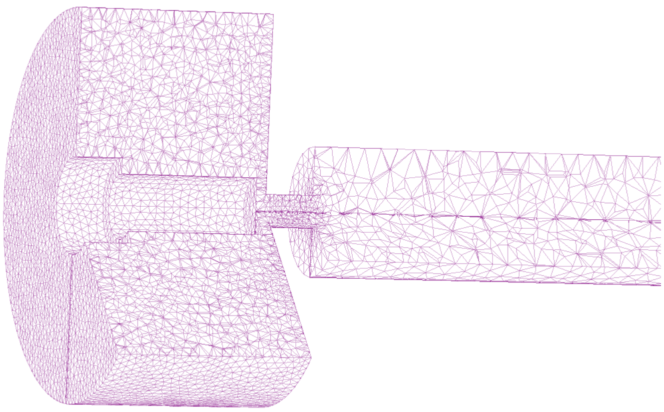


Figure 3. 3D Mesh of tetrahedral elements.

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 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).

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

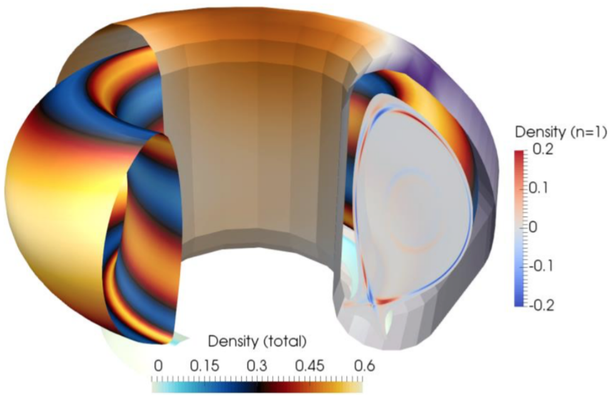


Figure 4. 3-D density structure at the separatrix and resistive wall potential of a n=1 saturated kink mode in ITER Q=10 scenario.

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.

COFFEE Project-Team

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]

LEMON Team

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.

MATHNEURO Team

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].

MORPHEME Project-Team

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.

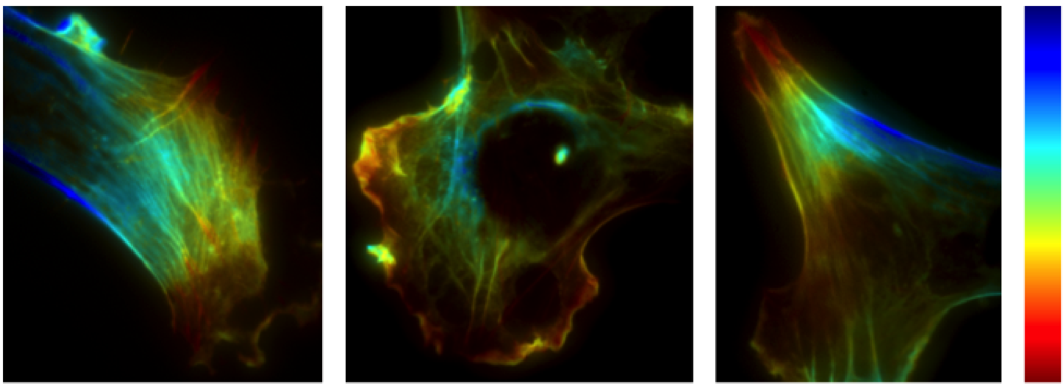


Figure 1. Example of color-coded representations for the reconstructed samples. The colors correspond to the depth (in the axial direction) of the biological structures (in the colorbar on the right: red = 0 nm and dark blue = 400 nm).

[0]Process of blood vessels creation from existing ones.

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 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.

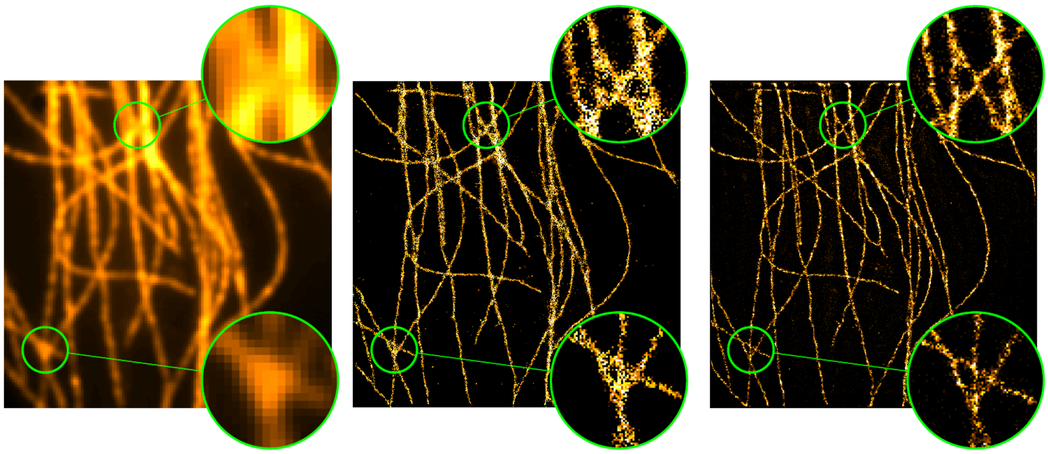


Figure 2. From left to right: Conventional Wide Field image, PALM with DAOSTORM (state of the art algorithm) reconstruction, PALM with the proposed reconstruction.

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.

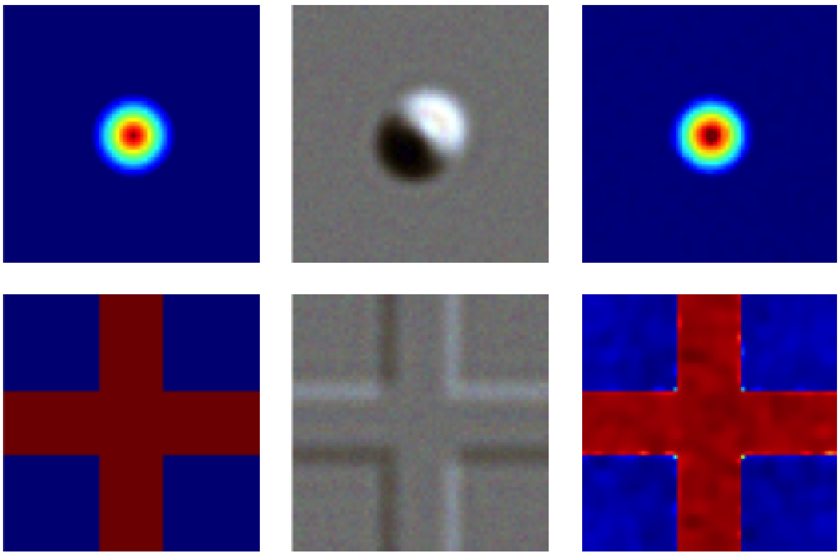


Figure 3. Data and results for the cone (top row) and cross (bottom row) objects. From left to right: true object, noisy DIC color image taken at shear angle $\frac{\pi}{4}$ rad *and corrupted with white Gaussian noise at SNR = 4.5 dB, and reconstructed phase with the LMSD method from observations at shear angles equal to* $-\pi/4$ rad *and* $\pi/4$ rad.

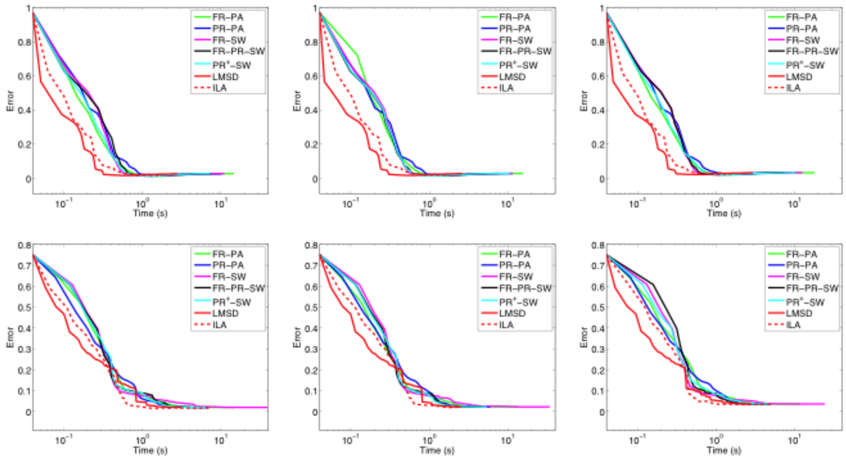


Figure 4. Error versus computational time plots for the cone (top row) and cross (bottom row) objects. From left to right: noise-free data, SNR = 9 dB and SNR = 4.5 dB.

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.

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.

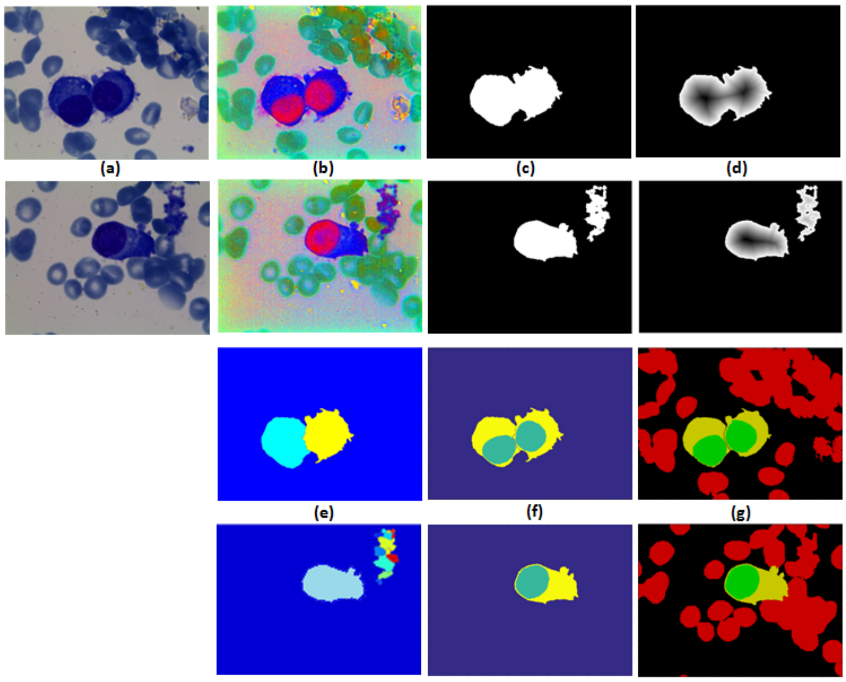


Figure 5. Image segmentation step: (a) Input image, (b) RGB Decorrelation stretch, (c) Binary mask, (d) Distance transform, (e) Watershed, (f) Segmented cell, (g) Ground truth.

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 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.

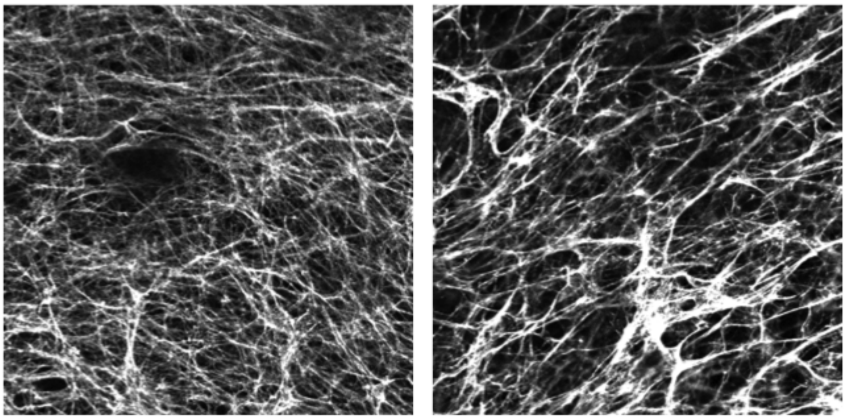


Figure 6. Two examples of extracellular matrices.

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).

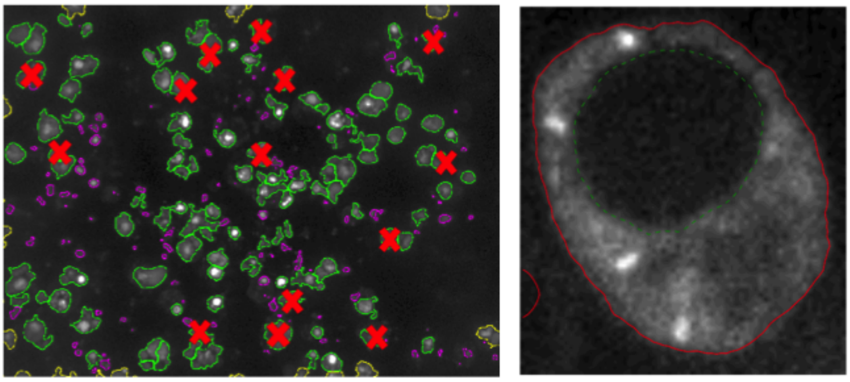


Figure 7. Left: automatic classification of the detected nuclei into living (encircled in green) or dead (with a red cross); objects encircled in yellow are cropped by the field of view, and objects encircled in purple are too small ; they are all discarded. Right: active contour segmentation of the cytoplasm of a cell (previously classified as a living cell); red contour: cytoplasm external boundary; green, dashed contour: nucleus boundary (also cytoplasm internal boundary).

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).

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.

[0]http://cellprofiler.org
[0]http://cellprofiler.org/cp-analyst

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.

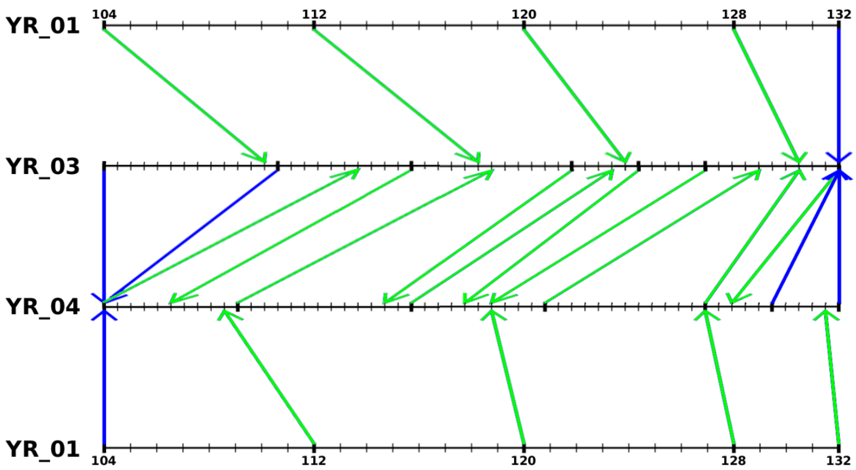


Figure 8. Inter-individual temporal registration result between three floral meristem 3D+t interpolated image sequences. Blue arrows correspond to border registrations.

5.10. Coherent temporal extrapolation of labeled images

Participants: Gaël Michelin, Grégoire Malandain.

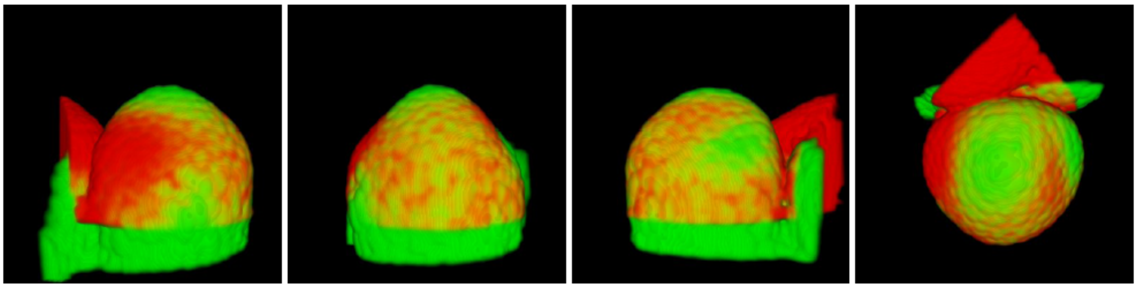


Figure 9. 3D views of the spatial registration of images from two flower meristems (in red and green) at the same developing stage.

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).

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.

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.

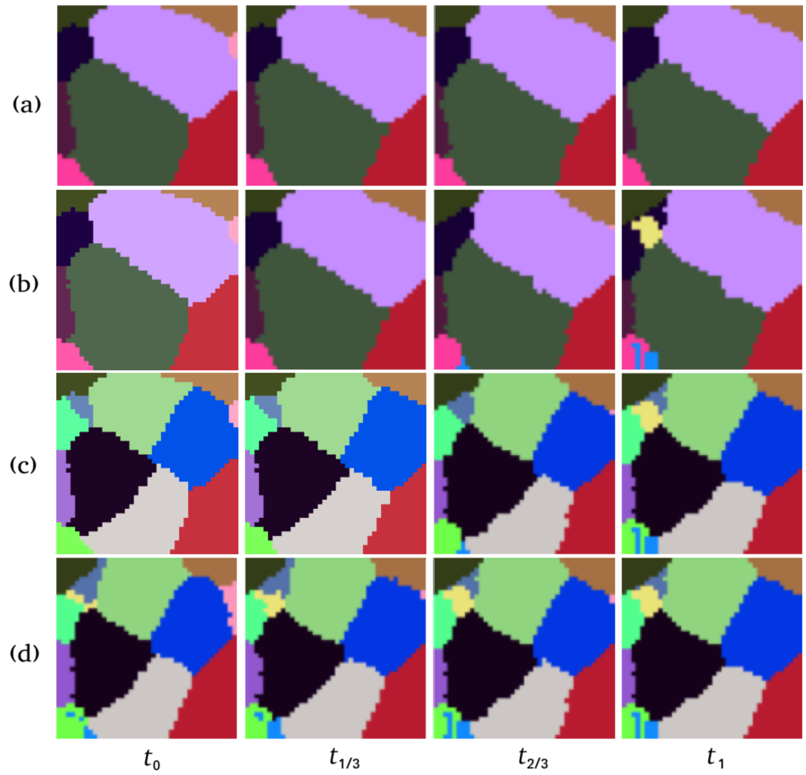


Figure 10. Images compounded of labeled regions at increasing time. (a) and (d) are the original sequences. One can see that the region borders of the corresponding groups of regions of these sequences do not superimpose perfectly. (b) and (c) are the images of transformed regions respectively from the 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.

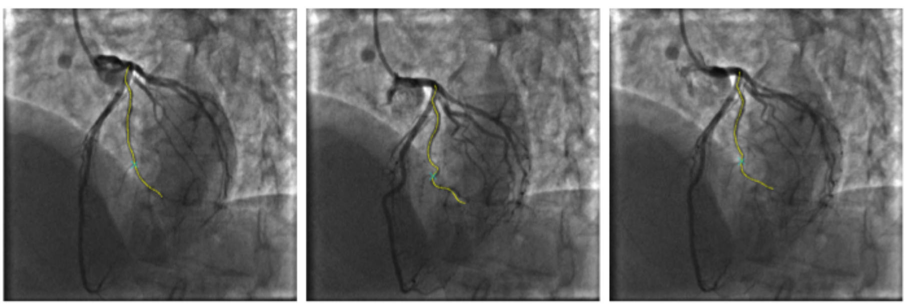


Figure 11. The 3 images show the projection of a 3D vessel in yellow and a remarkable point on the vessel (bifurcation) in blue at 3 different phases of the cardiac cycle.

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.

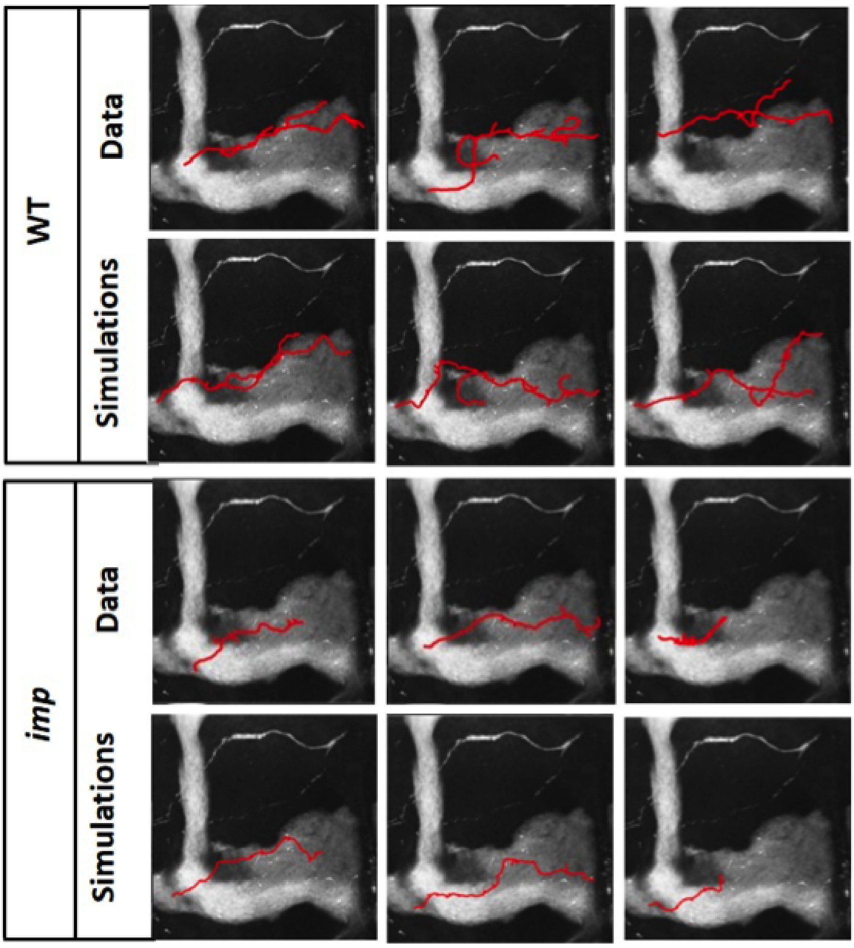


Figure 12. Wild type and imp mutant neurons from the database, contrasted to very similar neurons from our simulations.

VIRTUAL PLANTS Project-Team

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, HortSys, 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.

- *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

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.

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 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.

- *Design of 3D digital atlases of tissue development.*

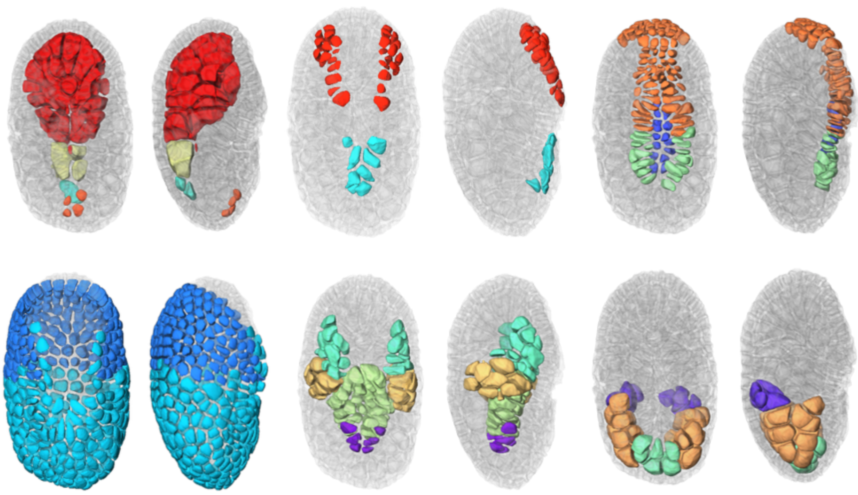


Figure 2. 3D projection of the segmented embryo at the early tailbud stage. The cells are colored by tissue type. The cells are slightly roded to allow their distinction. The other cells of the embryo are in transparent grey. The doral and lateral sides are shown.

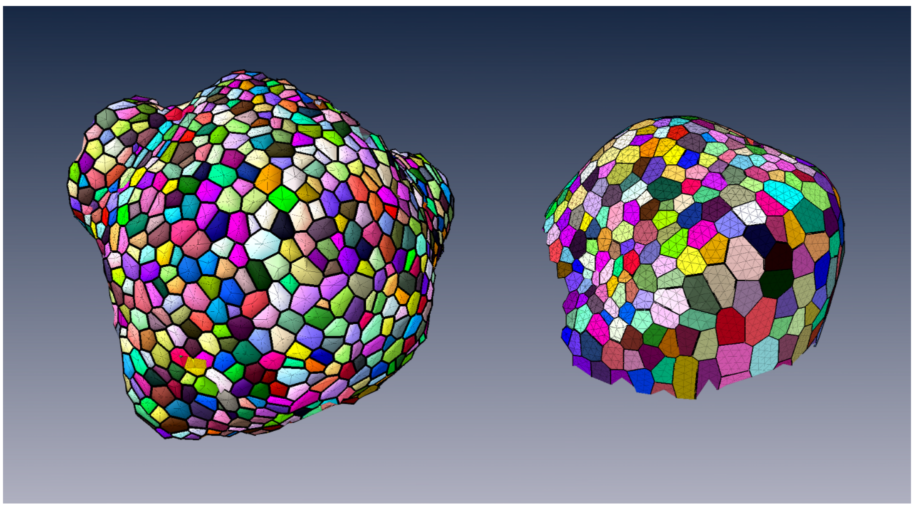


Figure 3. Triangular mesh representations of shoot apical meristem and flower meristem tissues obtained from MARS segmentations

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 developopped 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.

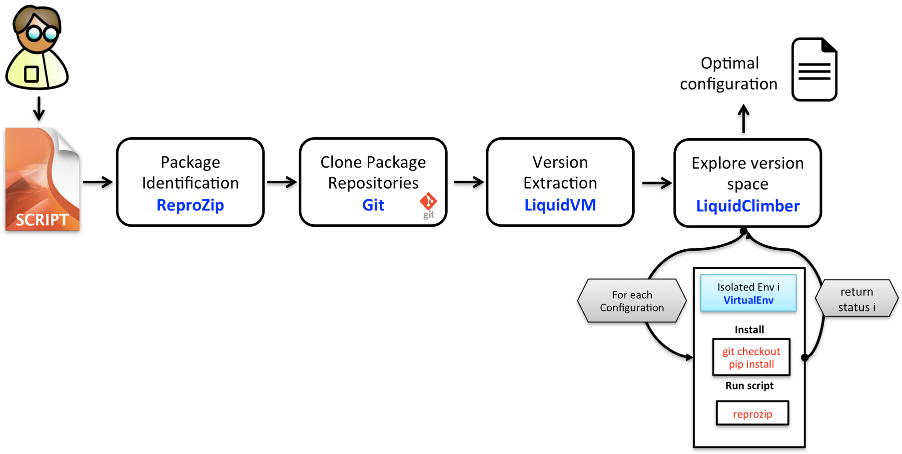


Figure 4. The steps of the operational subsystem: capture the execution of the initial configuration, liquify, fetch versions from git/svn etc., then deploy as directed by VersionClimber.

COATI Project-Team

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

[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.

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.

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) $\in$ 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.

DIANA Project-Team

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].

FOCUS Project-Team

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.

INDES Project-Team

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.

MAESTRO Project-Team

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.

AYIN Team

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.

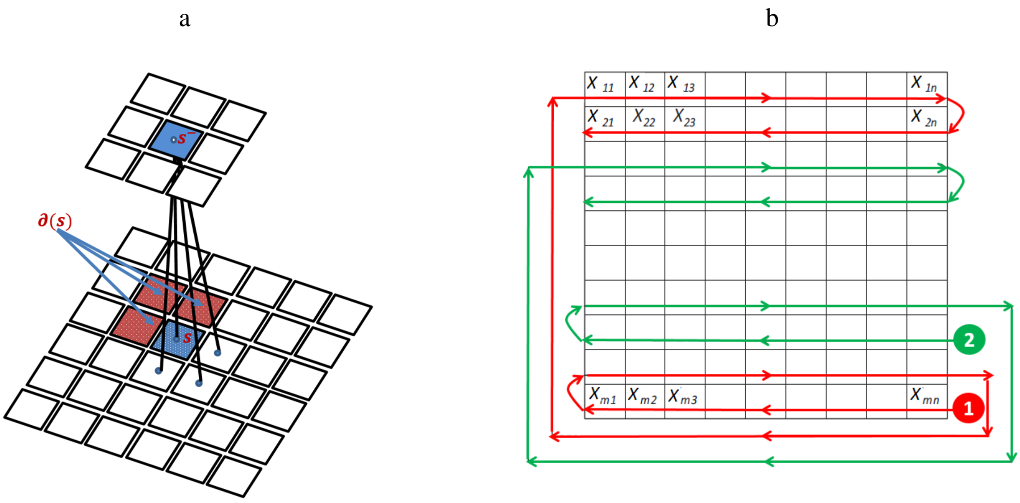


Figure 1. (a) Hybrid structure that combines a spatial grid using an SMMRF and a hierarchical MRF via a quad-tree. (b) Regular rectangular lattice S of size m x n: the "past" of site $s_{i,j}$ is the gray area, arrow lines show raster scan.

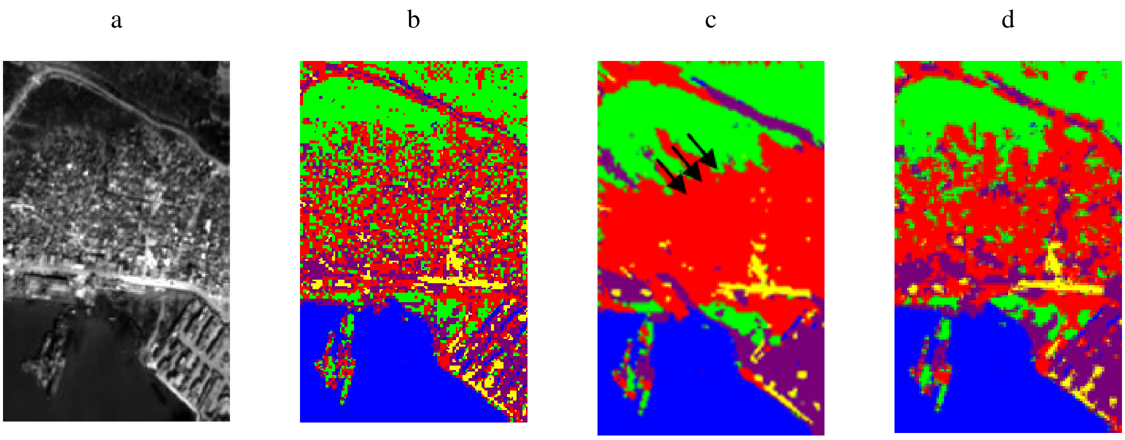


Figure 2. classification maps of optical (Pléiades) image (a) using the original Laferté method (b), the previous method in [2] (c) and the new proposed method (d).

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.

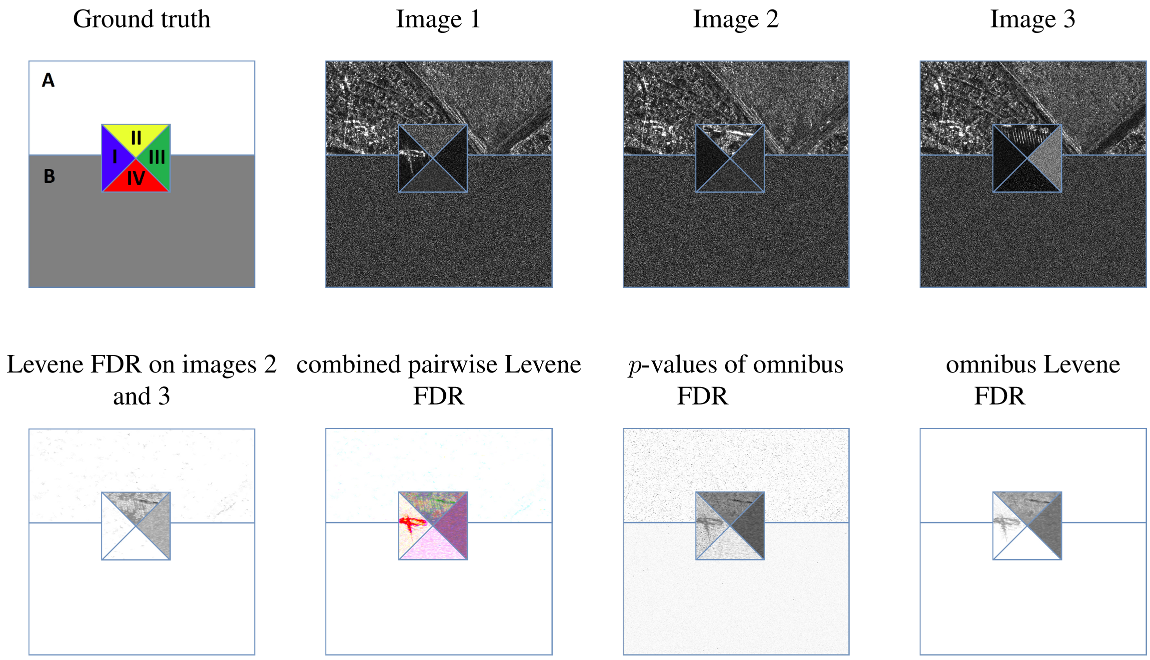


Figure 3. Semi-synthetic 3-image SAR sequence based on COSMO-SkyMed (©ASI) images of Haiti in 2011: (a) ground truth and (b)-(d) images, results of (e), (f) pairwise and (g), (h) omnibus Levene FDR-detection.

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.

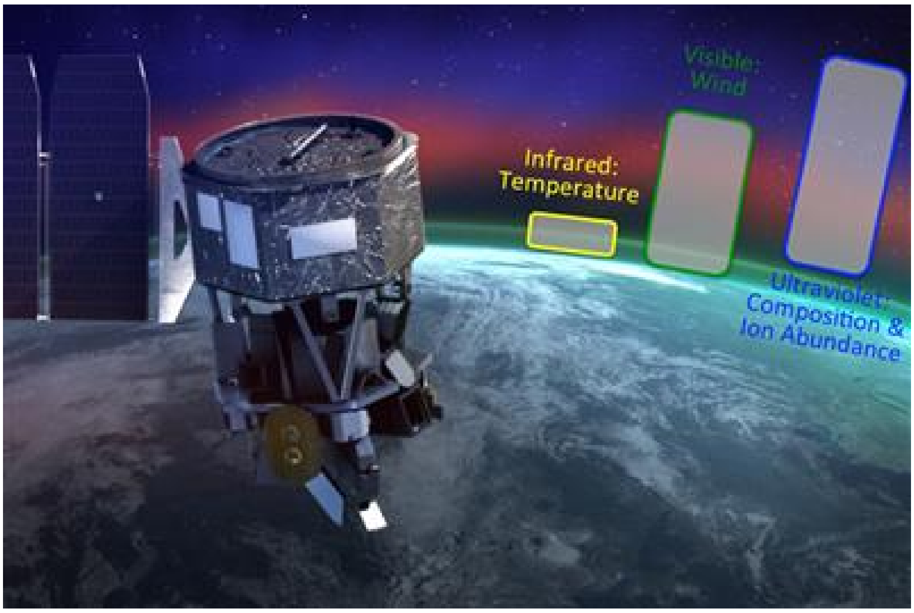


Figure 4. Ionospheric Connection Explorer satellite ©NASA.

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.

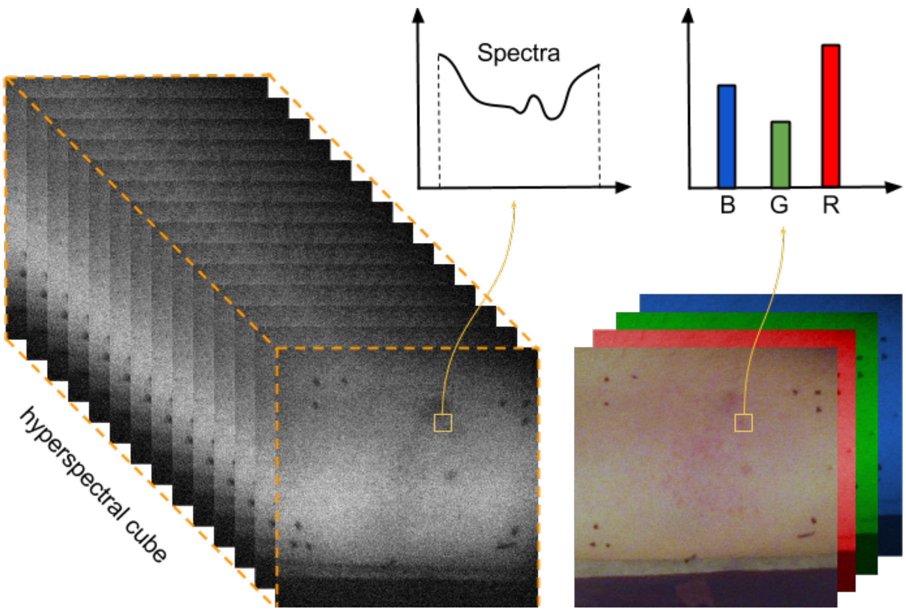


Figure 5. A schematic representation of hyperspectral vs. RGB image data. The image shows artificially induced erythema over the inside of the forearm of a volunteer.

GRAPHDECO Project-Team

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].

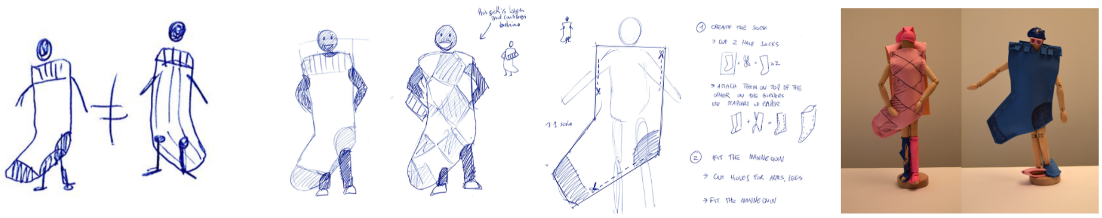


Figure 4. We asked participants to design a costume, from an initial sketch to a physical prototype.

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].

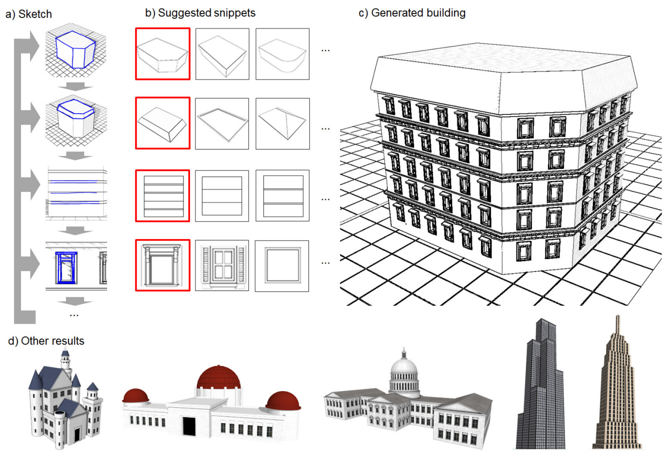


Figure 5. Our system allows novices to quickly create complex procedural 3D models of buildings by sketching.

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].

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

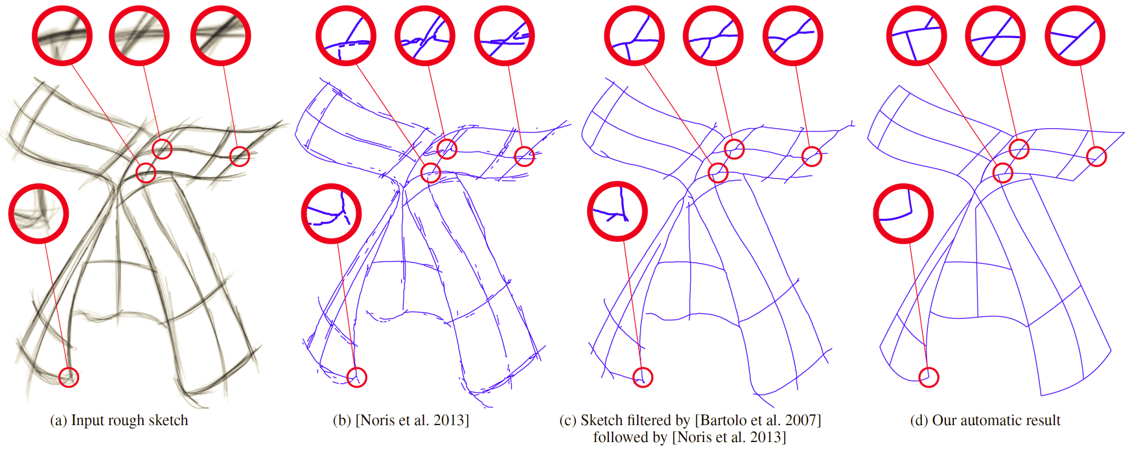


Figure 6. Rough sketches often contain overlapping strokes (a), which existing vectorization algorithms represent as multiple curves (b). Pre-filtering the drawing improves the vectorization, but produces spurious curve segments at junctions (c). Since existing algorithms analyze junctions locally, they 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.

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.

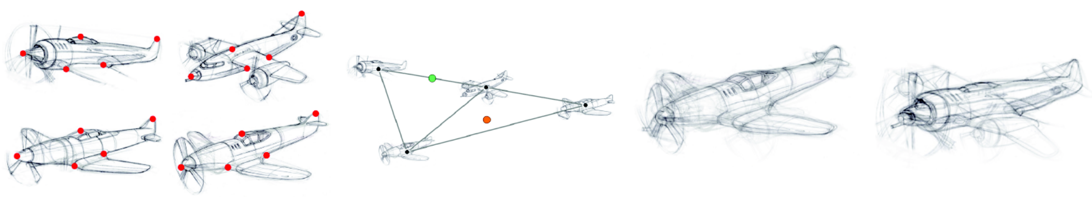


Figure 7. SketchSoup takes an unstructured set of sketches as input, along with a small number of correspondences (shown as red dots), registers the sketches and embeds them into a 2D interpolation space based on their shape differences. Users can explore the interpolation space to generate novel sketches.

6.1.5. Modeling Symmetric Developable Surfaces from a Single Photo

Participants: Amelie Fondevilla, Adrien Bousseau.

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.

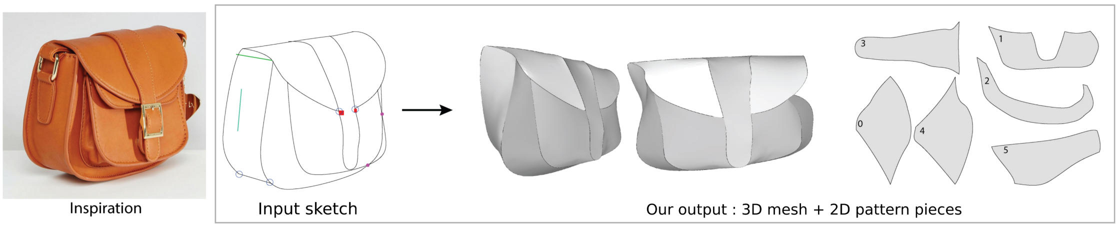


Figure 8. Our method reconstructs a 3D mesh and 2D pattern pieces of a sewed object from a single annotated drawing.

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].

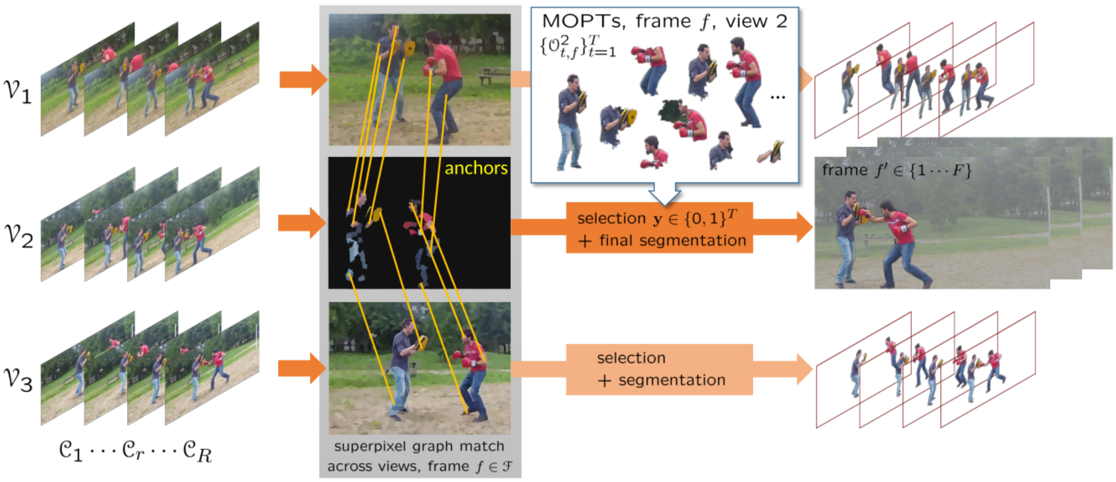


Figure 9. Synchronized videos of the same scene are partitioned into short clips. At a small number of instants where motion is sufficiently informative, cross-view correspondences between with similar appearance and motion are obtained by graph matching. In each view, matched superpixels, which are 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].

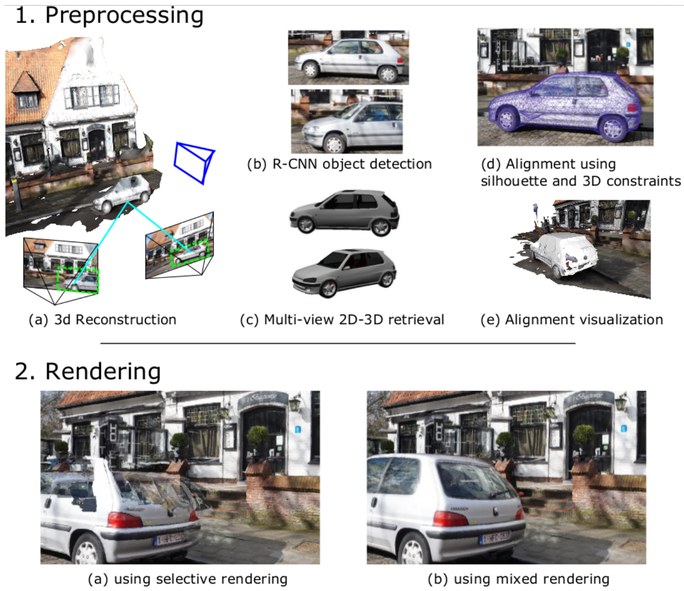


Figure 10. Overview of our pre-processing and rendering pipeline for Mixed Image-Based Rendering.

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].

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

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).

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].

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.

6.2.5. A Feasibility Study with Image-Based Rendered Virtual Reality in Patients with Mild Cognitive Impairment

Participant: George Drettakis.

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].

Figure 13. The VR and paper conditions of the study

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].

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.

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 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.

GRAPHIK Project-Team

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]*

HEPHAISTOS Project-Team

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.

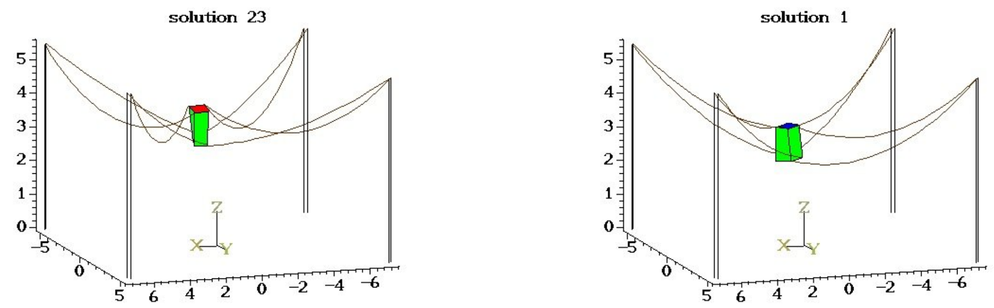


Figure 2. Two poses that are solutions of the forward kinematics, the left one being unstable while the right one is stable.

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.

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.

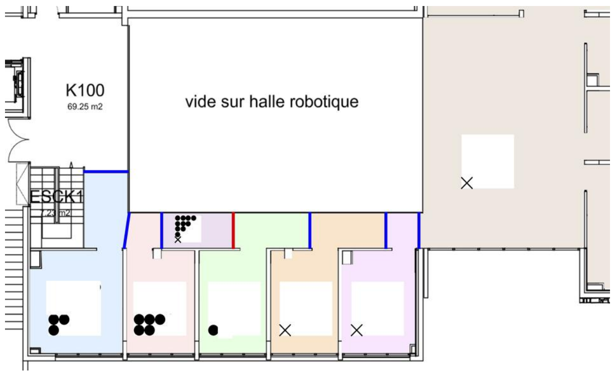


Figure 3. Occupancy of zone in a complex environment as measured by several stations

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.

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.

Figure 4. Rear view of the `ANG-med` walker with the 4 distance sensors that are used to monitor and assess rehabilitation exercises

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).

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].

LAGADIC Project-Team

7. New Results

7.1. Visual Perception

7.1.1. Micro/nano Manipulation

Participants: Le Cui, Eric Marchand.

Le Cui's Ph.D. [15] ended with a contribution related to visual tracking and estimation of the 3D pose of a micro/nano-object. It is indeed a key issue in the development of automated manipulation tasks using visual feedback. The 3D pose of the micro object can be estimated based on a template matching algorithm. Nevertheless, a key challenge for visual tracking in a scanning electron microscope (SEM) was the difficulty to observe the motion along the depth direction. We then proposed a template-based hybrid visual tracking scheme that uses luminance information to estimate the object displacement on x-y plane and uses defocus information to estimate object depth [54].

7.1.2. 3D Localization for Space Debris Removal

Participants: Aurélien Yol, Eric Marchand, François Chaumette.

This study is realized in the scope of the FP7 Removedebris project (see Section 9.3.1.1) [27]. We compared two vision-based navigation methods for tracking space debris in a low Earth orbit environment. The proposed approaches rely on a frame to frame model-based tracking in order to obtain the complete 3D pose of the camera with respect to the target [2]. The proposed algorithms robustly combine points of interest and edge features, as well as color-based features if needed. Experimental results have been obtained demonstrating the robustness of the approaches on synthetic image sequences simulating a CubeSat satellite orbiting the Earth [75].

7.1.3. 3D Localization for Airplane Landing

Participants: Noël Mériaux, François Chaumette, Patrick Rives, Eric Marchand.

This study is realized in the scope of the ANR VisioLand project (see Section 9.2.2). In a first step, we have considered and adapted our model-based tracker [2] to localize the aircraft with respect to the airport surroundings. Satisfactory results have been obtained from real image sequences provided by Airbus. In a second step, we are now considering to perform this localization from a set of keyframe images corresponding to the landing trajectory.

7.1.4. Scene Registration based on Planar Patches

Participants: Renato José Martins, Eduardo Fernandez Moral, Patrick Rives.

Image registration has been a major problem in computer vision over the past decades. It implies searching an image in a database of previously acquired images to find one (or several) that fulfill some degree of similarity, e.g. an image of the same scene from a similar viewpoint. This problem is interesting in mobile robotics for topological mapping, re-localization, loop closure and object identification. Scene registration can be seen as a generalization of the above problem where the representation to match is not necessarily defined by a single image (i.e. the information may come from different images and/or sensors), attempting to exploit all information available to pursue higher performance and flexibility. This problem is ubiquitous in robot localization and navigation. We propose a probabilistic framework to improve the accuracy and efficiency of a previous solution for structure registration based on planar representation. Our solution consists of matching graphs where the nodes represent planar patches and the edges describe geometric relationships. The maximum likelihood estimation of the registration is estimated by computing the graph similarity from a series of geometric properties (areas, angles, proximity, etc.) to maximize the global consistency of the graph. Our technique has been validated on different RGB-D sequences, both perspective and spherical [26].

7.1.5. Direct RGB-D Registration

Participants: Renato José Martins, Eduardo Fernandez Moral, Patrick Rives.

Dense direct RGB-D registration methods are widely used in tasks ranging from localisation and tracking to 3D scene reconstruction [7]. This work addresses a peculiar aspect which drastically limits the applicability of direct registration, namely the weakness of the convergence domain. In general, registration is performed only between close frames (small displacements), since dense registration tasks are particularly sensible to the local convexity of the cost error function. The main contribution of this work is an adaptive RGB-D error cost function that has a larger convergence domain and a faster convergence in both simulated and real data [67], [68]. This formulation employs the relative condition number metric to update the weighting of the RGB and depth costs. This approach is performed within a multi-resolution framework, where an efficient pixel selection for both RGB and ICP costs reduces the computational cost whilst preserving the precision. The formulation results in a larger region of attraction and faster convergence than classical RGB, ICP and RGB-D costs. Experiments was conducted using real sequences of indoor and outdoor images using perspective and spherical RGB-D sensors. Significant improvements was denoted in terms of the convergence stability and the speed of convergence in comparison with state-of-the-art methods.

7.1.6. Online localization and mapping for UAVs

Participants: Muhammad Usman, Paolo Robuffo Giordano, Eric Marchand.

Localization and mapping in unknown environments is still an open problem, in particular for what concerns UAVs because of the typical limited memory and processing power available onboard. In order to provide our quadrotor UAVs with high autonomy, we started studying how to exploit onboard cameras for an accurate (but fast) localization and mapping in unknown indoor environments. We chose to base both processes on the newly available Semi-Direct Visual Odometry (SVO) library (http://rpg.ifi.uzh.ch/software) which has gained considerable attention over the last years in the robotics community. The idea is to exploit dense images (i.e., with little image pre-processing) for obtaining an incremental update of the camera pose which, when integrated over time, can provide the camera localization (pose) w.r.t. the initial frame. In order to reduce drifts during motion, a concurrent mapping thread is also used for comparing the current view with a set of keyframes (taken at regular steps during motion) which constitute a “map” of the environment. We have started porting the SVO library to our UAVs and the preliminary results showed good performance of the localization accuracy against the Vicon ground truth. We are now planning to close the loop and base the UAV flight on the reconstructed pose from the SVO algorithm.

7.1.7. Reflectance and Illumination Estimation for Realistic Augmented Reality

Participants: Salma Jiddi, Eric Marchand.

The acquisition of surface material properties and lighting conditions is a fundamental step for photo-realistic Augmented Reality. Human visual cues remain sensitive to the global coherence within a computer-generated image. Absence or bad rendered virtual shadows, unconsidered specular reflections and/or occlusions, confused color perception such as an exuberantly bright virtual object are all elements which may not help an AR user interact and commit to a target application. In this work, we studied a new method for the estimation of the diffuse and specular reflectance properties of an indoor real static scene. Using an RGB-D sensor, we further estimate the 3D position of light sources responsible for specular phenomena and propose a novel photometry-based classification for all the 3D points. The resulting algorithm allows convincing AR results such as realistic virtual shadows as well as proper illumination and specularity occlusions [60].

7.1.8. Optimal Active Sensing Control

Participants: Paolo Salaris, Riccardo Spica, Paolo Robuffo Giordano.

This study concerns the problem of active sensing control. The objective is to improve the estimation accuracy of an observer by determining the inputs of the system that maximize the amount of information gathered by the outputs. In [9] this problem has been solved within the Structure from Motion (SfM) framework for 3D structure estimation problems, i.e. a point, a sphere and a cylinder, in the particular case where the observability property is instantaneously guaranteed. The optimal estimation strategy is hence given in terms of the instantaneous velocity direction of the camera velocities.

Recently, we have extended the optimal active sensing control to the case where the observability property is not instantaneously guaranteed. To simplify the analysis, we considered nonlinear differentially flat systems. Moreover, to quantify the richness of the acquired information the Observability Gramian (OG) has been used. We have hence defined a trajectory for the flat outputs of the system by using B-Spline curves and then, we have exploited an online gradient descent strategy to move the control points of such B-Spline in order to actively maximise the smallest eigenvalue of the OG over the whole fixed planning time horizon. While the system travels along its planned (optimized) trajectory, an Extended Kalman Filter (EKF) is used to estimate the system state. In order to keep memory of the past acquired sensory data for online re-planning, the OG is also computed on the past estimated state trajectories. This is then used for an online replanning of the optimal trajectory during the robot motion which is continuously refined by exploiting the estimated system state by the EKF. In order to show the effectiveness of our method we have considered a simple but significant case of a planar robot with a single range measurement. The simulation results show that, along the optimal path, the EKF converges faster and provides a more accurate estimate than along any other possible (non-optimal) paths. These results have been submitted to ICRA'2017.

7.2. Sensor-based Robot Control

7.2.1. Determining Singularity Configurations in IBVS

Participant: François Chaumette.

This theoretical study has been achieved through an informal collaboration with Sébastien Briot and Philippe Martinet from IRCCyN in Nantes, France. It concerns the determination of the singularity configurations of image-based visual servoing using tools from the mechanical engineering community and the concept of "hidden" robot. In a first step, we have revisited the welknown case of using three image points as visual feature, and then solved the general case of n image points [22]. The case of three image straight lines has also been solved for the first time [23].

7.2.2. Interval-based IBVS convergence domain computation

Participant: Vincent Drevelle.

This work aims to compute the set of camera poses from which IBVS will converge to the desired pose (that corresponds to the reference image). Starting from a (small) initial attraction domain of the desired pose (obtained using Lyapunov theory), we employ subpavings and guaranteed integration to iteratively increase the proven convergence domain, using a viability-based approach. Image-domain and pose-domain constraints are also enforced, like feature points visibility or workspace boundaries. First results have been obtained for a 3DOF line-scan camera IBVS case [56].

7.2.3. Visual Servoing of Humanoid Robots

Participants: Giovanni Claudio, Don Joven Agravante, Fabien Spindler, François Chaumette.

This study is realized in the scope of the BPI Romeo 2 and H2020 Comanoid projects (see Sections 9.2.7 and 9.3.1.2).

In a first step, we have considered classical kinematic visual servoing schemes for gaze control and manipulation tasks, such as can or box grasping. Two-hand manipulation has also been achieved using a master/slave approach [53], [81]. In a second step, we have designed the modeling of the visual features at the acceleration level to embed visual tasks and visual constraints in an existing QP controller [20][80]. Experimental results have been obtained on Romeo (see Section 6.9.4).

7.2.4. Model Predictive Visual Servoing

Participants: Nicolas Cazy, Paolo Robuffo Giordano, François Chaumette.

This study is realized in collaboration with Pierre-Brice Wieber, from Bipop group at Inria Rhône Alpes.

Model Predictive Control (MPC) is a powerful control framework able to take explicitly into account the presence of constraints in the controlled system (e.g., actuator saturations, sensor limitations, and so on). In this research activity, we studied the possibility of using MPC for tackling one of the most classical constraints of visual servoing applications, that is, the possibility to lose tracking of features because of occlusions, limited camera field of view, or imperfect image processing/tracking. The MPC framework depends upon the possibility to predict the future evolution of the controlled system over some time horizon, for correcting the current state of the modeled system whenever new information (e.g., new measurements) become available. We have also explored the possibility of applying these ideas in a multi-robot collaboration scenario where a UAV with a downfacing camera (with limited field of view) needs to provide localization services to a team of ground robots [13].

7.2.5. Model Predictive Control for Visual Servoing of a UAV

Participants: Bryan Penin, Riccardo Spica, François Chaumette, Paolo Robuffo Giordano.

Visual servoing is a welknown class of techniques meant to control the pose of a robot from visual input by considering an error function directly defined in the image (sensor) space. These techniques are particularly appealing since they do not require, in general, a full state reconstruction, thus granting more robustness and lower computational loads. However, because of the quadrotor underaction and inherent sensor limitations (mainly limited camera field of view), extending the classical visual servoing framework to the quadrotor flight control is not straightforward. For instance, for realizing a horizontal displacement the quadrotor needs to tilt in the desired direction. This tilting, however, will cause any downlooking camera to point in the opposite direction with, e.g., possible loss of feature tracking because of the limited camera field of view.

In order to cope with these difficulties and achieve a high-performance visual servoing of quadrotor UAVs, we are exploring the possibility of using techniques borrowed from Model-Predictive Control (MPC) for explicitly dealing with this kind of constraints during flight. Indeed, MPC is a class of (numerical) optimal control techniques able to explicitly take into account state and input constraints, as well as complex (and underactuated) nonlinear dynamics of the controlled system. In particular, the ability to predict, over some future time window, the behavior of the visual features on the image plane will allow the quadrotor to fly "blindly" for some limited phases, for then regaining tracking of any lost feature. This possibility will be crucial for allowing quick maneuvering guided by a direct visual feedback. We have started addressing the case of a simulated planar UAV as a representative case study, and we are now working towards an experimental validation with a real quadrotor UAV equipped with an onboard camera.

7.2.6. Visual-based shared control

Participants: Firas Abi Farraj, Nicolò Pedemonte, Paolo Robuffo Giordano.

This work concerns our activities in the context of the RoMaNS H2020 project (see Section 9.3.1.3 . Our main goal is to allow a human operator to be interfaced in an intuitive way with a two-arm system, one arm carrying a gripper (for grasping an object), and the other one carrying a camera for looking at the scene (gripper + object) and providing the needed visual feedback. The operator should be allowed to control the two-arm system in an easy way for letting the gripper approaching the target object, and she/he should also receive force cues informative of how feasible her/his commands are w.r.t. the constraints of the system (e.g., joint limits, singularities, limited camera fov, and so on).

We have started working on this topic by proposing a shared control architecture in which the operator could provide instantaneous velocity commands along four suitable task-space directions not interfering with the main task of keeping the gripper aligned towards the target object (this main task was automatically regulated). The operator was also receiving force cues informative of how much her/his commands were conflicting with the system constraints, in our case joint limits of both manipulators. Finally, the camera was always moving so as to keep both the gripper and the target object at two fixed locations on the image plane [46].

We have then extended this framework in two directions: first, by allowing the possibility of controlling a whole future trajectory for both arms (gripper+camera) while coping with the system constraints. The operator was then receiving an 'integral' force feedback along the whole planned trajectory: in this way, the operator's actions and the corresponding force cues were function of a planned trajectory (thus, carrying information over a future time window) that could be manipulated at runtime. Second, we studied how to integrate learning from demonstration into our framework by first using learning techniques for extracting statistical regularities of 'expert users' executing successful trajectories for the gripper towards the target object. Then, these learned trajectories were used for generating force cues able to guide novice users during their teleoperation task by the 'hands' of the expert users who demonstrated the trajectories in the first place. Both works have been submitted to ICRA'2017.

7.2.7. Direct Visual Servoing

Participants: Quentin Bateux, Eric Marchand.

In the direct visual servoing methods such as photometric framework, the images as a whole are used to define the control law. This can be opposed to the classical visual servoing approaches that relies on geometric features and where image processing algorithms that extract and track visual features are necessary. In [21], we proposed a generic framework to consider histograms as visual features. A histogram is an estimate of the probability distribution of a variable (for example the probability of occurrence in an intensity, color, or gradient orientation in an image). We demonstrated that the framework we proposed applies, but is not limited to, a wide set of histograms and allows the definition of efficient control laws.

Nevertheless, the main drawback for the direct visual servoing class of methods comparing to the classical geometric visual servoing methods is their comparatively limited convergence range. We then proposed in [48] a new direct visual servoing control law that relies on a particle filter to perform non-local and non-linear optimization in order to increase the convergence domain. To each particle considered we associate a virtual camera that predicts the image it should capture by using image transfer techniques. This new control law has been validated on a 6 DOF positioning task performed on our Gantry robot (see Section 6.9.1).

7.2.8. Audio-based Control

Participants: Aly Magassouba, François Chaumette.

This study is concerned with the application of sensor-based control approach to audio sensors. It is made in collaboration with Nancy Bertin from Panama group at Irisa and Inria Rennes-Bretagne Atlantique. Auditory features such as Interaural Time Difference (ITD), Interaural Level Difference (ILD), and sound energy have been modeled and integrated in various control schemes to control the motion of a mobile robot with two microphones onboard [66], [64]. Experiments with Romeo and Pepper (see Section 6.9.4) have also been achieved [65]. They show the robustness of closed loop sensor-based control with respect to coarse modeling and that explicit sound source localization is not a mandatory step for aural servoing.

7.3. Medical Robotics

7.3.1. Non-rigid Target Tracking in Ultrasound Images

Participants: Lucas Royer, Alexandre Krupa.

We pursued our work concerning the development of a real-time approach that allows tracking deformable soft tissue structures in 3D ultrasound sequences. In previous work we proposed a method which consists in estimating the target deformation by combining robust dense motion estimation and mechanical model simulation. This year we improved the robustness of our method to several image artefacts as the presence of large shadows, local illumination changes and image occlusions that occur due to the modification of the imaging gain and re-orientation of the ultrasound beam induced by probe motion. To achieve this, we proposed a new dissimilarity criterion between the current and reference images based on the Sum of Conditional Variance (SCV). Our new criterion, that we named Sum of Confident Conditional Variance (SCCV), consists in discriminating unconfident voxels thanks to the use of a pixel-wise quality measurement of the ultrasound images. This improved approach was experimentally validated on organic soft tissues and the obtained results were published in [40].

7.3.2. Optimization of Ultrasound Image Quality by Visual Servoing

Participants: Pierre Chatelain, Alexandre Krupa.

This study is realized in collaboration with Prof. Nassir Navab from the Technical University of Munich (TUM).

In previous work, we have developed ultrasound-based visual servoing methods to fulfill various tasks, such as compensating for physiological motion, maintaining the visibility of an anatomic target during ultrasound probe teleoperation, or tracking a surgical instrument. However, due to the specific nature of ultrasound images, guaranteeing a good image quality during the procedure remains a challenge. Therefore we pursued our study on the use of ultrasound confidence maps as a new modality for automatically positioning an ultrasound probe in order to improve the image quality. In addition to our visual servoing approach that optimizes the global quality of the image, this year we proposed a control fusion to optimize the acoustic window for a specific anatomical target which is tracked in the ultrasound images [50]. Recently, we extended our confidence-driven control to the out-of-plane motion of a 3D ultrasound probe and experimentally validated it on a human volunteer at TUM [14].

7.3.3. Visual Servoing using Shearlet Transform

Participants: Lesley-Ann Duflot, Alexandre Krupa.

In collaboration with the Femto-ST lab in Besançon, we proposed in a first-hand a solution to reduce the acquisition time of an Optical Coherence Tomography (OCT) 3D imaging scanner. This latter consists in sweeping a laser beam on a tissue sample of interest. To increase the frame rate of this imaging device we proposed to apply an optimal trajectory to the laser that covers entirely the image but without performing all the OCT measurements. The reconstruction of the missing data is then achieved by applying an updated Fast Iterative Soft-Thresholding Algorithm (FISTA) on a sparse representation of the image that is based on the shearlet transform [57]. In a second hand, we studied the feasibility of using the subsampled shearlet coefficients of an ultrasound image as the visual features of an image-based visual servoing. In a preliminary study we estimated numerically the interaction matrix that links the variation of the shearlet coarsest coefficients to the 6 degrees of freedom motion of the ultrasound probe and uses it in the visual servoing framework. The results obtained in cases of automatic probe positioning and phantom motion compensation demonstrated the efficiency of the shearlet-based features in terms of accuracy, repeatability, robustness and convergence behavior [59]. Then we proposed to consider a more efficient and adequate shearlet implementation that consists in a non-subsampled representation of the image. In this case the shearlet coefficients represent different images, focused on different singularities of the initial image, and we consider directly their pixel intensity values in the visual feature vector similarly to the photometry-based visual servoing approach. The modeling of the interaction matrix was analytically derived and experimental results demonstrated the reliability of the new method and its robustness to speckle noise [58].

7.3.4. 3D Steering of Flexible Needle by Ultrasound Visual Servoing

Participants: Jason Chevrie, Marie Babel, Alexandre Krupa.

The objective of this work is to provide robotic assistance during needle insertion procedures such as biopsy or ablation of localized tumor. In the past we only considered the control of the insertion and needle rotation along and around its main axis by the use of a duty-cycling control strategy. This latter consists in adapting online from visual feedback the orientation of a beveled-tip flexible needle during its insertion for controlling the needle curvature in 3D space that is induced by asymmetrical forces exerted on the bevel. However, such strategy limits the workspace of the needle tip. Therefore we proposed a new control method for flexible needle steering that combines direct base manipulation and needle tip based control. The direct base manipulation control is generated thanks to the use of a 3D model of a flexible beveled tip needle that gives the adequate motion of the needle base to obtain a given motion of the needle tip. This 3D model is based on virtual springs that characterize the needle mechanical interaction with soft tissue and is adapted online from visual tracking of the needle shape. From this model, a measure of the controllability of the needle tip degrees of freedom was proposed in order to mix the control between the direct base manipulation and the duty cycling technique

[51]. Preliminary results of an automatic needle tip positioning in a translucent gelatine phantom, observed by 2 orthogonal cameras, demonstrated the feasibility of the combination between direct base manipulation and needle tip control for reaching a desired target. This hybrid control allows better targeting capabilities in terms of larger needle workspace and reduced needle bending. In order to predict the trajectory of a needle during insertion under lateral motion of the tissue, we also improved our 3D model of the flexible needle to take into account the effect of the motion of the tissues on the needle shape. This was achieved thanks to the design of an algorithm based on an unscented Kalman filter that estimates the tissue motion. Results obtained from several needle insertions in a moving soft tissue phantom showed that our model gives good performance in terms of needle trajectory prediction. This model was also considered in a closed-loop control approach to allow automatic reaching of a target in case of tissue lateral displacement [52]. Future work will address the consideration of 3D ultrasound as visual feedback.

7.3.5. Enhancement of Ultrasound Elastography by Visual Servoing and Force Control

Participants: Pedro Alfonso Patlan Rosales, Alexandre Krupa.

Elastography imaging is performed by applying continuous stress variation on soft tissues in order to estimate a strain map of the observed tissues. It is obtained by estimating, from the RF (radio-frequency) signal along each scan line of the probe transducer, the echo time delays between pre- and post-compressed tissue. Usually, this continuous stress variation is performed manually by the user who manipulates the US probe and it results therefore in an user-dependent quality of the elastography image. To improve the ultrasound elastography imaging and provide quantitative measurement, we developed an assistant robotic palpation system that automatically moves a 2D ultrasound probe for optimizing ultrasound elastography [70]. The main originality of this work is the use of the elastography modality directly as input of the robot controller. Force measures are also considered in the probe control in order to automatically induce soft tissue deformation needed for real-time elastography imaging process.

7.4. Navigation of Mobile Robots

7.4.1. Visual Navigation from an Image Memory

Participants: Suman Raj Bista, Paolo Robuffo Giordano, François Chaumette.

This study is concerned with visual autonomous navigation in indoor environments. As in our previous works concerning navigation outdoors [4], the approach is based on a topological localization of the current image with respect to a set of keyframe images, but the visual features used for this localization as well as for the visual servoing are not composed of points of interest, but either on mutual information [71] following the idea proposed in [3], or straight lines that are more common indoors [38], or finally on a combination of points of interest and straight lines [11]. Satisfactory experimental results have been obtained using the Pioneer mobile robot (see Section 6.9.2).

7.4.2. Robot-Human Interactions during Locomotion

Participant: Julien Pettré.

In collaboration with the Gepetto team of Laas in Toulouse and the Mimetic group in Rennes, we have studied how humans avoid collision with a robot. Understanding how humans achieve such avoidance is crucial to better anticipate humans' reactions to the presence of a robot and to control the robot to adapt its trajectory accordingly. It is generally assumed that humans avoid a robot just like they avoid another human. In this work, we bring the empirical demonstration that humans actually set a specific strategy to avoid robots, and that, more precisely, they show a preference to give way to a robot which is on a collision course with them [41]. This results brings useful insight about human-robot interactions during locomotion, and provides useful guidelines to design reactive navigation techniques for mobile robots aimed at moving among humans.

7.4.3. Scene Mapping based on Intelligent Human/Robot Interactions

Participant: Patrick Rives.

For mobile robots to operate in compliance with human presence, interpreting the impact of human activities and responding constructively is a challenging goal. Towards this objective, mapping an environment allows robots to be deployed in diverse workspaces, marking this skill as a primary element in the integration of robots into human-populated environments. We proposed an effective approach for using human activity cues in order to enhance robot mapping and navigation and in particular in filtering noisy human detections, detecting passages, inferring space occupancy and allowing navigation within unexplored areas. Our contributions [36] are based on the development of intelligent interactions among conceptually different mapping levels, namely, the metric, social and semantic levels. Experiments, using the Hannibal platform (see Section 6.9.2), highlighted a number of strong dependences among these levels and the way in which they can be used to enhance individual performances and in turn the global robot operation.

7.4.4. Autonomous Social Navigation of a Wheelchair

Participants: Vishnu Karakkat Narayanan, Marie Babel.

This work is realized in collaboration with Anne Spalanzani (Chroma team - Inria Grenoble).

A key issue that hinders the adoption of assistive robotic technologies such as robotized wheelchair, in the real world, is that they need to operate in mostly human environments and among human crowds. Indeed intelligent wheelchairs need to be deployed in a human environment thereby making it essential for such robots to incorporate a sense of human-awareness. Simply put, humans are special objects that have to be perceived and acted on in a special manner by robots that interact with us humans. Thus one can define Human-aware Navigation as an intersection between human-robot interaction and robotic motion planning.

In this context we introduced a low-level velocity controller that could be employed by a social robot like a robotic wheelchair for approaching a group of interacting humans, in order to become a part of the interaction. Taking into account an interaction space that is created when at least two humans interact, a meeting point can be calculated where the robot should reach in order to equitably share space among the interacting group. We then proposed a sensor-based control law which uses the position and orientation of the humans with respect to the sensor as inputs, to reach the meeting point while respecting spatial social constraints [61]. Experiments using a mobile robot equipped with a single laser scanner, realized in collaboration with Ren Luo (Taiwan) within the Sampen Inria associated team, also proved the success of the algorithm in a noisy real world scenario [62].

In addition, a semi-autonomous framework for human-aware navigation in an intelligent wheelchair has been designed. A generalized linear control sharing framework was proposed that was able to progressively correct the user teleoperation in order to avoid obstacles and in order to avoid disturbance to humans. Meanwhile, we also proposed a Bayesian approach for user intention estimation. The formulation was partly inferred from the design of the controller for assisted doorway passing, wherein we hypothesized that predicting short term goals is sufficient for eliminating user intention uncertainty [16].

7.4.5. Semi-autonomous Control of a Wheelchair for Navigation Assistance

Participants: Louise Devigne, Vishnu Karakkat Narayanan, Marie Babel.

To address the wheelchair driving assistance issue, we proposed a unified shared control framework able to smoothly correct the trajectory of the electrical wheelchair [16]. The system integrates the manual control with sensor-based constraints by means of a dedicated optimization strategy. The resulting low-complex and low-cost embedded system is easily plugged onto on-the-shelf wheelchairs [55]. The robotic solution is currently under validation process with volunteering patients of Pôle Saint Hélier (France) who present different disabling neuro-pathologies preventing them to drive non-assisted wheelchairs.

Within the frame of ISI4NAVE associated team (see Section 9.4.1.2), this shared-control solution has been then coupled with first experimental biofeedback devices such as haptic devices. Preliminary tests have been conducted within the PAMELA facility at University College of London and within the rehabilitation center of Pôle Saint Hélier in Rennes (see Section 8.1.3). They involved regular wheelchair users as well as medical staff. We have demonstrated the ability of the framework to provide relevant assistance and now need to focus on methods to fine-tune parameters and customize/calibrate to the individual and evolving needs of each user.

7.5. Multi-robot and Crowd Motion Control

7.5.1. Advanced multi-robot control and estimation

Participant: Paolo Robuffo Giordano.

The challenge of coordinating the actions of multiple robots is inspired by the idea that proper coordination of many simple robots can lead to the fulfillment of arbitrarily complex tasks in a robust (to single robot failures) and highly flexible way. Teams of multi-robots can take advantage of their number to perform, for example, complex manipulation and assembly tasks, or to obtain rich spatial awareness by suitably distributing themselves in the environment. Within the scope of robotics, autonomous search and rescue, firefighting, exploration and intervention in dangerous or inaccessible areas are the most promising applications.

In the context of multi-robot (and multi-UAV) coordinated control, *connectivity* of the underlying graph is perhaps the most fundamental requirement in order to allow a group of robots accomplishing common goals by means of *decentralized* solutions. In fact, graph connectivity ensures the needed continuity in the data flow among all the robots in the group which, over time, makes it possible to share and distribute the needed information. We gave two contributions in this field: in the first one [35], we proposed a decentralized exploration strategy for a team of 3D agents able to guarantee exploration of a finite space in a finite amount of time while coping with the constraints of a connected sensing/communication graph for the robot group against sensing/communication constraints (limited range, occluded line-of-sight), and of obstacle and inter-robot collision avoidance. The strategy exploits a suitable state machine for assigning dynamic roles to the agents in the group for allowing completion of the exploration in finite time. Second, in [28] we studied how the choice of a leader agent in a leader-follower scenario could affect the performance of the group when tracking a desired formation (shape and gross motion). The proposed strategy allows selecting the "best leader" online as a function of the current group state (relative positions and velocities) and of the group topology (assumed connected). By cycling among several connected topologies during motion, we could show that our proposed leader selection algorithm provides the best performance among other possible choices (including the random one) while coping with the constraint of a connected (but possibly time-varying) topology.

These works were realized in collaboration with the robotics group at the Max Planck Institute for Biological Cybernetics, Tübingen, Germany, and the RIS group at Laas in Toulouse.

7.5.2. Rigidity-based methods for formation control

Participants: Fabrizio Schiano, Riccardo Spica, Andrea Peruffo, Paolo Robuffo Giordano.

Most multi-robot applications must rely on *relative sensing* among the robot pairs (rather than absolute/external sensing such as, e.g., GPS). For these systems, the concept of *rigidity* provides the correct framework for defining an appropriate sensing and communication topology architecture. Rigidity is a combinatorial theory for characterizing the "stiffness" or "flexibility" of structures formed by rigid bodies connected by flexible linkages or hinges. In a broader context, rigidity turns out to be an important architectural property of many multi-agent systems when a common inertial reference frame is unavailable. Applications that rely on sensor fusion for localization, exploration, mapping and cooperative tracking of a target, all can benefit from notions in rigidity theory. The concept of rigidity, therefore, provides the theoretical foundation for approaching decentralized solutions to the aforementioned problems using distance measurement sensors, and thus establishing an appropriate framework for relating system level architectural requirements to the sensing and communication capabilities of the system.

In the recent past, we have proposed a decentralized gradient-based rigidity maintenance action for a group of quadrotor UAVs [10]. By starting in a rigid configuration, the group of UAVs was able to estimate their relative position from sole relative distance measurements, and then use these estimated relative positions in a control action able to preserve rigidity of the whole formation despite presence of sensor limitations (maximum range and line-of-sight occlusions), possible collisions with obstacles and inter-robot collisions. This (rigidity-based) control/estimation framework has now been extended to the case of *bearing rigidity* for directed graphs: here, rather than distances the measurements are the 3D bearing vectors expressed in the local body-frame of each agent. The theory has been extended to the case of 3D agents evolving in $\mathbb{R}^3 \times \mathbb{S}^1$ by proposing a decentralized bearing controller/localization algorithm that only requires one single distance measurement (among an arbitrary pair of agents) for a correct convergence [72]. The proposed algorithm ensures stabilization towards a desired bearing formation, and allows for the possibility of actuating the motion directions in the null-space of the bearing constraints (that is, collective translations in 3D, expansion/retraction, and coordinated rotation about a vertical axis).

The need of a single distance measurement (for fixing the formation scale) has also been relaxed in [73] where an *active* scale estimation scheme has been proposed for allowing the (distributed) estimation of the various inter-agent distances online by processing the measured bearings and the known agent ego-motion (body-frame linear and angular velocities). Finally, we have also proposed an extension of the "distance" rigidity maintenance controller proposed in [10] to the case of bearing measurements (and bearing rigidity), by considering the typical sensing constraints of onboard cameras, that is, limited range, limited field of view, of possible mutual occlusions when two or more agents lie on the same line-of-sight. This work has been experimentally validated with 5 quadrotor UAVs, and has been submitted to ICRA'2017.

These works were realized in collaboration with the RIS group at Laas, Toulouse, and with Technion, Israel.

7.5.3. Cooperative localization using interval analysis

Participants: Ide Flore Kenmogne Fokam, Vincent Drevelle.

In the context of multi-robot fleets, cooperative localization consists in gaining better position estimate through measurements and data exchange with neighboring robots. Positioning integrity (i.e., providing reliable position uncertainty information) is also a key point for mission-critical tasks, like collision avoidance. The goal of this work is to compute position uncertainty volumes for each robot of the fleet, using a decentralized method (i.e., using only local communication with the neighbors). The problem is addressed in a bounded-error framework, with interval analysis and constraint propagation methods. These methods enable to provide guaranteed position error bounds, assuming bounded-error measurements. They are not affected by over-convergence due to data incest, which makes them a well sound framework for decentralized estimation. Ongoing work focuses on position uncertainty domain computation in image-based UAV localization [63], and its extension to cooperative localization in a multi-UAV fleet.

7.5.4. Numerical Models of Local Interactions during Locomotion

Participants: Julien Bruneau, Panayiotis Charalambous, David Wolinski, Julien Pettré.

The numerical models of local interactions are core components of reactive navigation techniques (which allows a robot to avoid dynamic obstacles) and of microscopic crowd simulation algorithms (which allows to simulate a crowd motion as a collection of agent trajectories). We have pursued our efforts to design local models of interactions which capture humans pedestrian behavior, to simulate how they adapt their trajectory so as to perform interactions with their neighbors [12]. This year, our efforts were focused on the simulation of grouping behaviors [39], and mid-term strategies human set to perform energy-efficient sequences of successive avoidance adaptations [24]. These two situations deal with complex situations of interactions, where several interactions of different kinds need to be combined to compute agents trajectories. For example, when moving in groups, agents have to keep close to the other members of their group while they should not collide with them, as well as they should avoid collision with any other agent or obstacle out of this group.

We also revisited the foundation of velocity-based models of local interaction for collision avoidance. Using a velocity-based model, a collision-free motion is computed for one agent by extrapolating the future motion of neighbor agents with respect to their current position and velocity. From this information, each agent can deduce the set of velocities (called admissible velocities) that lead to a collision-free motion in the near future. The extrapolation is generally simply based on a linear extrapolation of the future position along the current velocity vector. This is simplistic as it assumes that the current velocity vector is representative of the future motion, while it is often false when, for instance, the agent is currently performing adaptations due to ongoing collision avoidance, or when the agent is following a curvy path. To improve the accuracy of motion prediction and the resulting simulation, we have introduced a probabilistic representation of future position, that can be computed from a set of context elements such as the layout of the environment or the agents past motion [42]. We demonstrate in this work the high impact on the level of realism of resulting simulations. This work is implemented in the WarpDriver software (see Section 6.7).

Finally, we address applications of our simulators to the Computer Animation. Crowd simulation agents generally have a simplistic geometrical and kinematics models, typically, an oriented 2D circle moving on a flat surface. In Computer Animation, an animation of a crowd of 3D realistic characters can be computed on top of the agents simulation by computing their internal joints trajectories so as to perform walking motion along computed agents trajectories. However, the discrepancies between the 2D model of agents and 3D full body characters may result into residual collisions between character shapes. In this collaboration with the Mimetic team, we demonstrate that simple secondary animations for characters, such as local shoulder motions, can be efficiently triggered to camouflage those artefacts, with a very low computational overhead [29].

7.5.5. Motion Planning for Digital Characters

Participant: Julien Pettré.

Motion planning is an important component for agents and robot navigation and control, providing them the ability to perform geometrical reasoning over their environment to transform a high-level distant goal in their environment into a sequence of local motions and sub-goals to reach. This year, we have been involved into two collaborations dealing with motion planning. First collaboration was with the University of Utrecht in the Netherlands. We have proposed a method to evaluate and compare various environment decomposition techniques [74]. Environment decomposition is an important step to perform navigation planning in large static environments. Second collaboration was with the University of North Carolina in Chapel Hill (see Section 9.4.1.1). We have coupled a contact planner for virtual characters with ITOMP, a motion optimization technique to achieve complex motion in cluttered environment [69].

STARS Project-Team

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)

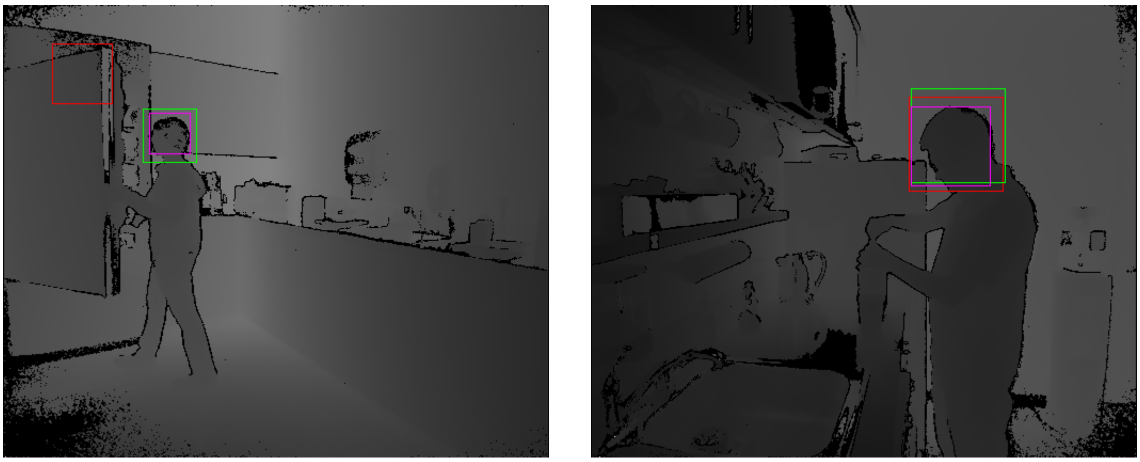


Figure 5. Examples of head detection where our algorithm successfully detects head. Pink square represents the ground truth, green rectangle represents our algorithm.

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

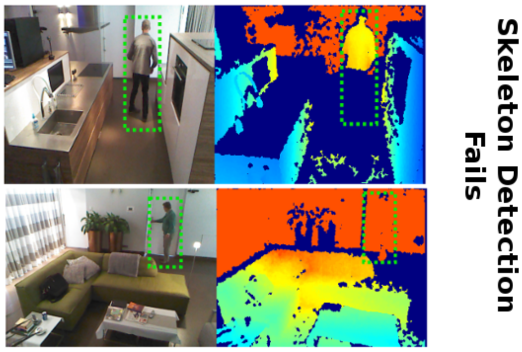


Figure 6. We show two examples where skeleton detection methods fail. Pictures on the left show RGB frame, pictures on the right show depth map (dark blue indicates missing depth information).

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.

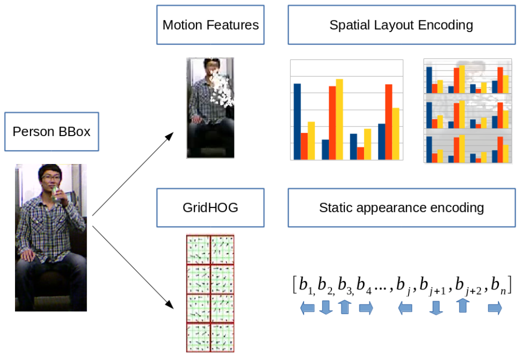


Figure 7. We show proposed method where we use people detection in place of skeleton. Next we propose to encode spatial-layout of visual words computed from motion features. In addition we propose GridHOG descriptor which encodes static appearance information.

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.

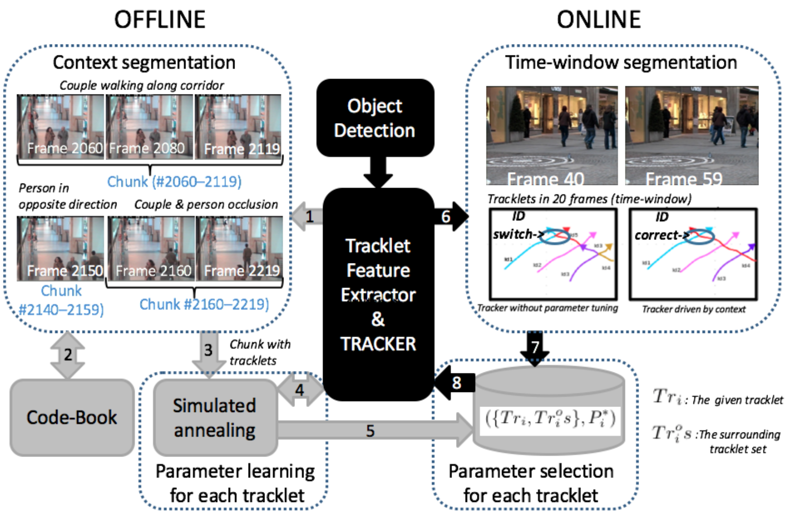


Figure 8. Our proposed framework.

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.

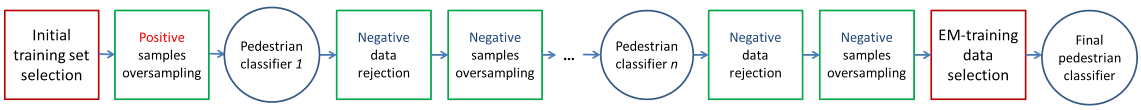


Figure 9. Training pipeline.

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:

$$Miss\ Rate = \frac{False\ Negatives}{True\ Positives + False\ Negatives} \tag{1}$$

		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]

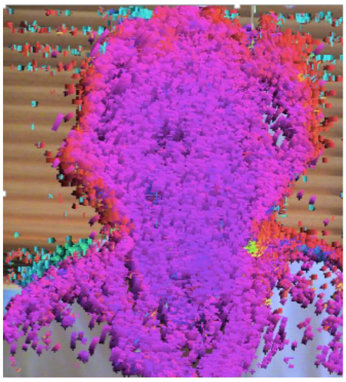


Figure 11. Expression recognition in AD patients based on dense trajectories and Fisher vectors. Dense trajectories visualization.

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.

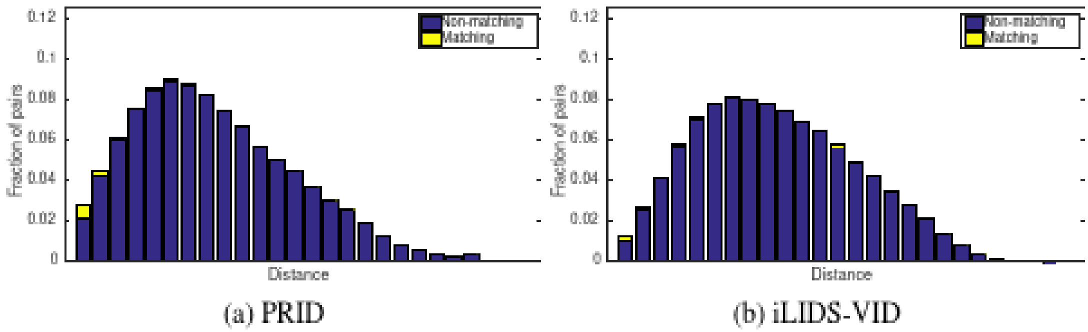


Figure 12. Distributions of distances between pairs of signature of randomly selected half of a) PRID, and b) iLIDS-VID datasets for MCM representation using Euclidean distance. The distributions are averaged for 10 trials.

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.

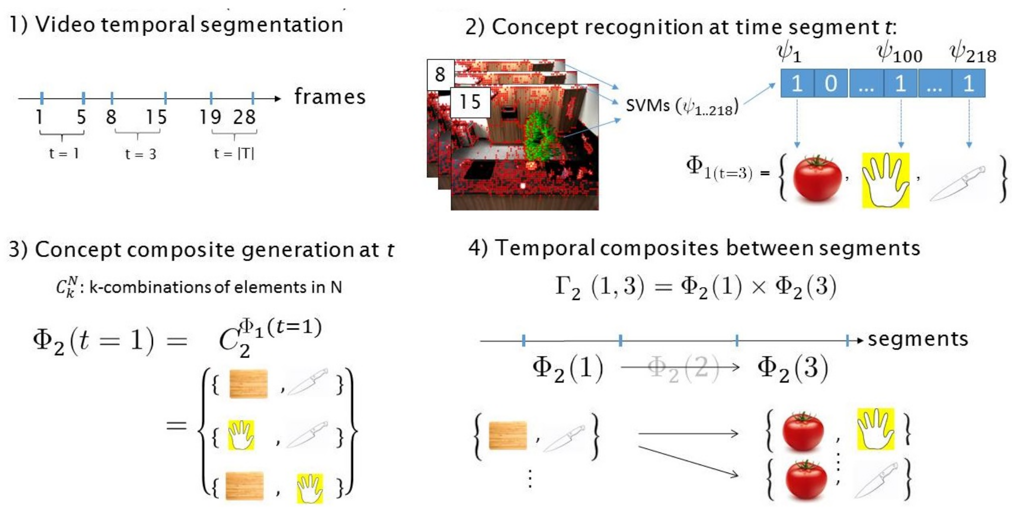


Figure 13. Semi-supervised learning of a video representation: 1) video temporal segmentation, 2) concept recognition 3) composite concept generation per time segment, 4) Temporal composite generation between segments.

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

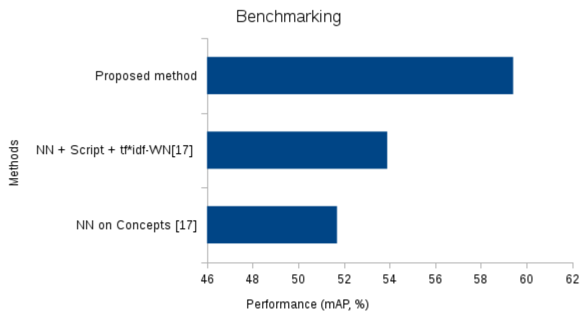


*Figure 14. Performance benchmarking of our approach against data set baselines: a) Nearest Neighbor classifier (NN) on concepts, script data, and tf*idf-WN, and b) NN only on concepts.*

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.

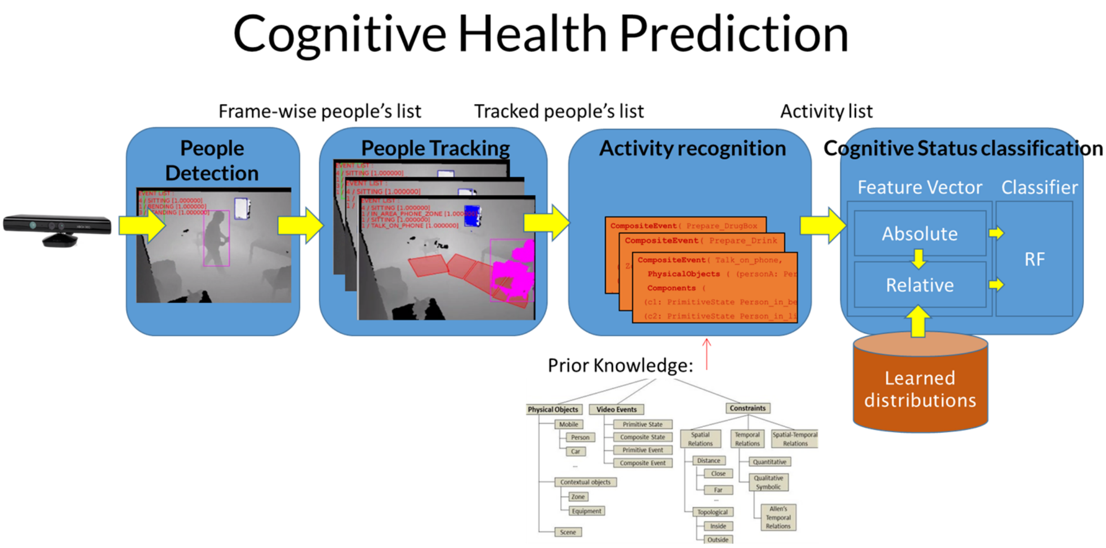


Figure 15. Automatic framework for visual recognition of cognitive health status: visual event recognition is responsible to detect and track people in the scene and recognize their events based on spatio-temporal relations with scene objects. Cognitive health classification represents absolute and relative information about the target classes.

Figure 16. Monitoring a senior performing at a gait-related event

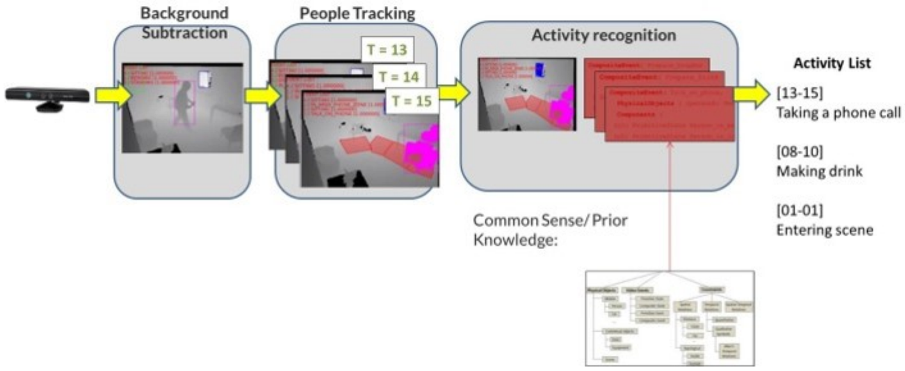


Figure 17. Pipeline for online activity recognition: given an acquisition camera (e.g. a Kinect), it firstly detects people using background subtraction algorithm, then it looks for appearance correspondence between people detected in the current frame with respect to past detections (past-present approach), and thirdly it recognizes the activities performed by each of the tracked people.

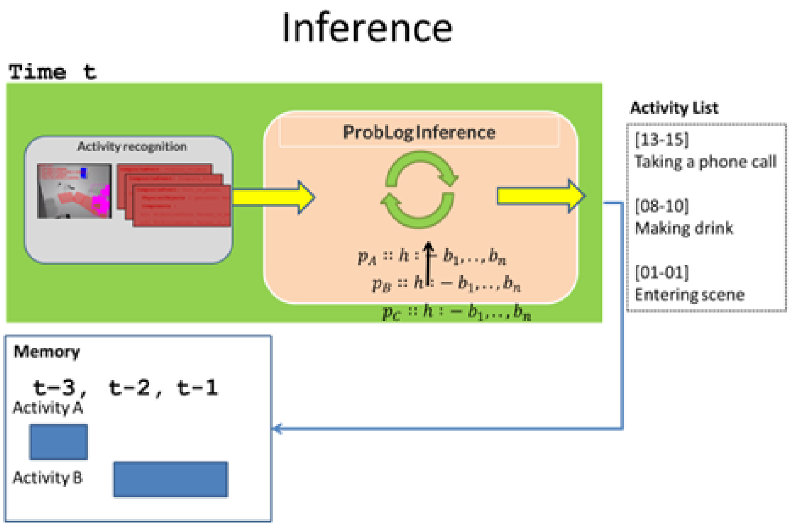


Figure 18. Temporal Inference using ProbLog engine. It takes as input deterministic observations and frame-wisely it recognizes the target events. Frame-events are aggregated into time intervals to create the time intervals of complex activities.

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.

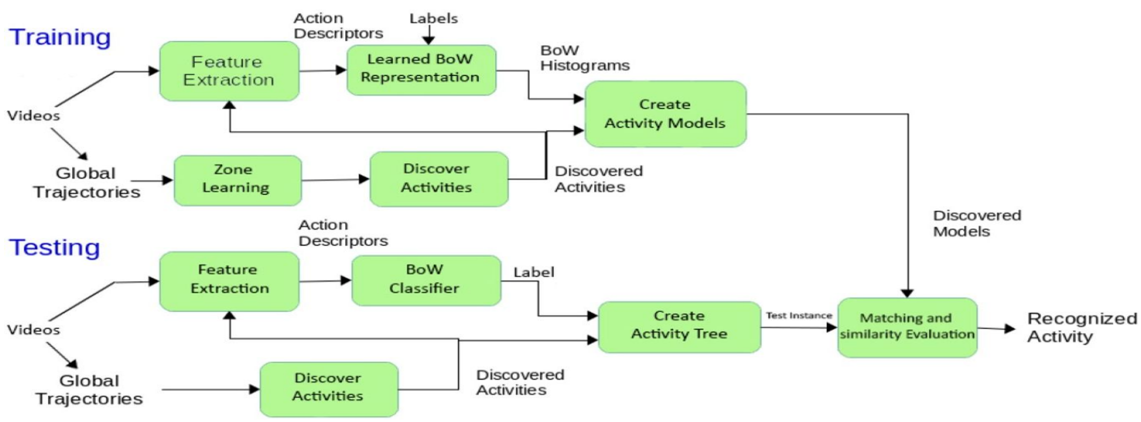


Figure 19. Architecture of the framework: Training and Testing phases

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.

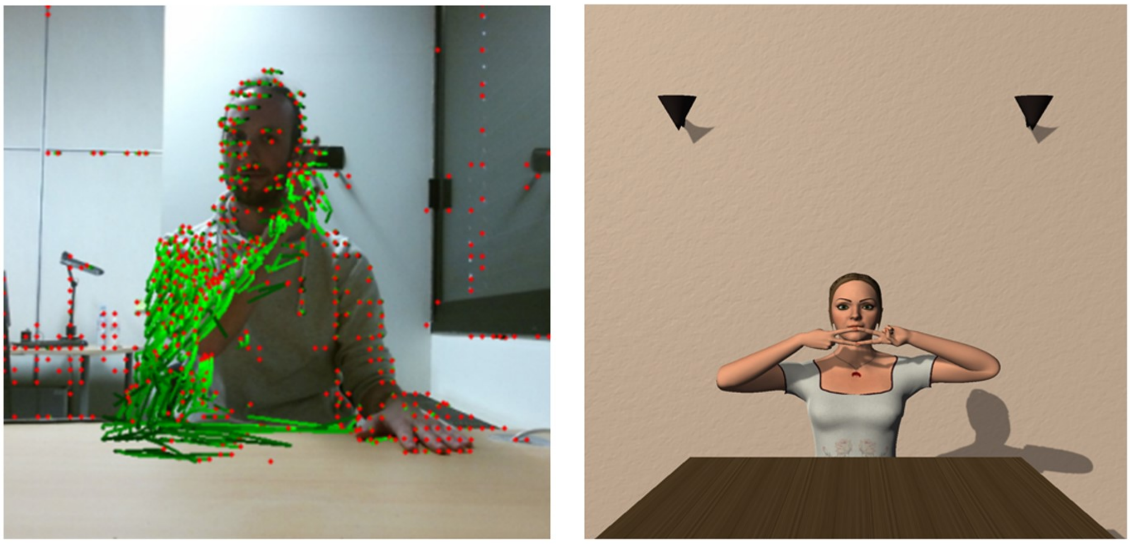


Figure 20. Left: Extracted motion descriptors while performing a gesture Right: virtual avatar guides patients in a virtual reality environment

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

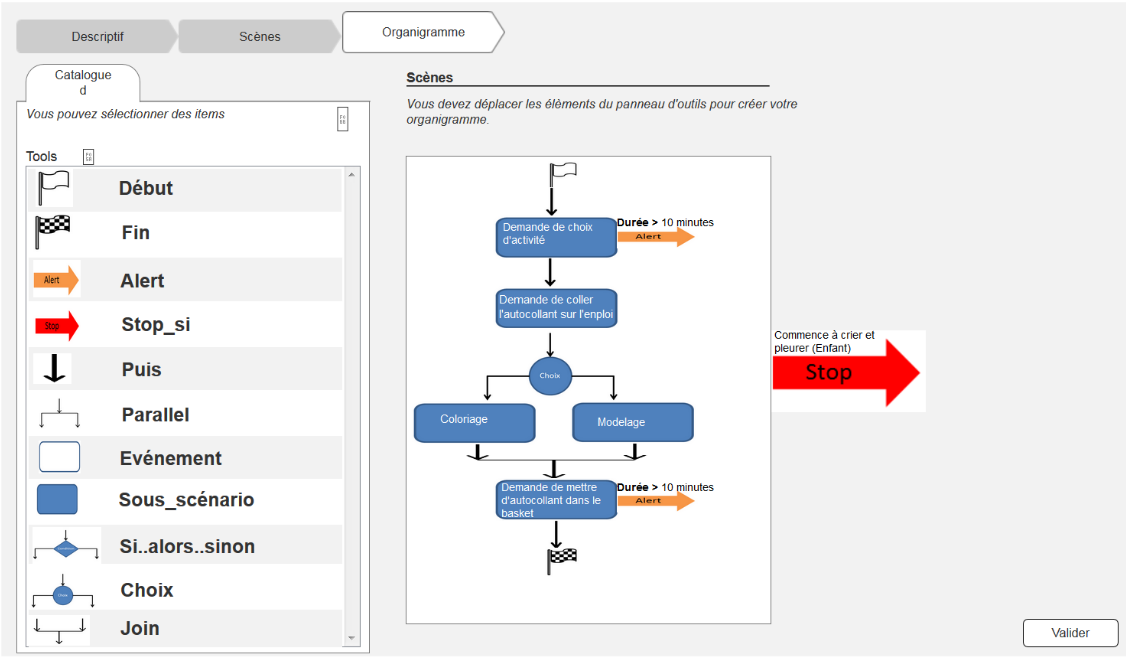


Figure 22. Generic flowchart

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.

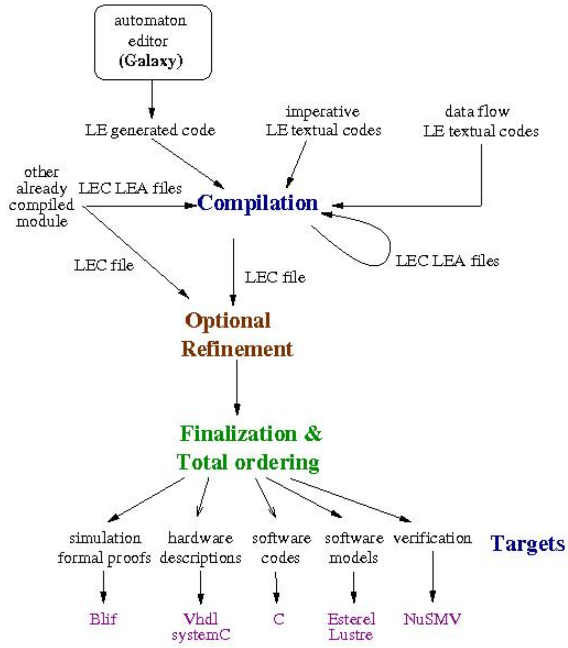


Figure 23. The Clem Toolkit

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.

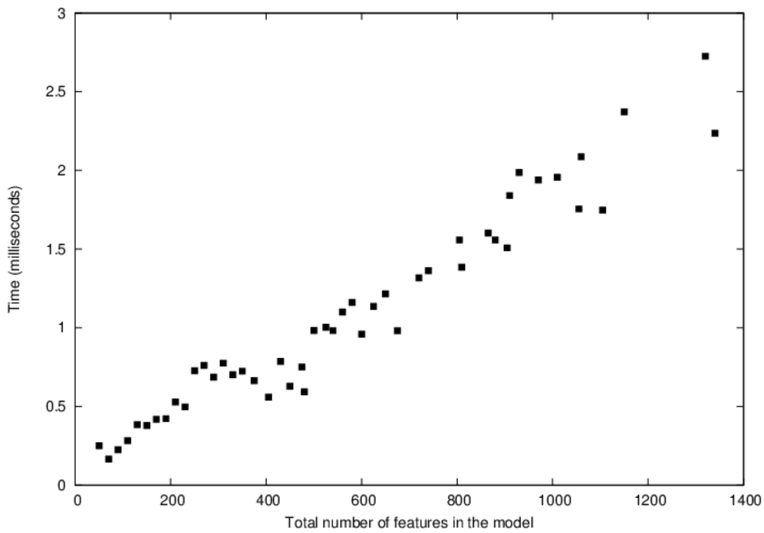


Figure 24. Computation time of initial models

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.

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.

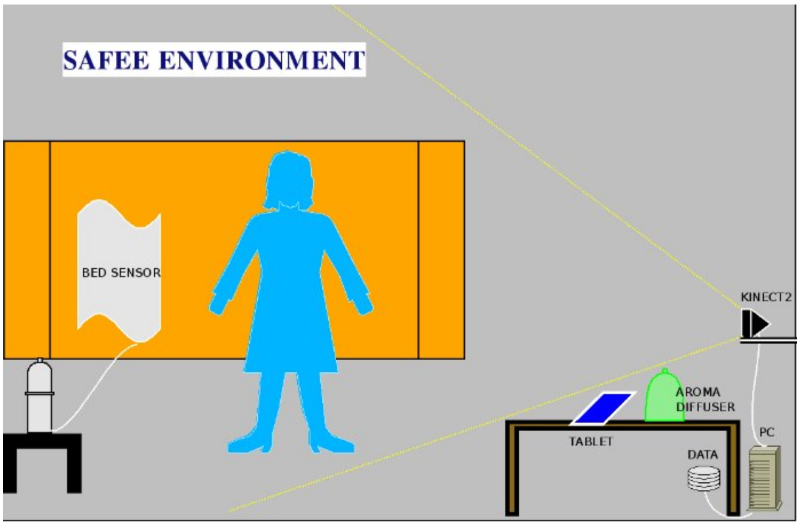


Figure 25. The Safee environment

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 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.

TITANE Project-Team

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.

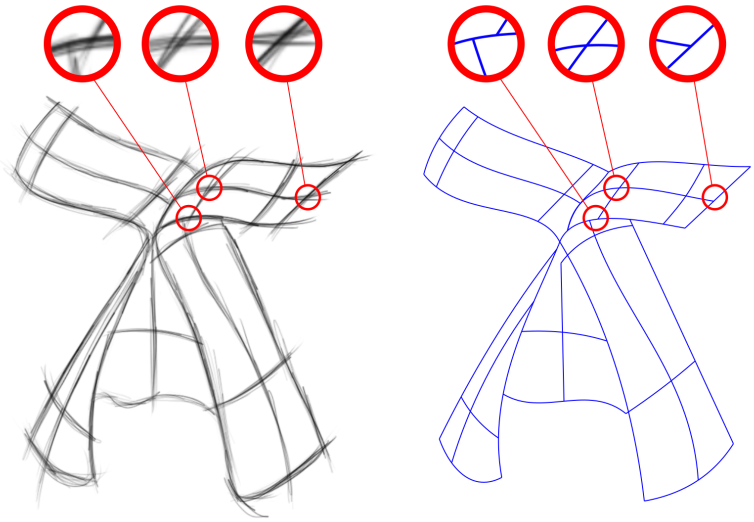


Figure 1. Line Drawing Vectorization. Rough sketches often contain overlapping strokes (left). Since existing algorithms analyze junctions locally, they cannot recover the proper topology of these seemingly similar line configurations. By adopting a global formulation that optimizes for both fidelity 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.

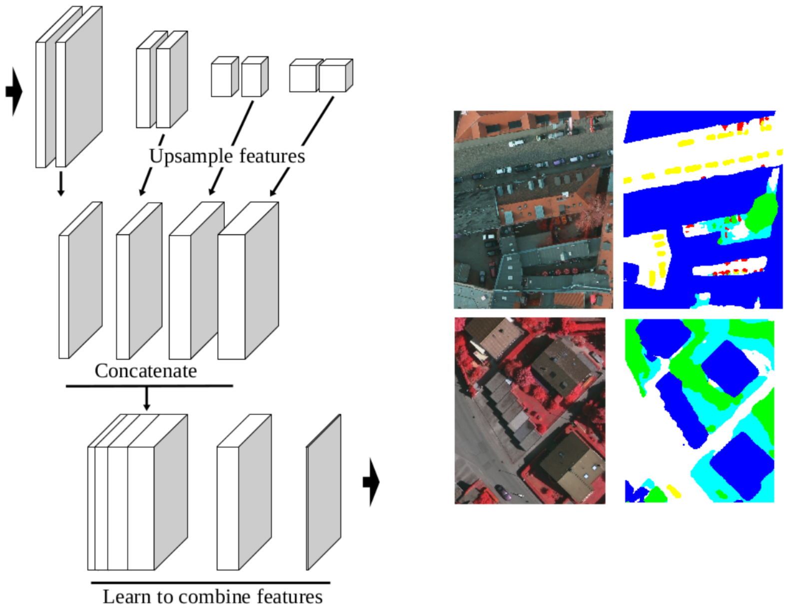


Figure 2. Our MLP network architecture (left) learns features at different resolutions and also learns how to combine those features. The technique was evaluated on the ISPRS 2D Semantic Segmentation Contest (right), providing competitive results.

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)

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].

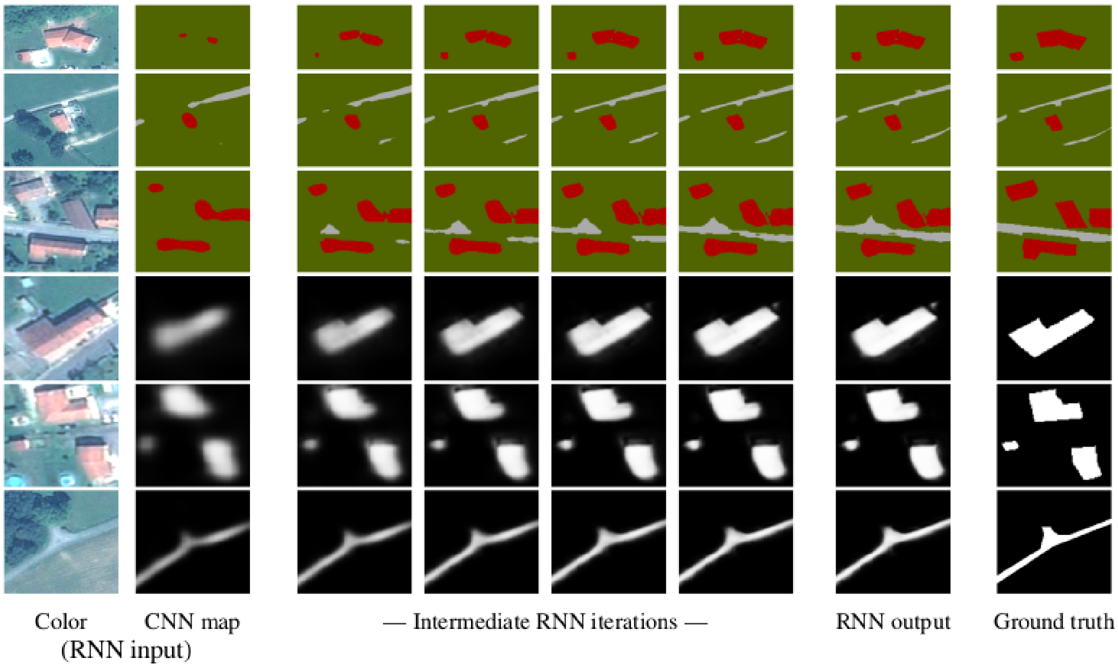


Figure 3. A recurrent neural network (RNN) learns an algorithm to iteratively correct the output of a coarse classification map. As a result, the satellite image classification maps become finer and better aligned to the real objects.

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].

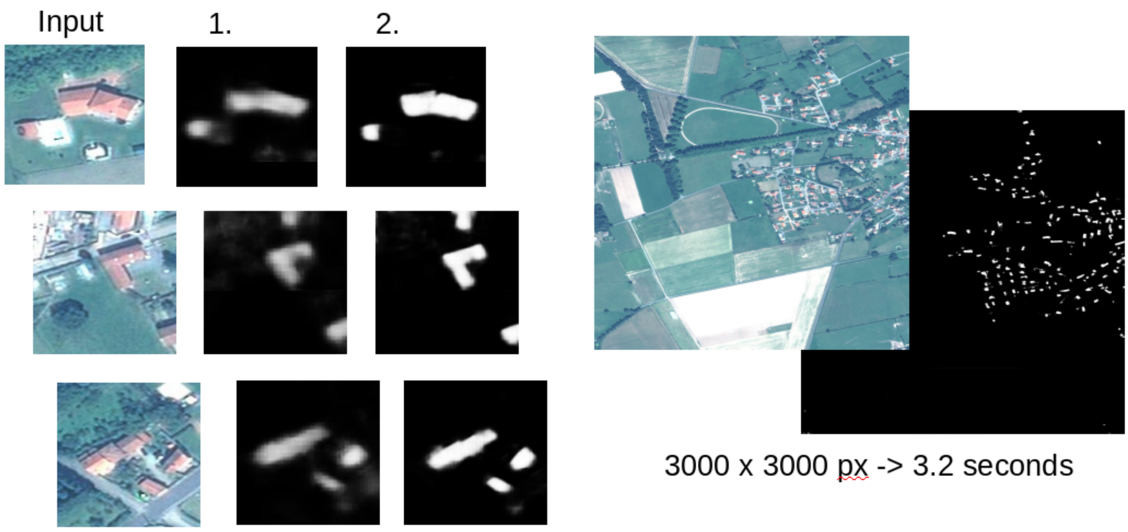


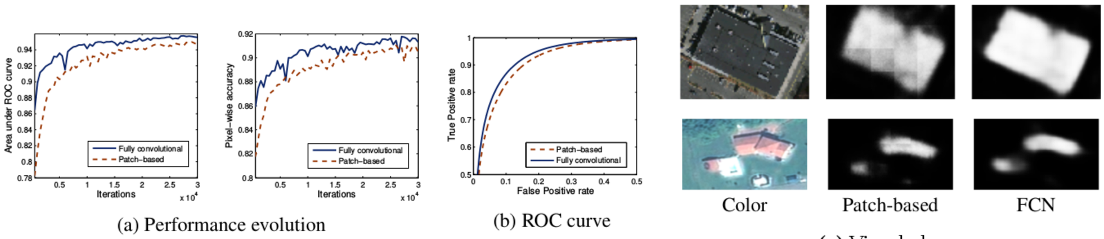
Figure 4. We train in a two-step scheme: first we train a fully convolutional network on large amounts of imperfect training data, to capture the generalities of the problem, which leads to coarse classification maps (1). In a second stage we fine-tune the network for few iterations on a precise manually 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].



(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.

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)

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.

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).

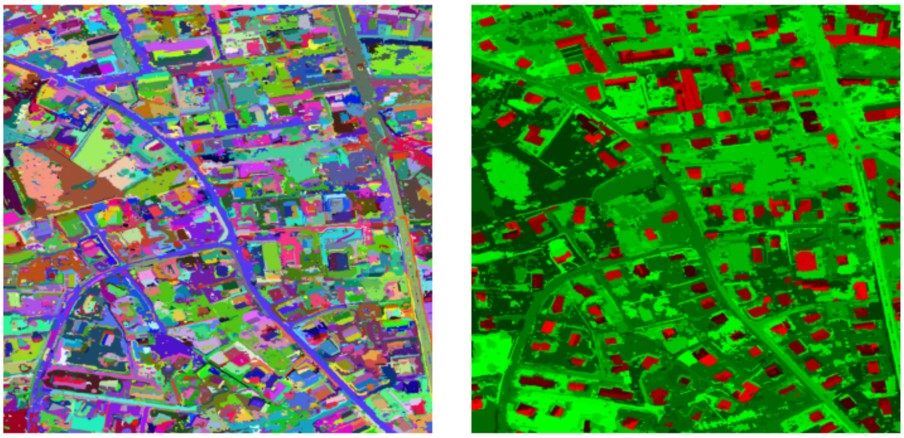


Figure 6. Results of (left) unsupervised segmentation and (right) supervised segmentation of the image into building (red) and non-building (green) regions, using 4×4 tiling scheme.

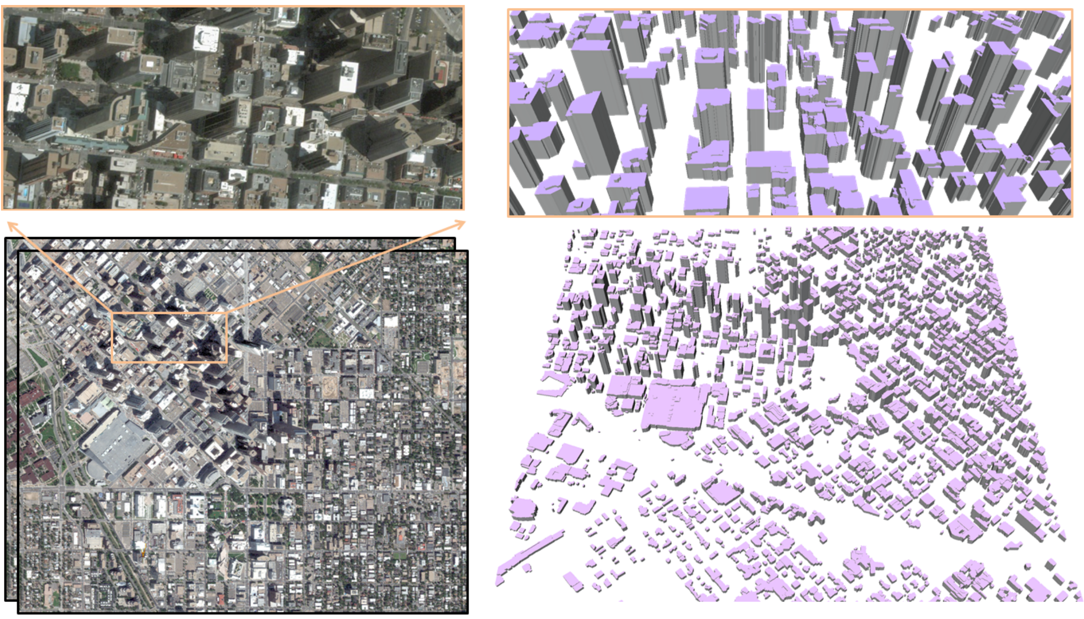


Figure 7. City reconstruction from satellites. Starting from a stereo pair of satellite images (left), our algorithm produces a compact and semantic-aware 3D model (right) in a few minutes.

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].

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.

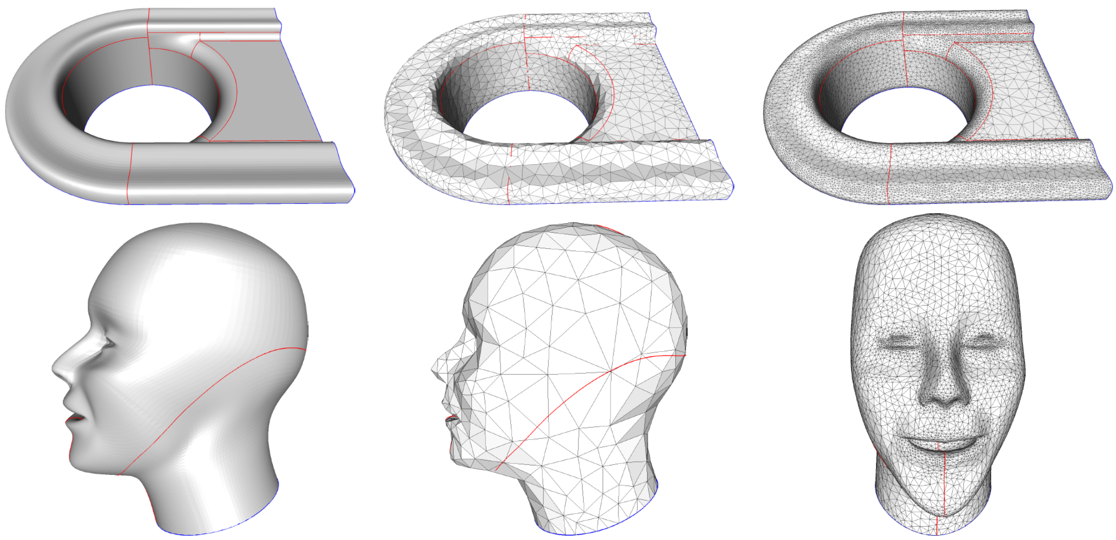


Figure 8. Seamless meshing. Top: meshing with two mesh sizing values. The initial point set is generated by sampling along the open boundary. Bottom: meshing across smooth edges (red). The initial point set is generated by sampling along the boundary edge (blue). Meshes generated with two sizing values (side and front view).

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 [].

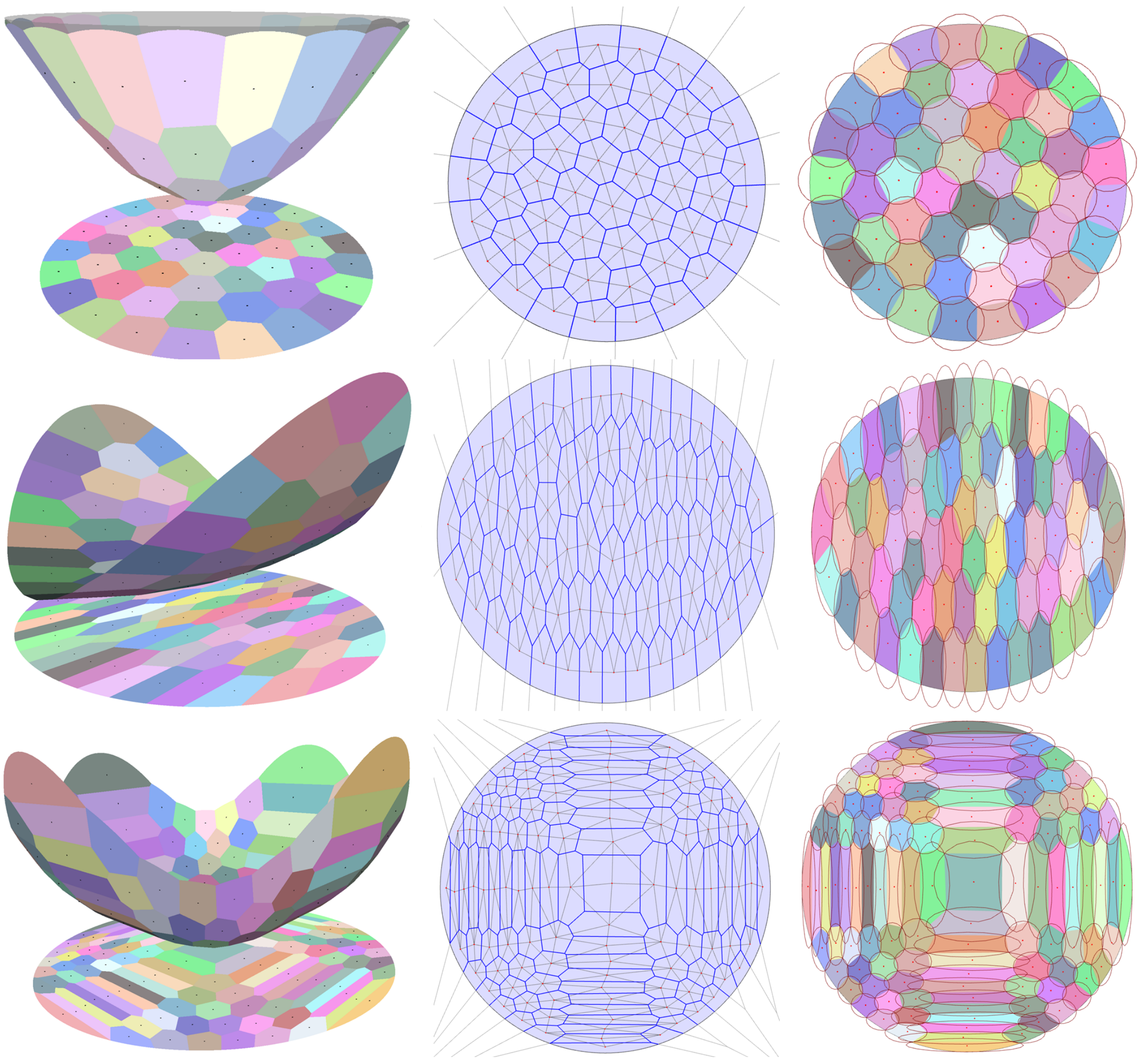


Figure 9. Optimal Voronoi Tessellations with Hessian-based Anisotropy. We show that the construction of an optimal piecewise-linear approximation of a function over a cell complex (left) extends the isotropic notion of Centroidal Voronoi Tessellations (CVT, top) to an anisotropic variant (middle and 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.

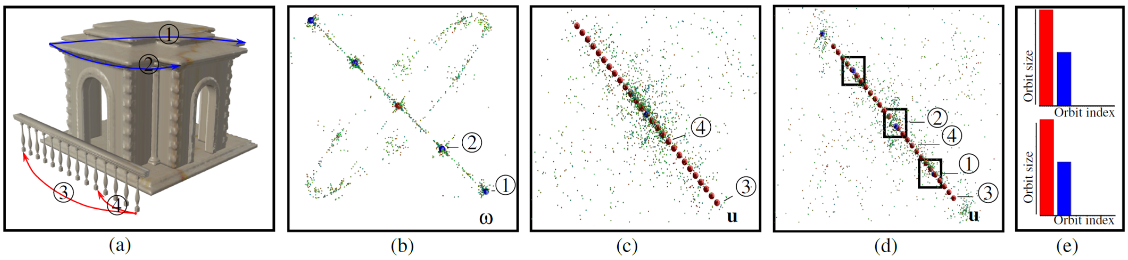


Figure 10. Our Lie algebra voting approach to symmetry and orbit detection maps SE(3) transformations into points in a logarithmic space composed of a rotation part and a translation part. The rotational orbit of the church and the translational orbit of the side railing (a) are mapped into collinear 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).

WIMMICS Project-Team

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.

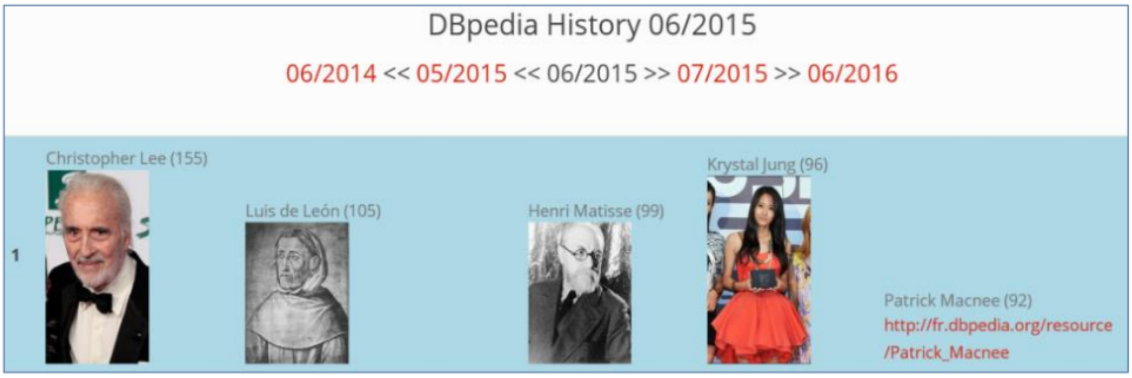


Figure 1. DBpedia Artist category with edition history

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.).

7.4. Analyzing and Reasoning on Heterogeneous Semantic Graphs

7.4.1. SPARQL Template Transformation Language

Participants: Olivier Corby, Catherine Faron-Zucker, Raphaël Gazzotti.

[0]http://dbpedia-live.inria.fr/sparql
[0] http://ns.inria.fr/provoc

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.

ZENITH Project-Team

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.