RESEARCH CENTER
Sophia Antipolis - Méditerranée

FIELD

Activity Report 2017

Section New Results

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ABS Project-Team

5. New Results

5.1. Modeling interfaces and contacts

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

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

Participants: F. Cazals, S. Marillet.

In collaboration with P. 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 [17], 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.

5.1.2. Anti-interleukin-6 signalling therapy rebalances the disrupted cytokine production of B cells from patients with active rheumatoid arthritis

Participants: F. Cazals, A. Lhéritier.

In collaboration with S. Fleischer (1. Charité University Medicine Berlin, Berlin, Germany), S. Ries (2. Deutsches Rheuma-Forschungszentrum Berlin, Berlin, Germany), P. Shen (2.), G.R. Burmester (1.), T. Dörner (1.), S. Fillatreau (2., Institut Necker-Enfants Malades, Université Paris Descartes, IHP Hôpital Necker Enfants Malades).

Rheumatoid arthritis (RA) is associated with abnormal B cell-functions implicating antibody-dependent and -independent mechanisms. B cells have emerged as important cytokine-producing cells, and cytokines are well-known drivers of RA pathogenesis. To identify novel cytokine-mediated B-cell functions in RA, in this work [16], we comprehensively analysed the capacity of B cells from RA patients with an inadequate response to disease modifying anti-rheumatic drugs to produce cytokines in comparison with healthy donors (HD). RA B cells displayed a constitutively higher production of the pathogenic factors interleukin (IL)-8 and Gro-α, while their production of several cytokines upon activation via the B cell receptor for antigen (BCR) was broadly suppressed, including a loss of the expression of the protective factor TRAIL, compared to HD B cells. These defects were partly erased after treatment with the IL-6-signalling inhibitor tocilizumab, indicating that abnormal IL-6 signalling contributed to these abnormalities. Noteworthy, the clinical response of individual patients to tocilizumab therapy could be predicted using the amounts of MIP-1β and β-NGF produced by these patients' B cells before treatment. Taken together, our study highlights hitherto unknown abnormal B-cell functions in RA patients, which are related to the unbalanced cytokine network, and are potentially relevant for RA pathogenesis and treatment.

5.2. Modeling macro-molecular assemblies

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

5.2.1. Complexity dichotomies for the minimum F-overlay problem

Participants: D. Mazauric, R. Watrigant.

In collaboration with N. Cohen (LRI, UMR de l'Université Paris-Sud et du CNRS), F. Havet (Université Côte d'Azur, I3S, UMR de l'Université Nice Sophia et du CNRS), I. Sau (LIRMM, UMR de l'Université Montpellier et du CNRS, and Universidade Federal do Ceará, Brazil).

The *connectivity inference* problem for native mass spectrometry aims at finding the most plausible pairwise contacts between the individual subunits of a macro-molecular assembly, given the composition of overlapping oligomers. The associated combinatorial optimization problem consists in determining a minimal-cardinality set of contact (edges) such that all the subunits of each oligomer must be "connected" (each oligomer must induce a connected graph). We studied in [18] the general inference problem that consists of considering more general properties on oligomers. For this new problem, we are given a list of possible topologies (graphs) for each oligomer and we aim at minimizing the total number of contacts between subunits. In terms of graphs, we are given a family of subgraphs that can match the structure of the oligomers. These new constraints reflect biophysical properties: a subunit has a limited number of neighbors (bounded maximum degree of the subgraphs), selected contacts are already known (a given subgraph contained in the complex), etc. We prove that the problem is NP-complete (no polynomial time algorithm, unless P = NP) for almost all cases.

5.3. Modeling the flexibility of macro-molecules

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

No new result on this topic in 2017.

5.4. Algorithmic foundations

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

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

5.4.1. Extracting the groupwise core structural connectivity network: bridging statistical and graph-theoretical approaches

Participant: D. Mazauric.

In collaboration with N. Lascano (Universidad de Buenos Aires, Argentina, Université Côte d'Azur, and Inria Sophia Antipolis - Méditerranée, EPI ATHENA), G. Gallardo (2. Université Côte d'Azur and Inria Sophia Antipolis - Méditerranée, EPI ATHENA), D. Wassermann (2).

Finding the common structural brain connectivity network for a given population is an open problem, crucial for current neuro-science. Recent evidence suggests there is a tightly connected network shared between humans. Obtaining this network will, among many advantages, allow us to focus cognitive and clinical analyses on common connections, thus increasing their statistical power. In turn, knowledge about the common network will facilitate novel analyses to understand the structure-function relationship in the brain. In [19], we present a new algorithm for computing the core structural connectivity network of a subject sample combining graph theory and statistics. Our algorithm works in accordance with novel evidence on brain topology. We analyze the problem theoretically and prove its complexity. Using 309 subjects, we show its advantages when used as a feature selection for connectivity analysis on populations, outperforming the current approaches.

5.4.2. Maximum flow under proportional delay constraint

Participant: D. Mazauric.

In collaboration with P. Bonami (LIF, UMR d'Aix-Marseille Université et du CNRS, and IBM ILOG CPLEX, Madrid), Y. Vaxès (LIF, UMR d'Aix-Marseille Université et du CNRS).

Network operators must satisfy some Quality of Service requirements for their clients. One of the most important parameters in telecommunication networks is the end-to-end delay of a unit of flow between a source node and a destination node. Given a network and a set of source destination pairs (connections), we consider in [14] the problem of maximizing the sum of the flow under proportional delay constraints. In this paper, the delay for crossing a link is proportional to the total flow crossing this link. If a connection supports non-zero flow, then the sum of the delays along any path corresponding to that connection must be lower than a given bound. The constraints of delay are on-off constraints because if a connection carries zero flow, then there is no constraint for that connection. The difficulty of the problem comes from the choice of the connections supporting non-zero flow. We first prove a general approximation ratio using linear programming for a variant of the problem. We then prove a linear time 2-approximation algorithm when the network is a path. We finally show a Polynomial Time Approximation Scheme when the graph of intersections of the paths has bounded treewidth.

5.4.3. Comparing two clusterings using matchings between clusters of clusters

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

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 [20], we go beyond these by providing a novel class of methods computing meta-clusters within each clustering– a meta-cluster is a group of clusters, together with a matching between these. Let the intersection graph of two clusterings be the edge-weighted bipartite graph in which the nodes represent the clusters, the edges represent the non empty intersection between two clusters, and the weight of an edge is the number of common items. We introduce the so-called D-family-matching problem on intersection graphs, with D the upper-bound on the diameter of the graph induced by the clusters of any meta-cluster. First we prove NP-completeness results and unbounded approximation ratio of simple strategies. Second, we design exact polynomial time dynamic programming algorithms for some classes of graphs (in particular trees). Then, we prove spanning-tree based efficient algorithms for general graphs. Our experiments illustrate the role of D as a scale parameter providing information on the relationship between clusters within a clustering and in-between two clusterings. They also show the advantages of our built-in mapping over classical cluster comparison measures such as the variation of information (VI).

5.4.4. The SBL

Participants: F. Cazals, T. 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), 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) [15]. For end-users, the SBL provides ready to use, state-of-the-art (1) applications to handle molecular models defined by unions of balls, to deal with molecular flexibility, to model macro-molecular assemblies. These applications can also be combined to tackle integrated analysis problems. For developers, the SBL provides a broad C++ toolbox with modular design, involving core (2) algorithms, (3) biophysical models and (4) modules, the latter being especially suited to develop novel applications. The SBL comes with a thorough documentation consisting of user and reference manuals, and a bugzilla platform to handle community feedback.

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

See also the section **New Software and Platforms**.

ACUMES Project-Team

6. New Results

6.1. Macroscopic traffic flow models on networks

Participants: Guillaume Costeseque, Nikodem Dymski, Paola Goatin, Nicolas Laurent-Brouty, Giulia Piacentini, Florent Berthelin [COFFEE, Inria], Antonella Ferrara [U Pavia, Italy], Simone Göttlich [U Mannheim, Germany], Oliver Kolb [U Mannheim, Germany].

In [38], we propose a new mathematical model accounting for the boundedness of traffic acceleration at a macroscopic scale. Our model is built on a first order macroscopic PDE model coupled with an ODE describing the trajectory of the leader of a platoon accelerating at a given constant rate. We use Wave Front Tracking techniques to construct approximate solutions to the Initial Value Problem. We present some numerical examples including the case of successive traffic signals on an arterial road and we compare the solution to our model with the solution given by the classical LWR equation in order to evaluate the impact of bounded acceleration.

The internship of Giulia Piacentini focused on traffic control via moving bottleneck of coordinated vehicles [35]. The possibility of properly controlling a moving bottleneck to improve the traffic flow was considered. The traffic is represented by means of a macroscopic model able to take into account the interactions with the bottleneck. This latter interacts with the surrounding flow modifying the traffic density and the flow speed profiles. An optimal control problem is stated by using the speed of the moving bottleneck as control variable. Specifically in this paper the MPC (Model Predictive Control) approach is used in order to get a fuel consumption reduction when the traffic is congested due to the presence of a fixed bottleneck on the highway. In addition we have demonstrated that no increase of the travel time is caused by the control application. The concept illustrated in this paper suggests a future innovative traffic control approach. Indeed the prospective of exploiting special vehicles with manipulable speed to control the traffic flow is particularly attractive given the expected increasing penetration rate of autonomous vehicles in traffic networks in future years.

In collaboration with S. Göttlich and O. Kolb, we studied macroscopic traffic flow models on a road network [36]. More precisely, we consider coupling conditions at junctions for the Aw-Rascle-Zhang second order model consisting of a hyperbolic system of two conservation laws. These coupling conditions conserve both the number of vehicles and the composition of traffic through the junction. The proposed Riemann solver is based on assignment coefficients, multi-objective optimization of fluxes and priority parameters. We prove that this Riemann solver is well posed in the case of special junctions, including 1-to-2 diverge and 2-to-1 merge.

In the setting of Florent Berthelin's secondement, we rigorously proved the convergence of the micro-macro limit for particle approximations of the Aw-Rascle-Zhang equations with a maximal density constraint [4]. The lack of BV bounds on the density variable is supplied by a compensated compactness argument.

6.2. Non-local conservation laws

Participants: Felisia Angela Chiarello, Paola Goatin, Elena Rossi.

F.A. Chiarello's PhD thesis focuses on non-local conservation laws. As a first result, we proved the well-posedness of entropy weak solutions for a class of scalar conservation laws with non-local flux arising in traffic modeling. We approximate the problem by a Lax-Friedrichs scheme and we provide L^∞ and BV estimates for the sequence of approximate solutions. Stability with respect to the initial data is obtained from the entropy condition through the doubling of variable technique. The limit model as the kernel support tends to infinity is also studied. See [33].

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

Participants: Alfio Borzí [Univ. Wurzburg], Abderrahmane Habbal, Souvik Roy [Univ. Wurzburg].

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 [48] a FPK-constrained control framework, where the drift was considered as control variable is developed and applied to crowd motion.

In [13] a new approach to modelling pedestrians' avoidance dynamics based on a Fokker–Planck (FP) Nash game framework is presented. In this framework, two interacting pedestrians are considered, whose motion variability is modelled through the corresponding probability density functions (PDFs) governed by FP equations. Based on these equations, a Nash differential game is formulated where the game strategies represent controls aiming at avoidance by minimizing appropriate collision cost functionals. The existence of Nash equilibria solutions is proved and characterized as a solution to an optimal control problem that is solved numerically. Results of numerical experiments are presented that successfully compare the computed Nash equilibria to the output of real experiments (conducted with humans) for four test cases.

6.4. Solving with games the coupled problem of conductivity or obstacle identification and data recovery

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

Based on previous successful attempts [104], [113] to tackle ill posed inverse problems a Nash games, we consider two developments :
The first one is related to joint obstacle shape/location and data recovery. We consider a game theory approach to deal with a geometric inverse problem related to the Stokes system. The problem consists in detecting an obstacle in a flow from incomplete measurements on the boundary of a domain. The approach that we propose deals simultaneously with the reconstruction of the missing data and the identification of one or more objects immersed in a viscous and incompressible fluid flow. The solution is interpreted in terms of Stackelberg-Nash equilibrium between both problems. We develop a new obstacle detection algorithm and we consider different numerical situations to illustrate the efficiency and robustness of the method.
The second one is dedicated to the electrocardiography inverse problem. 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 the data completion (heart electrical signal recovery) and conductivity identification at the same time.

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

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

Bayesian optimization methods are efficient to find solutions of multi-objective problems under very limited budgets of evaluation. An ongoing scope of research in multi-objective Bayesian optimization is to extend its applicability to a large number of objectives.

We have proposed in [127] 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.

Regarding the harsh many-objective optimization problems, the recovering of the set of optimal compromise solution generally requires lots of observations while being less interpretable, since this set tends to grow larger with the number of objectives. We thus propose to focus on a choice of a specific solution originating from game theory, the Kalai-Smorodinski solution, that possesses attractive properties [22] [19]. We further make it insensitive to a monotone transformation of the objectives by considering the objectives in the copula space. A tailored algorithm is proposed to search for the solution, which is tested on a synthetic problem.

6.6. Isogeometric analysis

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

We develop high-order isogeometric solvers, based on CAD representations for both geometry and solution space, for applications targeted by the team, in particular convection-dominated problems. Specifically, we investigate a Discontinuous Galerkin method for compressible Euler / Navier-Stokes 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 [34].

Recent extensions concern the capability to capture discontinuities in the solution, local refinement strategies by splitting algorithms [25] and high-order sensitivity analysis [24].

This topic is partially studied in A. Azaouzi's PhD work [21], [27], supervised by R. Duvigneau and M. Moakher.

6.7. Sensitivity equation method for hyperbolic systems

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

While the sensitivity equation method is a common approach for parabolic systems, its use for hyperbolic ones is still tedious, because of the generation of discontinuities in the state solution, yielding Dirac distributions in the sensitivity solution.

To overcome this difficulty, we investigate a modified sensitivity equation, that includes an additional source term when the state solution exhibits discontinuities, to avoid the generation of delta-peaks in the sensitivity solution. We consider as typical example the one-dimensional compressible Euler equations. Different approaches are tested to integrate the additional source term: a Roe solver, a Godunov method and a moving cells approach [20], [26], [32]. This study is achieved in collaboration with C. Chalons from University of Versailles, in the context of C. FIorini's PhD work.

6.8. Classification algorithms in Bayesian optimization

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

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

The method is applied to the optimization of foils and sails in the context of racing yachts [14], [18], [23], [28], in particular for the America's Cup in collaboration with Groupama team. This work is part of M. Sacher's PhD work at Ecole Navale.

6.9. Multifidelity surrogate modeling based on Radial Basis Functions

Participants: Jean-Antoine Désidéri, Cédric Durantin [CEA Leti, University Côte d'Azur], Alain Glière [CEA Leti], Justin Rouxel [CEA Leti].

Multiple models of a physical phenomenon are sometimes available with different levels of approximation. The high fidelity model is more computationally 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 models. 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 does not bring better results than co-kriging but can be considered as an alternative for multifidelity metamodeling [9].

6.10. Descent algorithm for nonsmooth stochastic multiobjective optimization

Participants: Jean-Antoine Désidéri, Quentin Mercier [ONERA Châtillon, University Côte d'Azur], Fabrice Poirion [ONERA Châtillon].

An algorithm for solving the expectation formulation of stochastic nonsmooth multiobjective optimization problems is proposed. The proposed method is an extension of the classical stochastic gradient algorithm to multiobjective optimization using the properties of a common descent vector defined in the deterministic context. The mean square and the almost sure convergence of the algorithm are proven. The algorithm efficiency is illustrated and assessed on an academic example [12].

6.11. Hessian transfer for multilevel and adaptive shape optimization

Participants: Badr Abou el majd [Hassan II University Casablanca], Jean-Antoine Désidéri, Abderrahamane Habbal, Ouail Ouchetto [Hassan II University Casablanca].

We have developed a multilevel and adaption parametric strategies solved by optimization algorithms which require only the availability of objective function values but no derivative information. The key success of these hierarchical strategies refer to the quality of the downward and upward transfers of information. In this paper, we extend our approach when using a derivative-based optimization algorithms. The aim is to better re-initialize the Hessian and the gradient during the optimization process based on our construction of the downward and upward operators. The efficiency of this proposed approach is demonstrated by numerical experiments on an inverse shape model [1].

APICS Project-Team

5. New Results

5.1. Inverse problems for Poisson-Laplace equations

Participants: Laurent Baratchart, Sylvain Chevillard, Juliette Leblond, Jean-Paul Marmorat, Konstantinos Mavreas, Christos Papageorgakis.

5.1.1. Inverse magnetization issues from planar data

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

The overall goal of IMPINGE 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). Depending on the nature of the rock sample, the magnetization distribution can either be considered to lie in a plane or in a parallelepiped of thickness r. Some of our results apply to both frameworks (the former appears as a limiting case when r goes to 0), while others concern the 2D case and have no 3-D counterpart yet.

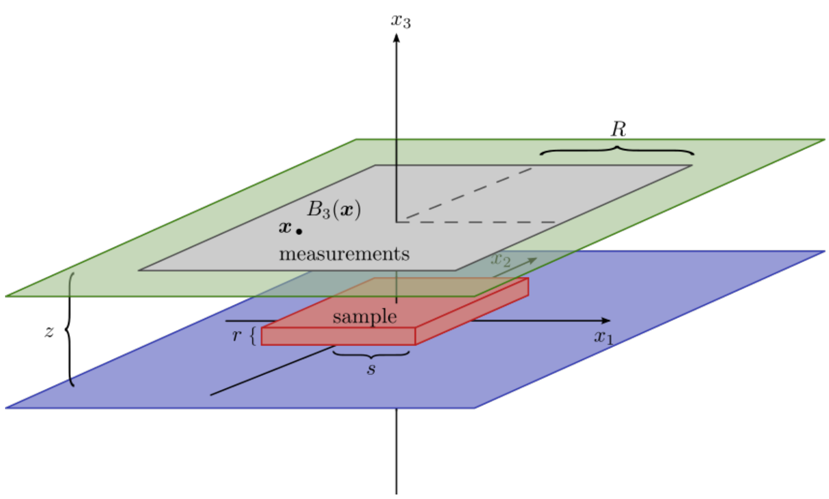


Figure 3. Schematic view of the experimental setup

Figure 3 presents a schematic view of the experimental setup: the sample lies on a horizontal plane at height 0 and its support is included in a parallelepiped. The vertical component B_3 of the field produced by the sample is measured on points of a horizontal square at height z.

We pursued this year our research efforts towards designing algorithms for net moment recovery. The net moment is the integral of the magnetization over its support, and it is a valuable piece of information to physicists which has the advantage of being determined solely by the field: whereas two different magnetizations can generate the same field, the net moment depends only on the field and not on which magnetization produced it. Hence the goal may be described as to build a numerical magnetometer, capable of analyzing data close to the sample. This is in contrast to classical magnetometers which regard the latter as a single dipole, an approximation which is only valid away from the sample and is not suitable to handle weak fields which get quickly blurred by ambient magnetic sources. This research effort was paid in two different, complementary directions.

The first approach consists in using the fact that the integral of B_3 against polynomials of order less or equal to 1 on some domains symmetric with respect to the origin provides an estimate of the net moment, asymptotically when R grows large [34]. This approach was tested this year on real data measured with the SQUID microscope at MIT. Applying directly the formulas on the measured data led to poor results, and we identified this issue as a consequence of electronic noise (drift of the measured field). This noise was impeding the method, especially when R was large, preventing one from getting estimates of the net moment with an error smaller than about 10%. By modeling this fairly deterministic drift as an affine function of the space variables, we were able to pretty much cancel out its effect. With this correction, the curve obtained when R varies follows fairly accurately the theoretical asymptotic behavior. We fit this curve with the one corresponding to the theoretical behavior, which allows us to extrapolate its value at infinity, hence giving us an estimate of the net moment. The results on some experimental data (chondrules) are promising. Yet, results on some other data sets are still unsatisfactory and remain to be understood.

The second approach attempts to generalize the previous expansions in the case when R is moderately large. This work is carried out in the thin slab framework, modeling the sample as a rectangle. Last year, we set up a bounded extremal problem (BEP, see Section 3.3.1) consisting in finding the functions ϕ_i $(i = 1, 2, 3)$ such that $|\langle m_i\rangle - \iint \phi_i(x_1, x_2) B_3(x_1, x_2)\,\mathrm{d}x_1\mathrm{d}x_2|$ is least possible under the constraint that $\|\nabla\phi_i\|_2 \leq M$, where M is a user-defined parameter. This year, we sharpened our regularity results on the solutions with respect to space variables and the parameters of the problem (*e.g.*, the level of constraint M), and considered several resolution schemes. We implemented an algorithm approximately solving for the critical point equation, using a finite elements method. Numerical experiments on synthetic data confirm the validity of the approach with small noise, see [21]. The addition of a synthetic noise, however, has revealed sensitivity to a poor signal / noise ratio, in particular at measurement points close to the edges of the measurement slab where the estimator oscillates heavily. Such oscillations are the price to pay for an estimation procedure which uses data on a measurement set not much bigger than the sample. This is an interesting feature of the method, and further analysis is needed to offset the noise effect. Notice that the work [21] also includes 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 started this year to design an alternate procedure to compute a good linear estimator. It consists in expanding it on a family of piecewise affine functions, with a restricted number of pieces. This still needs 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. On a related topic, we also derived explicit formulas for the adjoint operator B_3^* to B_3 (in appropriate L^2 spaces), when applied to polynomials. This adjoint operator is central to the construction of linear estimators, and these formulas suggest one could work efficiently with polynomial bases. This work is still in progress.

Concerning full inversion of thin samples, after preliminary experiments on regularization with L^1 constraints (a heavy trend in linear inverse problems today to favor sparse solutions), we started studying magnetizations modeled by signed measures. A loop decomposition of silent sources was obtained, which makes precise in the 2-D setting the structure theorem of [78]. Moreover, a characterization of equivalent sources having minimal total variation has been obtained when the support of the magnetization is very scattered (purely 1-unrectifiable, which holds in particular for dipolar models) and also for certain magnetizations of geophysical interest like unidirectional ones. Thus, it seems that constraining the total variation to regularize the recovery process is appropriate in some important cases. The theoretical analysis has shown that the optimum is then always sparse, in that it has Hausdorff dimension at most 1. This stems from the real analyticity of operators relating the magnetization to the field, which prevents them from assuming constant level on large sets. An implementation is currently being set up with promising results. Yet, a deeper understanding on how to adjust the parameters of the method is required. This topic is studied in collaboration with D. Hardin and C. Villalobos from Vanderbilt University.

Besides, we considered a simplified 2-D setup for magnetizations and magnetic potentials (of which the magnetic field is the gradient). When both the sample and the measurement set are parallel intervals, some best approximation issues related to inverse recovery and relevant BEP problems in Hardy classes of holomorphic functions (see Section 3.3.1) were solved in [19]. Note that, in the present case, the criterion no longer acts on the boundary of the holomorphy domain (namely, the upper half-plane), but on a strict subset thereof, while the constraint acts on the support of the approximating function. Both involve real parts of functions in the Hilbert Hardy space of the upper half-plane. This is joint work with D. Ponomarev (see Section 7.5.1). Some extensions are the subject of ongoing work with E. Pozzi (Department of Mathematics and Statistics, St Louis Univ., St Louis, Missouri, USA). They concern more precise approximation criteria, and the development of resolution schemes using the Fourier basis. Meanwhile, BEP in Bergman classes of analytic or generalized analytic functions are under being studied with B. Delgado Lopez (see Sections 3.2 , 7.5.1).

For magnetizations supported in a volume Ω with boundary $\partial\Omega$, there is a greater variety of silent sources, since they have much more space to live in. Now, to each magnetization m supported in Ω there is a unique magnetization supported on $\partial\Omega$ (the balayage of m) and producing the same field outside Ω. Thus, describing silent sources supported on $\partial\Omega$ is a way to factor out some of the complexity of the situation. When m is located in the plane, the Hardy-Hodge decomposition introduced in [38] (see Section 3.3.1) was used there to characterize all silent magnetizations from above (resp.below) as being those having no harmonic gradient from below (rep. above) in their decomposition. When m is supported on a compact surface, a similar decomposition exists for $\mathbb{R}^3$-valued vector fields on $\partial\Omega$, (see Section 5.4), that allows to characterize all magnetizations on $\partial\Omega$ which are silent from outside as being those whose harmonic components satisfy a certain spectral relation for the double layer potential on $\partial\Omega$. The analysis and the algorithmic use of that equation for recovery or moment estimation remain to be worked out.

Other types of inverse magnetization problems can be tackled using such techniques, in particular global Geomagnetic issues which arise in spherical geometry. This year, in collaboration with C. Gerhards from the University of Vienna (Austria), we developed a method to separate the crustal component of the Earth's magnetic field from its core component, if an estimate of the field is known on a subregion of the globe [23] . This assumption is not unrealistic: parts of Australia and of northern Europe are considered as fairly well understood from the magnetostatic view point. We look forward to test the algorithm against real data, in collaboration with Geophysicists

5.1.2. Inverse magnetization issues from sparse cylindrical 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 think that the Moon used to have a magnetic dynamo for a while. However, the exact process that triggered and fed this dynamo is still not understood, much less why it stopped. The overall goal of the project is to devise models to explain how this dynamo phenomenon was possible on the Moon.

The geophysicists from Cerege went a couple of times to NASA to perform measurements on a few hundreds of samples brought back from the Moon by Apollo missions. The samples are kept inside bags with a protective atmosphere, and geophysicists are not allowed to open the bags, nor to take out samples from NASA facilities. Moreover, the process must be carried out efficiently as a fee is due to NASA by the time when handling these moon samples. Therefore, measurements were performed with some specific magnetometer designed by our colleagues from Cerege. This device measures the components of the magnetic field produced by the sample, at some discrete set of points located on circles belonging to three cylinders (see Figure 4). The objective of Apics is to enhance the numerical efficiency of post-processing data obtained with this magnetometer.

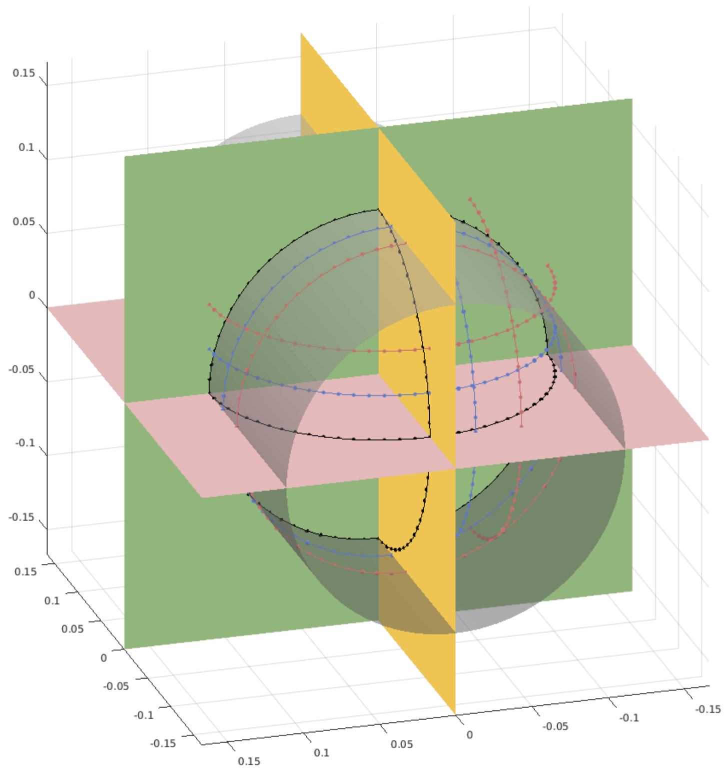


Figure 4. Typical measurements obtained with the instrument of Cerege. Measurements of the field are performed on nine circles, given as sections of three cylinders. On each circle, only one component of the field is measured: the component B_h along the axis of the corresponding cylinder (blue points), 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 taken in previous years. Under the hypothesis that the field can be well explained by a single magnetic pointwise dipole, and using ideas similar to those underlying the FindSources3D tool (see Sections 3.4.2 and 5.1.3), we try to recover the position and the moment of the dipole using the available measurements.

In a given cylinder, using the associated cylindrical system of coordinates, recovering the position of the dipole boils down to determine its height z, its radial distance ρ and its azimuth ϕ. In principle, the rational approximation technique that we are using returns, for the circle of measurements at height h, the unique complex pole ξ_h of order five belonging to the corresponding normalized disk of some rational function. From this pole, the complex number $u_h = \xi_h + \frac{1}{\xi_h} = \frac{1+\rho^2+(h-z)^2}{\rho}\, e^{i\phi}$ can be estimated. 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, only an approximation of u_h is computed. The question is then to reliably combine the information provided by all circles of measurements, in order to recover z, ρ and ϕ. The azimuth is fairly easy to obtain: we can estimate it, *e.g.*, by taking the mean value of the argument of ξ_h, for all h for which we have a measurement circle, possibly excluding one of them when the provided estimate seems to be clearly different from the others. As regards the reconstruction of ρ and z, we designed this year two new strategies.

The first strategy consists in observing that $\rho\,|u_h| = 1{+}\rho^2 + h^2 - 2hz + z^2$, whence doing the difference with the same equation obtained at height h': $\rho\,(|u_h| - |u_{h'}|) = (h^2 - h'^2) - 2(h - h')z$. This provides a linear relation between the unknowns ρ and z. Three measurement circles provide us with two independent relations and are in principle enough to recover ρ and z. Numerical experiments showed that this recovery strategy is unsatisfactory: it is fairly sensitive to approximation errors on the estimates $|u_h|$ and $|u_{h'}|$, hence the estimation procedure is unstable. However, it might become more robust if data were available on more than three circles per cylinder. Exploring this idea is an on-going piece of work. If successful, it will suggest an easy modification of the magnetometer of Cerege for future measurements campaigns.

The second strategy directly uses the pole ξ_h instead of u_h, hence avoiding numerical steps that are possible sources of errors. It consists in observing that $|\xi_h|$ is maximal, with respect to h, when $h = z$ and it is then equal to $\rho e^{i\phi}$. A rough estimate of ρ is hence given by the maximal value of $|\xi_h|$ among the three values of h available for each cylinder. The position of the dipolar source is then estimated by combining the estimates of ρ and ϕ obtained on all three cylinders. The moment is then computed from this estimated position, solving a linear system by least-squares techniques. Although not sophisticated, this method gave promising results on synthetic examples, with more or less noise, see the submitted work [25]. This is still on-going work which constitutes the main topic of the PhD thesis of K. Mavreas.

5.1.3. Inverse problems in medical imaging

This work is conducted in collaboration with Maureen Clerc and Théo Papadopoulo, from the team Athena (Inria Sophia).

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], [43] on the behavior of poles in best rational approximants of fixed degree to functions with branch points, it was shown how to proceed via best rational approximation on a sequence of 2-D disks cut along the inner sphere, for the case where there are finitely many sources (see Section 4.3).

In this connection, a dedicated software FindSources3D (FS3D, see Section 3.4.2) is being developed, in collaboration with the Inria team Athena and the CMA - Mines ParisTech. In addition to the modular and ergonomic platform version of FS3D, 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 that correspond to measurements of the electrical potential, one should consider *triple* poles; for (magnetic) field data however, like in Section 5.1.2 or from MEG – magneto-encephalography –

data, one should consider poles of order five). 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, the version of the software currently under development takes as inputs actual EEG measurements, like time signals, and performs a suitable singular value decomposition in order to separate independent sources.

Magnetic data from MEG recently became available along with EEG data, by our medical partners at the hospital la Timone; indeed, it is now possible to use simultaneously both measurement devices, in order to measure both the electrical potential and a component of the magnetic fields. This should enhance the accuracy of our source recovery algorithms. We will add the treatment of MEG data as another functionality of the software FS3D.

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 Inria team Athena and BESA GmbH, see Section 6.1.2). In layered models, it concerns the estimation of the conductivity of the skull (an intermediate layer). First, the conductivity of the skull can differ from one individual to another, or for the same person, along the time, and is much smaller than those of the surrounding layers (the brain and the scalp). A preliminary issue in this direction was to estimate a single-valued skull conductivity from one EEG recording. Existence, uniqueness, stability properties and a recovery scheme for this conductivity value were established in the spherical setting when the sources are known, see [10]. When the sources are unknown, we must look for additional data (additional clinical and/or functional EEG, EIT, ...) that could be incorporated in order to recover both the sources locations and the skull conductivity. Second, 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 actually possess quite different conductivities. The influence of the second on the overall model is also studied in [10], together with a numerical process allowing to estimate the hard bone conductivity value together with a dipolar source, in realistic geometries.

We also began to consider the inverse problem of recovering the parameters of a skin tumor from thermal measurements, in a 2-D model that takes the form of a static Schrödinger equation. This is joint work with F. Ferranti (IMT Atlantique, Microwave Department) and the topic of the internship of G. Dervaux, see Section 7.5.1 .

5.2. Matching problems and their applications

Participants: Laurent Baratchart, Martine Olivi, Gibin Bose, 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) as well as with, Fabien Ferrero (LEAT, Sophia-Antipolis, France) Leonardo Lizzi (LEAT, Sophia-Antipolis, France).

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.

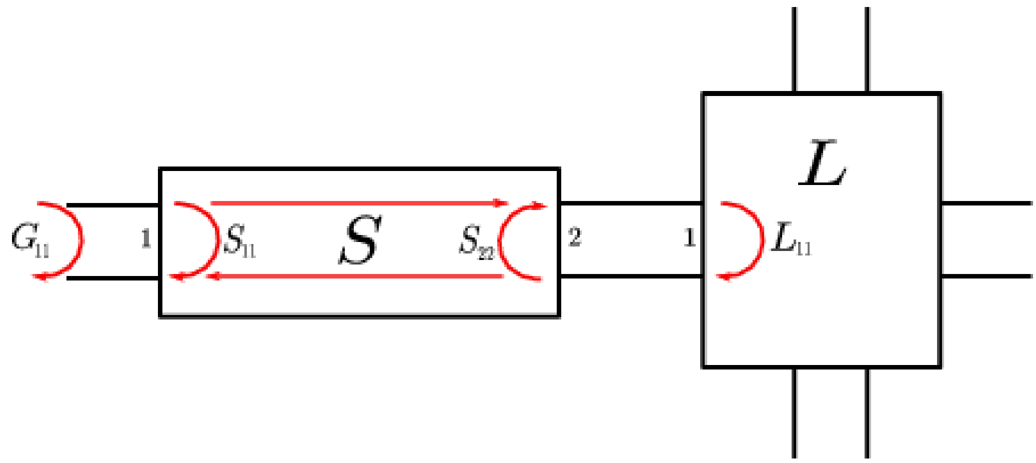


Figure 5. Filter plugged on a system with reflection coefficient L_{11}

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:

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

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. The detailed mathematical proofs can be found in [11].

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. It can serve as a starting point for heavier optimization procedures, where the matching and rejection specifications are expressed uniformly over the bandwidth. Although the practical results thus obtained are quite convincing, we have no proof of their global optimality. This has led us to seek alternative approaches allowing us to assess, at least in simple cases, global optimality of the obtained response. By optimality of a response we mean, as in classical filtering, a best match of the response in the uniform norm on a given pass-band, while meeting given rejection constraints on a stop-band. 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, 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 in degree 1), it is therefore possible to perform filter synthesis with a guarantee on the global optimality of the obtained characteristics. The constructive aspects of this approach, relying on convex duality and linear programming, were presented in [16], together with an implementation using a SIW (substrate integrated filter). For antennas with a transmission coefficient of higher degree, like dual band antennas, we developed a convex relaxation of the matching problem which yields a set lower bounds on the matching error, for every considered degree of the overall system (matching system + load). This substantially improves Helton’s approach, that furnishes a single global theoretical lower bound independent of the degree, obtained via an infinite degree H^∞ relaxation of the problem.A preliminary version of this approach was presented in [15], while a more detailed paper is under way. We consider this to be an important breakthrough concerning this classical problem in electronics. The implementation of the method involves solving a convex optimization problem on the cone of positive polynomials under some non-linear, yet convex, matrix inequality constraints. Solving the latter combining logarithmic barrier functions and Lagrangian relaxation techniques provided us, for example, with an excellent initial design for a matching network dedicated to an array of dual-band antennas with circular polarization, studied in the context of the ANR Cocoram. Design of matching networks for complex antennas is also considered in collaboration with LEAT, within the context of Gibin’s Bose PhD.

5.3. Stability assessment of microwave amplifiers and design of oscillators

Participants: Laurent Baratchart, Sylvain Chevillard, Martine Olivi, Fabien Seyfert, Sébastien Fueyo, Adam Cooman.

The goal is here to help design amplifiers, in particular to detect instability at an early stage of the design. Activity in this area is gaining importance with the coming of a doctoral (S. Fueyo) and a postdoctoral (A. Cooman) student along with planned software developments. Application of our work to oscillator design methodologies started recently with Smain Amari from the Royal Military College of Canada (Kingston, Canada).

As opposed to Filters and Antennas, Amplifiers and Oscillators are active components that intrinsically entail a non-linear functioning. The latter is due to the use of transistors governed by electric laws exhibiting saturation effects, and therefore inducing input/output characteristics that are no longer proportional to the magnitude of the input signal. Hence they typically produce non-linear distortions. A central question arising in the design of amplifiers is to assess stability. The latter may be understood around a functioning point when no input but noise is considered, or else around a periodic trajectory when an input signal at a specified frequency is applied. For oscillators, a precise estimation of their oscillating frequency is crucial during the design process. As regards devices devised to operate at relative low frequencies, time domain simulations, based on the integration of the underlying non-linear dynamical system, answers these questions satisfactorily. For complex microwave amplifiers and oscillators, the situation is however drastically different: the time step necessary to integrate the transmission line's dynamical equations (which behave like simple electrical wire at low frequency) becomes so small that simulations are intractable in reasonable time. In addition to this problem, most linear components of these circuits are known through their frequency response, and require therefore a preliminary, numerically unstable step to obtain their impulse response, prior to any time domain simulation.

For all these reasons it is widely preferred to perform the analysis of such systems in the frequency domain. In the case of stability issues around a functioning point, where only small input signals are considered, the stability of the linearized system obtained by a first order approximation of each non-linear dynamic is considered. This is done by means of the analysis of transfer impedance functions computed at some ports of the circuit. We have shown, that under some realistic hypothesis on the building blocks of the circuit, these transfer functions are meromorphic functions of the frequency variable s, with at most a finite number of unstable poles in the right half-plane [20]. Dwelling on the unstable/stable decomposition in Hardy Spaces, we developed a procedure to assess the stability or instability of the transfer functions at hand, from their evaluation on a finite frequency grid [12]. The data are generally supplied by circuit simulators, used by microwave device designers. We are currently working towards precise estimation techniques of the unstable poles of these transfer functions, hence on the evaluation of their rational unstable part. Our approach involves here the AAK theory, furnishing at low cost a rough estimate of the desired singularities, combined with specialized versions of stable rational approximation procedures. Practical application of this work are sought among the microwave amplifier design community as well as for the synthesis of oscillators: for the latter, a precise location of one unstable poles is necessary. A software toolbox is being developed for this purposes, and a collaboration on this project has started with Smain Amari from the Royal Military College on microwave oscillator design.

When stability is studied around a periodic trajectory, which is determined in practice by Harmonic Balance algorithms, linearization yields a linear time varying dynamical system with periodic coefficients and a periodic trajectory thereof. While in finite dimension the stability of such systems is well understood via the Floquet theory, this is no longer the case in the infinite dimensional setting when delays are considered. Dwelling on the theory of retarded systems, S. Fueyo's PhD work has made remarkable progress on this topic by showing that, for certain simple circuits with properly positioned resistors, the monodromy operator is a compact perturbation of a stable operator, and that only finitely many unstable point of its spectrum can occur. A practical application of this result is to generalize the previously described techniques of stability assessment around a functioning point into a stability assessment technique around periodic trajectories. This can be recast in terms of the finiteness of the number of abscissas of unstable poles of the Harmonic Transfer functions of the circuit. It will be of great importance to generalize such considerations to more complex circuits, whose structure is less well understood at present.

5.4. The Hardy-Hodge decomposition

Participant: Laurent Baratchart.

(This is joint work with Qian T. and Dang P. from the university of Macao.) It was proven in previous year that on a smooth compact hypersurface Σ embedded in $\mathbb{R}^n$, a $\mathbb{R}^n$-valued vector field of L^p class decomposes as the sum of a harmonic gradient from inside Σ, a harmonic gradient from outside Σ, and a tangent divergence-free field. This year we extended this result to Lipschitz surfaces for $2-\varepsilon < p < 2+\varepsilon'$, where ε and ε' depend on the Lipschitz constant of the surface. We also proved that the decomposition is valid for $1 < p < \infty$ when Σ is VMO-smooth (*i.e.*Σ is locally the graph of Lipschitz function with derivatives in VMO). By projection onto the tangent space, this gives a Hodge decomposition for 1-forms on a Lipschitz surface, which is apparently also new since existing results deal with smooth surfaces (but forms of any degree). This result was reported at the invited session on Harmonic Analysis and Inverse Problems of the Mathematical Congress of the Americas, an article is being written to report on it.

AROMATH Project-Team

6. New Results

6.1. Waring-like decompositions of polynomials

Participant: Alessandro Oneto.

In [9], we consider particular types of *additive decompositions* of homogeneous polynomials. The classical decomposition is the *Waring decomposition*, where we decompose polynomials as sums of powers of linear forms. Another well studied decomposition is the sometimes-called *Chow decomposition*, where we decompose polynomials as sums of products of linear forms. These are the extremal cases of the additive decompositions considered in this work. For a fixed partition $(d_1, ..., d_s) \vdash d$ of the degree of the polynomial, we consider decompositions as sums of degree forms of the form $\ell_1^{d_1} \cdots \ell_s^{d_s}$, where the ℓ's are linear forms. The homogeneous polynomials of the form $\ell_1^{d_1} \cdots \ell_s^{d_s}$ are parametrized by particular linear projections of certain Segre-Veronese varieties. The main results of this work concerns the dimension of the secant varieties to these projections of Segre-Veronese varieties. In particular, we compute their dimensions in the binary case (forms in two variables) and the case of secant lines varieties for any partition and any number of variables. From these results, we deduce the dimension of higher secant varieties in some particular cases.

This is a joint work with M. V. Catalisano, Luca Chiantini, and A. V. Geramita.

6.2. Waring loci and the Strassen conjecture

Participant: Alessandro Oneto.

In [8], we introduce the notion of the *Waring locus* of a homogeneous polynomial. A *Waring decomposition* is an expression of a polynomial as sum of powers of linear forms. The smallest length of such a decomposition is called the *Waring rank* of the polynomial. A very difficult challenge is to compute the rank and a minimal decomposition of a given form. The Waring locus of a polynomial is the locus of linear forms that appear in a minimal decomposition of it. The idea behind this construction is to find an iterative approach to construct Waring decompositions *step-by-step*, by adding one power at the time. Moreover, we give a version of the famous *Strassen conjecture* on the additivity of rank for sums of polynomials in independent sets of variables. We compute the Waring loci in several cases as binary forms, quadrics, monomials and plane cubics and for some other particular families of polynomials.

This is a joint work with E. Carlini, and M. V. Catalisano.

6.3. Minkowski sums and Hadamard products of algebraic varieties

Participant: Alessandro Oneto.

In [26], we study two particular geometric constructions. Given two affine algebraic varieties, we define their *Minkowski sum* as the (Zariski) closure of the set of coefficient-wise sums of pairs of points in the two varieties. Given two projective varieties, we define their *Hadamard product* as the (Zariski) closure of the set of coefficient-wise multiplications of pairs of points in the two varieties. In particular, we focus on computing their dimensions and degrees in terms of the ones of the original varieties. Hadamard products are of particular interests as they can be used to parametrize particular families of tensors which rise naturally by studying Restricted Boltzmann Machines, which are particular structures used in Statistics and Machine Learning.

This is a joint work with N. Friedenberg, and R. Williams.

6.4. Polynomial-exponential decomposition from moments

Participant: Bernard Mourrain.

In [12], we analyze the decomposition problem of multivariate polynomial-exponential functions from truncated series and present new algorithms to compute their decomposition. Using the duality between polynomials and formal power series, we first show how the elements in the dual of an Artinian algebra correspond to polynomial-exponential functions. They are also the solutions of systems of partial differential equations with constant coefficients. We relate their representation to the inverse system of the roots of the characteristic variety. Using the properties of Hankel operators, we establish a correspondence between polynomial exponential series and Artinian Gorenstein algebras. We generalize Kronecker theorem to the multivariate case, by showing that the symbol of a Hankel operator of finite rank is a polynomial-exponential series and by connecting the rank of the Hankel operator with the decomposition of the symbol. A generalization of Prony's approach to multivariate decomposition problems is presented, exploiting eigenvector methods for solving polynomial equations. We show how to compute the frequencies and weights of a minimal polynomial-exponential decomposition, using the first coefficients of the series. A key ingredient of the approach is the flat extension criteria, which leads to a multivariate generalization of a rank condition for a Carathéodory-Fejér decomposition of multivariate Hankel matrices. A new algorithm is given to compute a basis of the Artinian Gorenstein algebra, based on a Gram-Schmidt orthogonalization process and to decompose polynomial-exponential series. A general framework for the applications of this approach is described and illustrated in different problems. We provide Kronecker-type theorems for convolution operators, showing that a convolution operator (or a cross-correlation operator) is of finite rank, if and only if, its symbol is a polynomial-exponential function, and we relate its rank to the decomposition of its symbol. We also present Kronecker-type theorems for the reconstruction of measures as weighted sums of Dirac measures from moments and for the decomposition of polynomial-exponential functions from values. Finally, we describe an application of this method for the sparse interpolation of polylog functions from values.

6.5. Fast algorithm for border bases of Artinian Gorenstein algebras

Participant: Bernard Mourrain.

Given a multi-index sequence σ, we present in [23] a new efficient algorithm to compute generators of the linear recurrence relations between the terms of σ. We transform this problem into an algebraic one, by identifying multi-index sequences, multivariate formal power series and linear functionals on the ring of multivariate polynomials. In this setting, the recurrence relations are the elements of the kernel I_σ of the Hankel operator H_σ associated to σ. We describe the correspondence between multi-index sequences with a Hankel operator of finite rank and Artinian Gorenstein Algebras. We show how the algebraic structure of the Artinian Gorenstein algebra A_σ associated to the sequence σ yields the structure of the terms σ_α for all $\alpha \in \mathbb{N}^n$. This structure is explicitly given by a border basis of A_σ, which is presented as a quotient of the polynomial ring $K[x_1, ..., x_n]$ by the kernel I_σ of the Hankel operator H_σ. The algorithm provides generators of I_σ constituting a border basis, pairwise orthogonal bases of A_σ and the tables of multiplication by the variables in these bases. It is an extension of Berlekamp-Massey-Sakata (BMS) algorithm, with improved complexity bounds. We present applications of the method to different problems such as the decomposition of functions into weighted sums of exponential functions, sparse interpolation, fast decoding of algebraic codes, computing the vanishing ideal of points, and tensor decomposition. Some benchmarks illustrate the practical behavior of the algorithm.

6.6. Structured low rank decomposition of multivariate Hankel matrices

Participants: Jouhayna Harmouch, Bernard Mourrain.

In [11], we study the decomposition of a multivariate Hankel matrix H_σ as a sum of Hankel matrices of small rank in correlation with the decomposition of its symbol σ as a sum of polynomial-exponential series. We present a new algorithm to compute the low rank decomposition of the Hankel operator and the decomposition of its symbol exploiting the properties of the associated Artinian Gorenstein quotient algebra A_σ. A basis of A_σ is computed from the Singular Value Decomposition of a sub-matrix of the Hankel matrix H_σ. The frequencies and the weights are deduced from the generalized eigenvectors of pencils of shifted sub-matrices of H_σ. Explicit formula for the weights in terms of the eigenvectors avoid us to solve a Vandermonde system. This new method is a multivariate generalization of the so-called Pencil method for solving Prony-type decomposition problems. We analyze its numerical behavior in the presence of noisy input moments, and describe a rescaling technique which improves the numerical quality of the reconstruction for frequencies of high amplitudes. We also present a new Newton iteration, which converges locally to the closest multivariate Hankel matrix of low rank and show its impact for correcting errors on input moments.

This is a joint work with Houssam Khalil.

6.7. Decomposition of low rank multi-symmetric tensor

Participants: Jouhayna Harmouch, Bernard Mourrain.

In [22], we study the decomposition of a multi-symmetric tensor T as a sum of powers of product of linear forms in correlation with the decomposition of its dual T^* as a weighted sum of evaluations. We use the properties of the associated Artinian Gorenstein Algebra A_τ to compute the decomposition of its dual T^* which is defined via a formal power series τ. We use the low rank decomposition of the Hankel operator Hτ associated to the symbol τ into a sum of indecomposable operators of low rank. A basis of A_τ is chosen such that the multiplication by some variables is possible. We compute the sub-coordinates of the evaluation points and their weights using the eigen-structure of multiplication matrices. The new algorithm that we propose works for small rank. We give a theoretical generalized approach of the method in n dimensional space. We show a numerical example of the decomposition of a multi-linear tensor of rank 3 in 3 dimensional space.

This is a joint work with Houssam Khalil.

6.8. Tensor decomposition and homotopy continuation

Participant: Bernard Mourrain.

A computationally challenging classical elimination theory problem is to compute polynomials which vanish on the set of tensors of a given rank. By moving away from computing polynomials via elimination theory to computing pseudowitness sets via numerical elimination theory, we develop in [3] computational methods for computing ranks and border ranks of tensors along with decompositions. More generally, we present our approach using joins of any collection of irreducible and nondegenerate projective varieties $X_1, ..., X_k \subset \mathbb{P}^N$ defined over $\mathbb{C}$. After computing ranks over $\mathbb{C}$, we also explore computing real ranks. Various examples are included to demonstrate this numerical algebraic geometric approach.

This is a joint work with Alessandra Bernardi, Noah S. Daleo, Jonathan D. Hauenstein.

6.9. Effective criteria for bigraded birational maps

Participant: Laurent Busé.

In [6], 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 the product of two projective lines to the projective plane 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 Nicolás Botbol (University of Buenos Aires), Marc Chardin (University of Paris VI), Hamid Seyed Hassanzadeh (University of Rio de Janeiro), Aron Simis (University of Pernambuci) and Quang Hoa Tran (University of Paris VI).

6.10. Discriminants of complete intersection space curves

Participant: Laurent Busé.

In [19], we develop a new approach to the discriminant of a complete intersection curve in the 3-dimensional projective space. By relying on the resultant theory, we first prove a new formula that allows us to define this discriminant without ambiguity and over any commutative ring, in particular in any characteristic. This formula also provides a new method for evaluating and computing this discriminant efficiently, without the need to introduce new variables as with the well-known Cayley trick. Then, we obtain new properties and computational rules such as the covariance and the invariance formulas. Finally, we show that our definition of the discriminant satisfies to the expected geometric property and hence yields an effective smoothness criterion for complete intersection space curves. Actually, we show that in the generic setting, it is the defining equation of the discriminant scheme if the ground ring is assumed to be a unique factorization domain.

This is a joint work with Ibrahim Nonkané (University of Ouaga II).

6.11. Matrix Representations by Means of Interpolation

Participants: Ioannis Emiris, Christos Konaxis, Clément Laroche.

In [20] we examine implicit representations of parametric or point cloud models, based on interpolation matrices, which are not sensitive to base points. We show how interpolation matrices can be used for ray shooting of a parametric ray with a surface patch, including the case of high-multiplicity intersections. Most matrix operations are executed during pre-processing since they solely depend on the surface. For a given ray, the bottleneck is equation solving. Our Maple code handles bicubic patches within 1 second, though numerical issues might arise. Our second contribution is to extend the method to parametric space curves and, generally, to codimension > 1, by computing the equations of (hyper)surfaces intersecting precisely at the given object. By means of Chow forms, we propose a new, practical, randomized algorithm that always produces correct output but possibly with a non-minimal number of surfaces. For space curves, we obtain 3 surfaces whose polynomials are of near-optimal degree; in this case, computation reduces to a Sylvester resultant. We illustrate our algorithm through a series of examples and compare our Maple prototype with other methods implemented in Maple, i.e., Gröbner basis and implicit matrix representations. Our Maple prototype is not faster but yields fewer equations and seems more robust than Maple's implicitize; it is also comparable with the other methods for degrees up to 6.

Joint work with I.S. Kotsireas.

6.12. Efficient certication of numeric solutions to eigenproblems

Participant: Bernard Mourrain.

In [24], we present an efficient algorithm for the certication of numeric solutions to eigenproblems. The algorithm relies on a mixture of ball arithmetic, a suitable Newton iteration, and clustering of eigenvalues that are close.

This is a joint work with Joris Van Der Hoeven.

6.13. Approximating multidimensional subset sum and minkowski decomposition of polygons

Participants: Ioannis Emiris, Anna Karasoulou.

In [10] we consider the approximation of two NP-hard problems: Minkowski Decomposition (MinkDecomp) of lattice polygons in the plane and the closely related problem of Multidimensional Subset Sum (kD-SS) in arbitrary dimension. In kD-SS we are given an input set S of k-dimensional vectors, a target vector t and we ask if there exists a subset of S that sums up to t. We prove, through a gap-preserving reduction, that, for general dimension k, kD-SS is not in APX although the classic 1D-SS is in PTAS. On the positive side, we present an $O(n^3/\epsilon^2)$ approximation grid based algorithm for 2D-SS, where n is the cardinality of the set and $\epsilon > 0$ bounds the difference of some measure of the input polygon and the sum of the output polygons. We also describe two approximation algorithms with a better experimental ratio. Applying one of these algorithms, and a transformation from MinkDecomp to 2D-SS, we can approximate Mink-Decomp. For an input polygon Q and parameter ϵ, we return two summands A and B such that $A + B = Q'$ with Q' being bounded in relation to Q in terms of volume, perimeter, or number of internal lattice points, an additive error linear in and up to quadratic in the diameter of Q. A similar function bounds the Hausdorff distance between Q and Q'. We offer experimental results based on our implementation.

Joint with C. Tzovas.

6.14. High-dimensional approximate r-nets

Participants: Ioannis Emiris, Ioannis Psarros.

The construction of r-nets offers a powerful tool in computational and metric geometry. In [17], we focus on high-dimensional spaces and present a new randomized algorithm which efficiently computes approximate r-nets with respect to Euclidean distance. For any fixed $\epsilon > 0$, the approximation factor is $1 + \epsilon$ and the complexity is polynomial in the dimension and subquadratic in the number of points. The algorithm succeeds with high probability. More specifically, the best previously known LSH-based construction is improved in terms of complexity by reducing the dependence on ϵ, provided that ϵ is sufficiently small. Our method does not require LSH but, instead, follows Valiant's (2015) approach in designing a sequence of reductions of our problem to other problems in different spaces, under Euclidean distance or inner product, for which r-nets are computed efficiently and the error can be controlled. Our result immediately implies efficient solutions to a number of geometric problems in high dimension, such as finding the $(1 + \epsilon)$-approximate kth nearest neighbor distance in time subquadratic in the size of the input.

Joint with G. Avarikioti, L. Kavouras.

6.15. Extraction of tori from minimal point sets

Participants: Laurent Busé, André Galligo.

In [7], a new algebraic method for extracting tori from a minimal point set, made of two oriented points and a simple point, is proposed. We prove a degree bound on the number of such tori; this bound is reached on examples, even when we restrict to smooth tori. Our method is based on pre-computed closed formulae well suited for numerical computations with approximate input data.

6.16. Scaffolding skeletons using spherical Voronoi diagrams

Participants: Alvaro Fuentes Suarez, Evelyne Hubert.

Given a skeleton made of line segments we describe how to obtain a coarse mesh (or scaffold) of a surface surrounding it. We emphasize in [21] the key result that allows us to complete a previous approach that could not treat skeletons with cycles.

6.17. G^1-smooth splines on quad meshes with 4-split macro-patch elements

Participants: Ahmed Blidia, Bernard Mourrain.

We analyze the space of differentiable functions on a quad-mesh $\mathcal{M}$, which are composed of 4-split spline macro-patch elements on each quadrangular face. We describe explicit transition maps across shared edges, that satisfy conditions which ensure that the space of differentiable functions is ample on a quad-mesh of arbitrary topology. These transition maps define a finite dimensional vector space of G^1 spline functions of bi-degree $\leq (k, k)$ on each quadrangular face of $\mathcal{M}$. We determine the dimension of this space of G^1 spline functions for k big enough and provide explicit constructions of basis functions attached respectively to vertices, edges and faces. This construction requires the analysis of the module of syzygies of univariate b-spline functions with b-spline function coefficients. New results on their generators and dimensions are provided. Examples of bases of G^1 splines of small degree for simple topological surfaces are detailed and illustrated by parametric surface constructions.

This is a joint work with Nelly Villamizar

6.18. Hermite type spline spaces over rectangular meshes with complex topological structures

Participants: André Galligo, Bernard Mourrain.

Motivated by the Magneto HydroDynamic (MHD) simulation for Tokamaks with Isogeometric analysis, we present in [14] a new type of splines defined over a rectangular mesh with arbitrary topology, which are piecewise polynomial functions of bidegree (d, d) and C^r parameter continuity. In particular, we compute their dimension and exhibit basis functions called Hermite bases for bicubic spline spaces. We investigate their potential applications for solving partial differential equations (PDEs) over a complex physical domain in the framework of Isogeometric analysis. In particular, we analyze the property of approximation of these spline spaces for the L^2-norm. Despite the fact that the basis functions are singular at extraordinary vertices, we show that the optimal approximation order and numerical convergence rates are reached by setting a proper parameterization.

This is a joint work with Meng Wu, Bernard Mourrain, André Galligo, Boniface Nkonga

6.19. H^1-parameterizations of complex planar physical domains in isogeometric analysis

Participants: André Galligo, Bernard Mourrain.

Isogeometric analysis (IGA) is a method for solving geometric partial differential equations (PDEs). Generating parameterizations of a PDE's physical domain is the basic and important issues within IGA framework. In [13], we present a global H^1-parameterization method for a planar physical domain with complex topology.

This is a joint work with Meng Wu, Boniface Nkonga.

6.20. Convergence rates with singular parameterizations for solving elliptic boundary value problems in isogeometric analysis

Participant: Bernard Mourrain.

In [15], we present convergence rates for solving elliptic boundary value problems with singular parameterizations in isogeometric analysis. First, the approximation errors with the $L^2(\Omega)$-norm and the $H^1(\Omega)$-seminorm are estimated locally. The impact of singularities is considered in this framework. Second, the convergence rates for solving PDEs with singular parameterizations are discussed. These results are based on a weak solution space that contains all of the weak solutions of elliptic boundary value problems with smooth coefficients. For the smooth weak solutions obtained by isogeometric analysis with singular parameterizations and the finite element method, both are shown to have the optimal convergence rates. For non-smooth weak solutions, the optimal convergence rates are reached by setting proper singularities of a controllable parameterization, even though convergence rates are not optimal by finite element method, and the convergence rates by isogeometric analysis with singular parameterizations are better than the ones by the finite element method.

This a joint work with Meng Wu, Yicao Wang, Boniface Nkonga, Changzheng Cheng.

6.21. Geometric modeling and deformation for shape optimization of ship hulls and appendages

Participants: Elisa Berrini, Bernard Mourrain.

The precise control of geometric models plays an important role in many domains such as computer-aided geometric design and numerical simulation. For shape optimization in computational fluid dynamics (CFD), the choice of control parameters and the way to deform a shape are critical. In [4], we describe a skeleton-based representation of shapes adapted for CFD simulation and automatic shape optimization. Instead of using the control points of a classic B-spline representation, we control the geometry in terms of architectural parameters. We assure valid shapes with a strong shape consistency control. Deformations of the geometry are performed by solving optimization problems on the skeleton. Finally, a surface reconstruction method is proposed to evaluate the shape's performances with CFD solvers. We illustrate the approach on two problems: the foil of an AC45 racing sail boat and the bulbous bow of a fishing trawler. For each case, we obtain a set of shape deformations and then we evaluate and analyzed the performances of the different shapes with CFD computations.

This is a joint work with Yann Roux, Matthieu Durand, Guillaume Fontaine.

6.22. Geometric model for automated multi-objective optimization of foils

Participants: Elisa Berrini, Bernard Mourrain.

The work in [18] describes a new generic parametric modeler integrated into an automated optimization loop for shape optimization. The modeler 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. As an application, we propose to perform a multi-objective shape optimization of an AC45 foil. The modeler is linked to the fluid solver AVANTI, coupled with Xfoil, and to the optimization toolbox FAMOSA.

This is a joint work with Régis Duvigneau, Matthieu Sacher, Yann Roux.

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, Charles Raffaelli [CHU, Nice], 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). 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 modelling ; anatomical variability ; cochlear implant ; temporal bone

- We introduced an automated and reproducible framework for cochlear shape analysis [13].
- We introduced a new cochlear segmentation method within a generative probabilistic Bayesian framework for CT images [6].
- We studied the shape variability with a large database of CT images (N = 987) and quantified the bilateral symmetry in cochlear anatomy.
- We provided a proof of concept for the estimation of postoperative cochlear implant electrode-array position from clinical CT (Fig. 1).

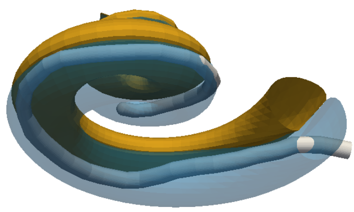


Figure 1. Cochlear implant electrode-array position (white) with respect to scala tympani (blue) and scala vestibuli (orange)

6.1.2. Prediction of Post-Ablation Outcome in Atrial Fibrillation Using Shape Parameterization and Partial Least Squares Regression

Participants: Shuman Jia [Correspondent], Claudia Camaioni, Marc Michel Rohe, Pierre Jaïs, Xavier Pennec, Hubert Cochet, Maxime Sermesant.

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

We proposed an application of diffeomorphometry and partial least squares regression to address the problem of post-ablation outcome in atrial fibrillation.

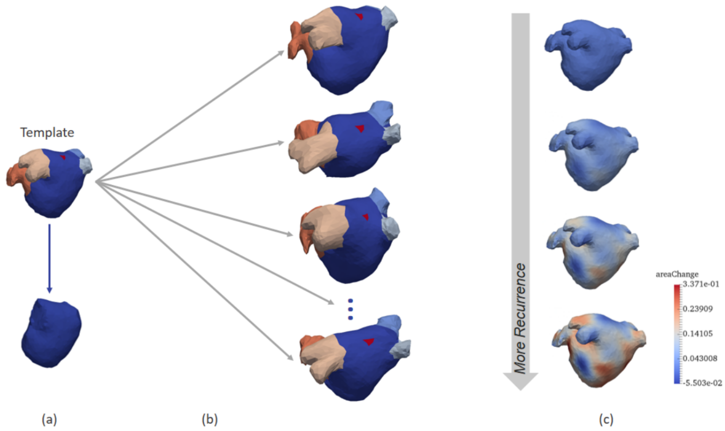


Figure 2. Extraction of remodeling information vs. recurrence. (a) average shape in control group; (b) deformation from the template to patient-specific shapes; (c) deformation mode correlated with recurrence.

As illustrated in Fig. 2 , we computed a template of left atrial shape in control group and then established point-to-point correspondence between patient-specific shapes and the template. The diffeomorphic deformations are encoded and applied in partial least squares regression to predict ablation success, which outperformed the left atrial volume index.

6.1.3. Cardiac Imaging and Machine Learning for Electrostructural Tomography

Participants: Tania Marina Bacoyannis [Correspondent], Hubert Cochet [IHU Liryc, Bordeaux], Maxime Sermesant.

This work is funded within the ERC Project ECSTATIC from the IHU Liryc, in Bordeaux.

Machine Learning, Cardiac modeling, Personalised simulation, Inverse problem of ECG, Electrical simulation, Inverse problem.

By using non-invasive electrical data (Body Surface Potential Mapping), we aim to develop a machine learning approach that can improve electrophysiological cardiac modeling in order to improve diagnosis and predict the response to therapy. This project involves measured and simulated data. For example, we processed experimental data provided by the IHU Liryc, gathered during an experiment on an healthy pig's heart (Figure 3). The simulated potentials appeared to be close to the measurements (Figure 4). The short-term goal is to reconstruct semi-automatically the simulated personalized activation maps.

6.1.4. VT-Scan: image based modelling of cardiac electrophysiology to guide catheter radiofrequency ablation of re-entrant ventricular tachycardia

Participants: Nicolas Cedilnik [Correspondent], Maxime Sermesant, Hubert Cochet, Pierre Jaïs, Frédéric Sacher.

This work was funded by IHU Liryc, Bordeaux.

cardiac electrophysiology modelling, cardiac imaging, ventricular tachycardia, catheter ablation, arrhythmia

- We used cardiac CT images to estimate infarct scar density and location using an automated thickness computation.
- A wavefront propagation speed was derived from this thickness in order to parametrize an Eikonal model of cardiac electrophysiology (see 5).

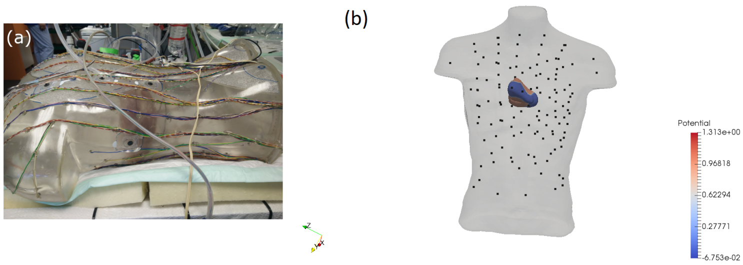


Figure 3. (a) Torso- tank experimental setup with perfused pig heart,(b) Representation of the experimental Torso for BSPM registration of the healthy pig heart, Torso's electrodes and the estimated activation map

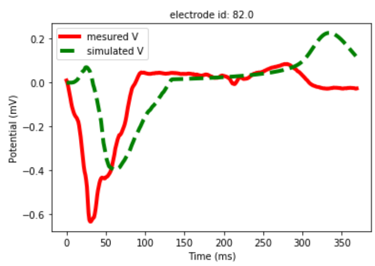


Figure 4. Example of BSPM signals on the Torso's electrode number 82

- We were able to match our simulations to recorded ventricular tachycardia patterns obtained during catheter ablation procedures, on 10 different ventricular tachycardias.
- This work was presented at the Functionnal Imaging and Modelling of the Heart conference in Toronto[34].

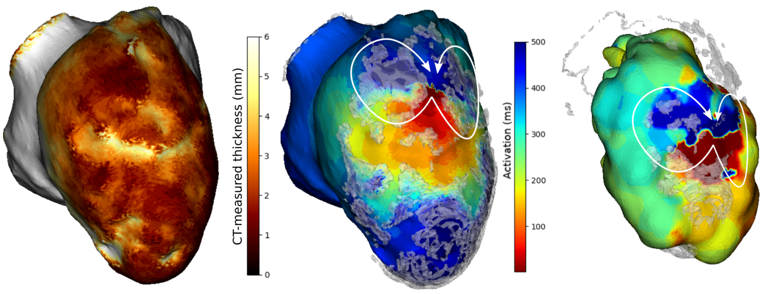


Figure 5. Example of a patient-specific simulation of a proven re-entrant wavefront propagation pattern. [Left] CT-measured myocardial wall thickness, projected on a CT-derived 3D mesh. [Middle] Myocardial activation simulation result using our framework. [Right] Activation recorded during a ventricular tachycardia catheter ablation

6.1.5. Deep Learning for Tumor Segmentation

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

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

deep learning, semi-supervised learning, segmentation, MRI, tumors

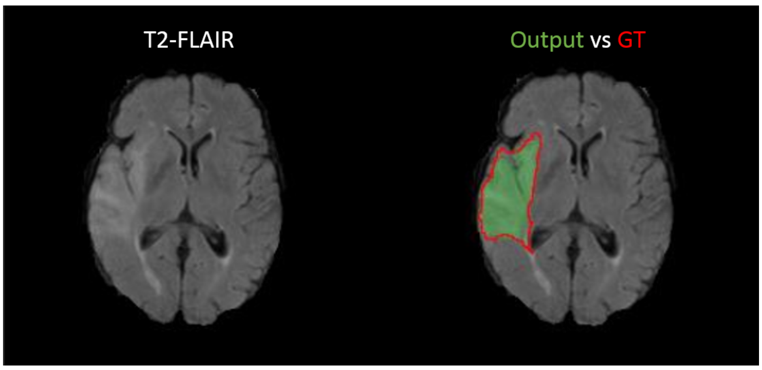


Figure 6. Left: axial slice of a brain MR image presenting a malignant tumor. Right: GT truth (red contour) vs segmentation produced by our semi-supervised method.

- We designed an algorithm for semi-supervised learning of neural nets for segmentation of tumors. The proposed system produces accurate binary segmentations (Figure 6) on unseen images with a limited number of ground truth segmentations used during the training phase.

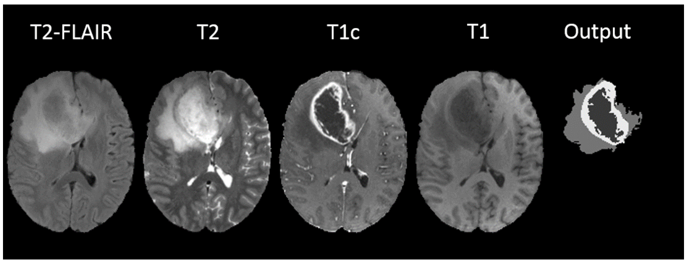


Figure 7. Multimodal MR and the multi-class tumor segmentation produced by our system.

- We proposed an efficient system based on Convolutional Neural Networks for multi-class segmentation of tumors in multimodal MR images (Figure 7). In particular, we proposed a new approach for treating different MR sequences and we introduced a new approach for ensembling 2D and 3D networks. We evaluated our method on the public benchmark of BRATS 2017 challenge and we obtained a top-3 performance among 60 participating teams.

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

Participants: Wen Wei [Correspondent], Nicholas Ayache [Inria], Olivier Colliot [ARAMIS].

Multiple Sclerosis, MRI, PET

Multiple sclerosis (MS) is a demyelinating and inflammatory disease of the central nervous system . 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 for MS patients. Figure 8 shows an example of multiple MRI pulse sequences for MS studies.

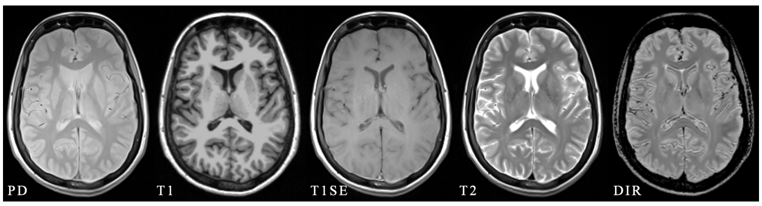


Figure 8. Proton density (PD), T1 spin-echo (T1SE), T1-w, T2-w, double inversion recovery (DIR) weighted images are used for MS studies.

6.1.7. Robust and 3D-Consistent Cardiac Segmentation by Deep Learning

Participants: Qiao Zheng [Correspondent], Hervé Delingette [Inria], Nicolas Duchateau [Université Claude Bernard Lyon 1], Nicholas Ayache [Inria].

Cardiac Segmentation, Deep Learning, MRI, Robustness, Consistency

We propose a method based on deep learning to perform cardiac segmentation on short axis MRI image stacks. An example of segmentation is presented in Figure 9 . The method is trained on a large database and then tested on other state-of-the-art cohorts. Results comparable or even better than the state-of-the-art in terms of distance measures are achieved. They prove the contribution of our method to enhance spatial consistency, and its generalization ability to unseen cases even from other databases.

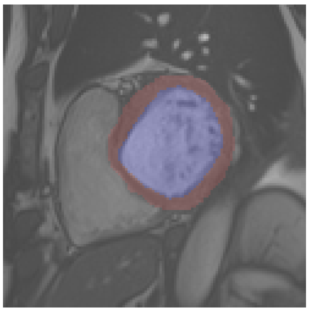


Figure 9. An example of cardiac segmentation.

6.1.8. Joint analysis of radiomic and metabolomic features to improve diagnosis and therapy in oncology

Participants: Fanny Orlhac [Correspondent], Charles Bouveyron, Hervé Delingette, Nicholas Ayache, Olivier Humbert [CAL], Jacques Darcourt [CAL], Thierry Pourcher [CEA], Fanny Vandenbos [CHU Nice].

Inria postdoctoral fellowship for 16 months

Radiomics, Metabolomics, Statistical learning

This work is done in collaboration with the Centre Antoine Lacassagne and the TIRO team (Transporter in Imagery and Radiotherapy for Oncology, CEA-UNS) located in Nice.

- The project consists to jointly analyze histogram, shape and textural features extracted from medical images (radiomics) and metabolomic data in oncology (see Figure 10).
- The goal is to better characterize tumor heterogeneity from both data sources in order to provide a personalized patient management.
- The work focuses on two pathologies: breast cancer and glioblastoma.

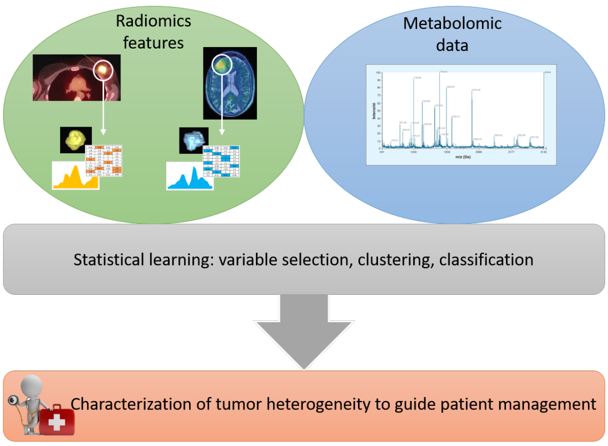


Figure 10. Joint analysis of radiomic and metabolomic features.

6.1.9. Heart & Brain: discovering the link between cardiovascular pathologies and neurodegeneration through biophysical and statistical models of cardiac and brain images.

Participants: Jaume Banús Cobo [Correspondent], Maxime Sermesant, Marco Lorenzi.

Uinversité Côte d'Azur (UCA)

Lumped models - Medical Imaging - Biophysical simulation - Machine learning

The project aims at developing a computational model of the relationship between cardiac function and brain damage from large-scale clinical databases of multi-modal and multi-organ medical images. We will use advanced statistical learning tools for discovering relevant imaging features related to cardiac dysfunction and brain damage from large datasets of medical images and clinical information; these measurements will be combined within a unified mechanistic framework to understand and validate the relationship between cardiac function, vascular pathology and brain damage. The goal is to provide an unprecedented instrument for the in-vivo assessment of latent neurodegenerative conditions in the general population, and will be validated with respect to established indices of cognitive decline and to specific sub-population for which the ground truth is known.

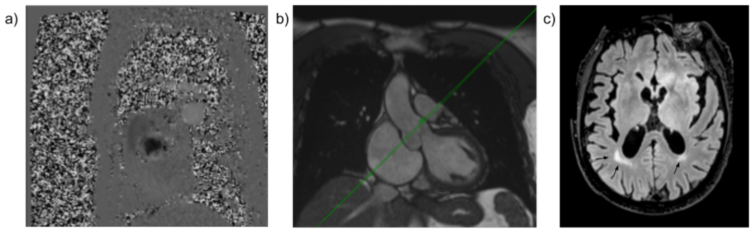


Figure 11. a) Aortic valve flow imaging, view obtained from the plane represented in the left ventricular outflow tract (LVOT) cine b); c) T2 FLAIR image in which white matter hyperintensities (WMHs) are visible.

6.1.10. Statistical learning on large databases of heterogeneous imaging, cognitive and behavioural data

Participants: Luigi Antelmi [Correspondant], Marco Lorenzi, Nicholas Ayache, Valeria Manera, Philippe Robert.

statistical learning, neuroimaging, big data, multimodal

The aim of our work is to develop scalable learning models for the joint analysis of heterogeneous biomedical data. The project will be applied to the investigation of neurological disorders from collections of brain imaging, body sensors, biological and clinical data available in current large-scale health databases. The resulting methodological framework will be tested on the UK Biobank, as well as on pathology-specific clinical data, as provided by the ADNI [0], or INSIGHT [0] initiatives.

From the methodological perspective, the project will focus on the development of computationally efficient formulations of probabilistic latent variable models. These approaches will highlight meaningful relationship among biomarkers that will be used to develop optimal strategies for disease quantification and prediction (Fig. 12).

[0] http://adni.loni.usc.edu/
[0] http://alzheimer-recherche.org/9248/etude-insight/

The research is within the MNC3 initiative (Médecine Numérique: Cerveau, Cognition, Comportement) funded by Université Côte d'Azur (UCA), and will be performed in collaboration with the Institut Claude Pompidou (CHU of Nice).

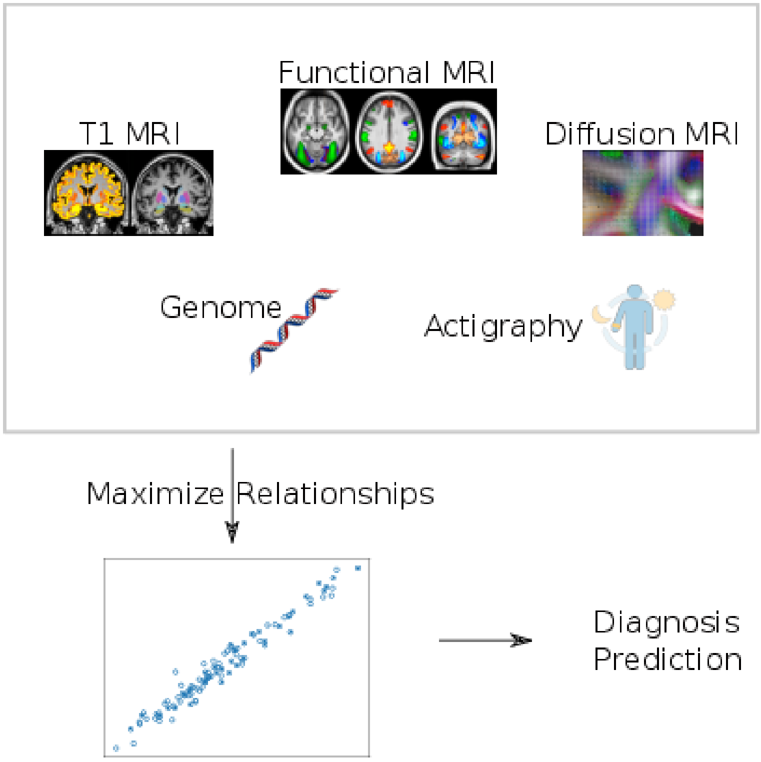


Figure 12. Adopted framework: development of computationally efficient formulations of probabilistic latent variable models to highlight meaningful relationship among biomarkers for disease quantification and prediction.

6.1.11. Robust non-rigid registration through agent-based action learning

Participants: Julian Krebs [Correspondent], Hervé Delingette, Tommaso Mansi [Siemens [Siemens Healthineers, Medical Imaging Technologies], Nicholas Ayache.

This PhD is carried out between the Asclepios research group, Inria Sophia Antipolis and Medical Imaging Technologies, Siemens Healthineers, Princeton, New Jersey, USA.

Deformable Registration, Deep Learning, Reinforcement Learning

We developed a deep learning-based approach for organ-specific deformable registration in 3-D [39] by:

- reformulating deformable registration as an agent-based learning problem (Fig. 13)
- using a low-parametric parametric statistical deformation model
- applying a novel ground truth generator which allows generating millions of synthetically deformed training samples requiring only a few real deformation estimations

Improved performance has been demonstrated with respect to traditional algorithms.

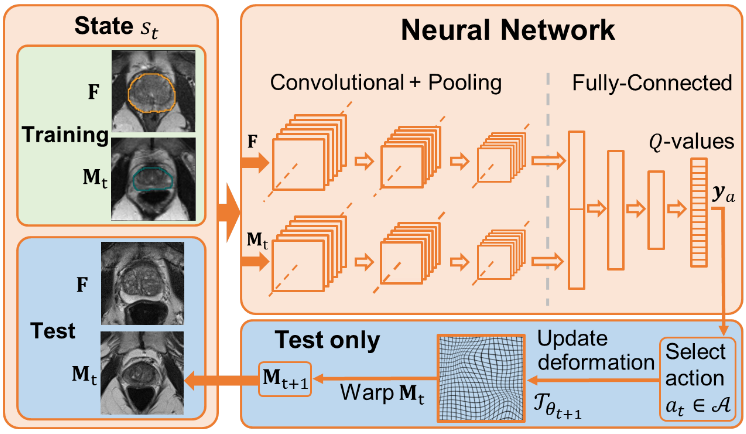


Figure 13. Dual-stream network used for the agent's action estimations including single-stage Markov Decision Process for testing (blue background).

6.2. Computational Anatomy

6.2.1. Inconsistency of Template Estimation in Quotient Spaces

Participants: Loïc Devilliers [Correspondent], Stéphanie Allassonnière [Université Paris-Descartes], Alain Trouvé [ENS Paris-Saclay], Xavier Pennec.

Inria postdoctoral fellowship for 16 months

Template estimation, Fréchet Mean, Quotient Spaces, Inconsistency, Consistency Bias

- A central issue in Computational Anatomy is to compute an unbiased template prototype of our data images (the template) in the presence of two effects: the noise in the ambient space and the unknown registration of the data. The template estimation is usually performed by minimizing the discrepancy after registration (and iterating), which corresponds geometrically to the computation of the Fréchet mean in the quotient space. So far, it was generally believed that the template estimation with this method was unbiased.
- We show in this work that inconsistency is in fact the general situation when the ambient space is an infinite dimensional linear space. In [15] we prove that this method is generally inconsistent when the action is isometric. Moreover the consistency bias has been quantified [35] thanks to a Taylor expansion in the noise level. Besides, we provide proofs of inconsistency for non isometric action [15] when the noise level is large enough.

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

The usual algorithm of brain template estimation is asymptotically biased, therefore inconsistent: even with an infinite number of brain images in the database, the template estimate may not converge to the brain anatomy it is meant to estimate. In [22]:

- we present a methodology that quantifies spatially the brain template's asymptotic bias, see Figure 14
,

- we propose a topologically constrained adaptation of the template computation, that constructs a hierarchical template with bounded bias, and we apply it to the Open Access Series of Imaging Studies (OASIS) database.

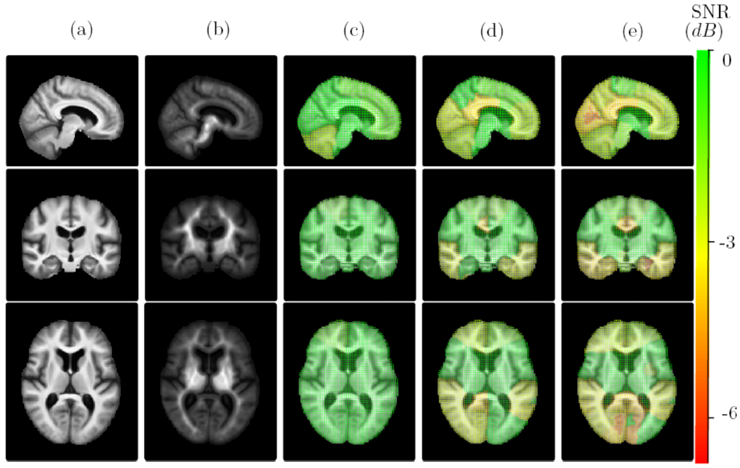


Figure 14. Here we investigate the brain template's consistency as an estimator of a unique anatomy, with respect to the signal-over-noise ratio (SNR) of different regions. The SNR is related to the ratio of the maximum difference in intensity of the region, on the intensity variability averaged on corresponding registered subjects. (a) Template, (b) Template whitened by the intersubject variability, (c) Region-wise inconsistency for a SNR threshold = 1.3, (d) for threshold = 2, (e) for threshold = 4 (dimensionless).

6.2.3. SVF-Net: Learning Deformable Registration Using Shape Matching

Participants: Marc Michel Rohe [Correspondent], Xavier Pennec, Maxime Sermesant.

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

Registration, Deep Learning, Shape Matching

We propose an innovative approach for registration based on the deterministic prediction of the parameters from both images instead of the optimization of a energy criteria [44]. The method relies on a fully convolutional network (see Fig. 15). Whereas convolutional networks have seen a widespread expansion and have been already applied to many medical imaging problems such as segmentation and classification, its application to registration has so far faced the challenge of defining ground truth data on which to train the algorithm. Here, we present a novel training strategy to build reference deformations which rely on the registration of segmented regions of interest. The speed and robustness of this registration algorithm make it a strong candidate within a multi-atlas segmentation pipeline [45].

6.2.4. Reduced Representation of Segmentation and Tracking in Cardiac Images for Group-Wise Longitudinal Analysis

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

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

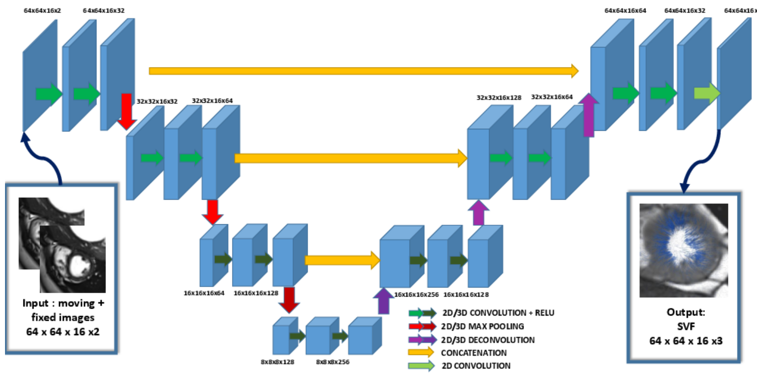


Figure 15. Fully convolutional neural networks for $3D$ registration: The inputs are the fixed and the moving $3D$ images. The output is a dense SVF symmetrically mapping the two images defined on the initial image grid.

Medical image analysis, Non-rigid registration, Deep learning, Statistical model reduction, Longitudinal analysis

We study image-based methods for the analysis of cardiac motion to enable group-wise statistics, automatic diagnosis and longitudinal study [10]. This is achieved by combining advanced medical image processing with machine learning methods and statistical modelling. The first axis of this work is to define an automatic method for the segmentation of the myocardium. The second axis of this work is focused on the improvement of cardiac motion tracking methods in order to define relevant low-dimensional representations. Finally, in the last axis, we apply the previously defined representation to the problem of diagnosis and longitudinal analysis. These three axes form an end to end framework for the study of cardiac motion starting from the acquisition of the medical images to their automatic analysis. Such a framework could be used for diagnosis and therapy planning in order to improve the clinical decision making with a more personalised computer-aided medicine.

6.2.5. A model of brain morphological evolution

Participants: Raphaël Sivera [Correspondent], Hervé Delingette, Marco Lorenzi, Xavier Pennec, Nicholas Ayache.

Longitudinal modeling, deformation framework, brain morphology, Alzheimer's disease, aging.

We proposed a deformation-based generative model of the brain morphological evolution that can joinly describes the effect of aging and Alzheimer's disease. It relies on longitudinal description of the aging and disease consequences and can be use to compute image-based cross-sectional progression markers (see Figure 16). This approach is able to propose a description of the disease evolution, population and subject-wise.

6.2.6. Statistical Learning of Heterogeneous Data in Large-Scale Clinical Databases

Participants: Clement Abi Nader [Correspondent], Nicholas Ayache, Marco Lorenzi.

The research takes place within the MNC3 initiative (Médecine Numérique: Cerveau, Cognition, Comportement) funded by Université Côte d'Azur (UCA), and is performed in collaboration with the Institut Claude Pompidou (CHU of Nice).

Longitudinal modeling, brain structure, Alzheimer's disease, aging, Gaussian processes, ICA.

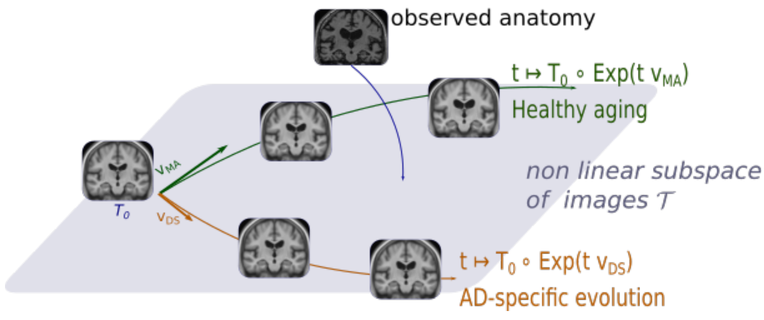


Figure 16. Left: z-values associated with group-wise differences between controls and Alzheimer-diagnosed subjects. Right: Areas of statistically significant differences.

Through this project we aim at developing novel scalable spatio-temporal analysis tools to identify clinical and biological modulators of structural and functional brain changes across time. The project relies on the extension of current un-/semi-supervised image analysis approaches (such as independent component analysis, ICA) to encode priors on spatial and temporal properties of the signal measured in brain images. The application to currently available large-scale biomedical datasets (such as the UK Biobank) will be addressed by focusing on scalable and distributed learning methods.

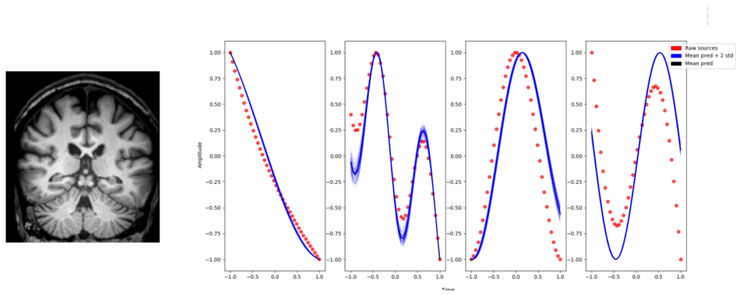


Figure 17. On the left, a coronal slice of a T1 weighted brain MRI. On the right we observe the temporal trajectories that best explain the evolution of the observed brain MRI times series from the UKBIOBANK study. Each trajectory representing the evolution of a meaningful biological and clinical sub-structure of the brain.

6.3. Computational Physiology

6.3.1. Non-invasive personalisation of a cardiac electrophysiology model from body surface potential mapping

Participants: Sophie Giffard Roisin [Correspondent], Maxime Sermesant, Nicholas Ayache, Hervé Delingette.

This work has been supported by the European Project FP7 under grant agreement VP2HF (no 611823) and the Marie Curie Actions European Industrial Doctorate CardioFunXion project (with Universitat Pompeu Fabra and Philips as partners).

Cardiac Modelling, Personalised Simulation, Inverse Problem of ECG, Electrical Simulation

Within the VP2HF project, non-invasive cardiac electrical data has been acquired at St Thomas' Hospital, London. It consists in Body Surface Potential Mapping (BSPM), which are recordings of the electrical potential on several locations on the surface of the torso. In [37], we use non-invasive data (body surface potential mapping, BSPM) to personalise complex cardiac electrical activation patterns such as multiple onset activation locations. We have used a relevance vector regression (see Figure 18) and we have evaluated our method on clinical datasets.

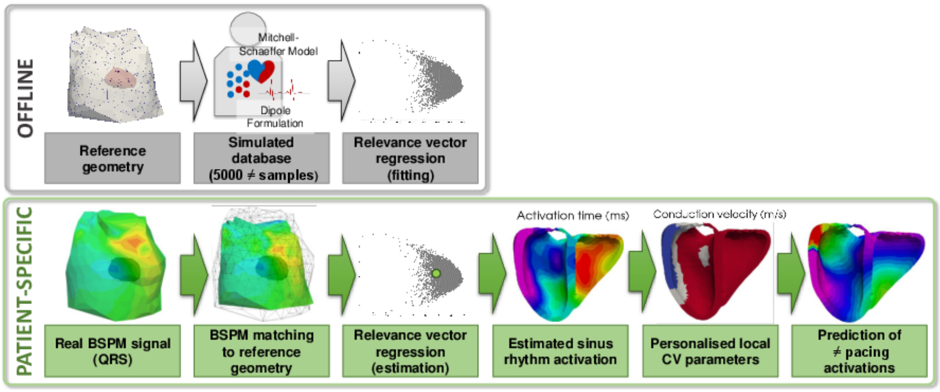


Figure 18. Pipeline of the non-invasive model personalisation

6.3.2. Mulfidelity-CMA Personalisation Algorithm and Personalised 3D Modeling for Longitudinal Analysis

Participants: Roch Philippe Molléro [Correspondent], Xavier Pennec, Hervé Delingette, Alan Garny, 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 Modelling, Personalised Simulation, Longitudinal Analysis, Parameter Estimation, Finite Element Mechanical Modelling

- We extended the multiscale 0D/3D personalisation approach previously published to build a fast, flexible and computationally efficient *multifidelity personalisation*. This algorithm called **Multifidelity-CMA** can be used to personalise hundreds of cases per day without specific manual supervision, fine-tuning of the algorithm or precomputation. The method was published in a scientific journal [24].
- We built more than **140 personalised 3D simulations** in the context of two longitudinal studies. We first used personalised parameters to model short-term transient effects in digestion ([33] and a poster presentation at FIMH Conference 2016), then to analyze long-term evolution of the cardiac function in cardiomyopathies ([42] and a poster presentation at MICCAI Conference 2017). In particular we showed that the use of priors reduces considerably the variance in the population of estimated parameters leading a better conditionning of parameter values whose variability in the population only reflects physiological properties of the cases. In particular we projected personalised parameters onto the axis of a classifier which discriminates between a cohort of healthy and diseased cases, and showed that the evolution of parameter values suggests an improvement of the cardiac function under therapy since the parameters of the follow-up acquisition are closer to the *healthy side* of the classifier (see Figure 19).

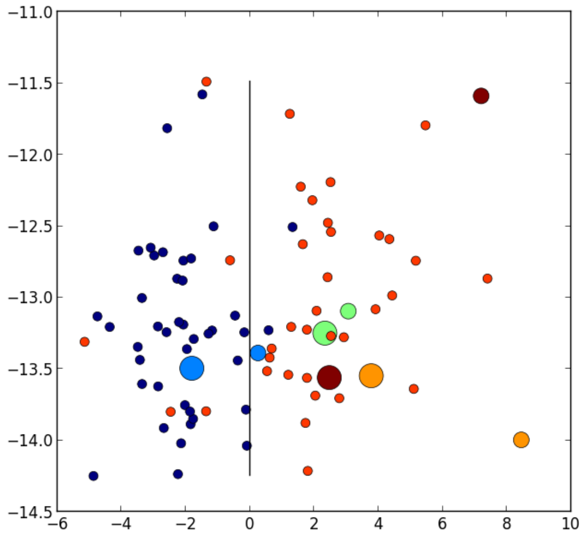


Figure 19. Projection of personalised parameters on the main direction of a LDA classifier between the healthy cases (dark blue dots) and cardiomyopathy (other dots) cases (x-axis) and an principal orthogonal direction of this vector (y-axis). The dots in light blue, brown, orange and green correspond to 4 patients for which the data was available both at baseline (small dot) and follow-up (larger dot).

ATHENA Project-Team

7. New Results

7.1. Computational Diffusion MRI

7.1.1. Spatio-Temporal dMRI Acquisition Design: Reducing the Number of qt Samples Through a Relaxed Probabilistic Model

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

Acquisition time is a major limitation in recovering brain microstructure with diffusion Magnetic Resonance Imaging. Finding a sampling scheme that maximizes signal quality and satisfies given time constraints is NP-hard. We alleviate that by introducing a relaxed probabilistic model of the problem, for which nearly-optimal solutions can be found effectively. Our model is defined in the qt-space, so that it captures both spacial and temporal phenomena. The experiments on in-vivo diffusion images of the C57Bl6 wild-type mice reveal superiority of our technique over random sampling and even distribution in the qt-space.

This work has been published in [33].

7.1.2. Diffusion MRI microstructure models with in vivo human brain Connectom data: results from a multi-group comparison

Participants: Uran Ferizi [CMIC, Dept. of Computer Science, UCL, UK], Rutger Fick, Rachid Deriche.

A large number of mathematical models have been proposed to describe the measured signal in diffusion-weighted (DW) magnetic resonance imaging (MRI) and infer properties about the white matter microstructure. However, a head-to-head comparison of DW-MRI models is critically missing in the field. To address this deficiency, we organized the "White Matter Modeling Challenge" during the International Symposium on Biomedical Imaging (ISBI) 2015 conference. This competition aimed at identifying the DW-MRI models that best predict unseen DW data. in vivo DW-MRI data was acquired on the Connectom scanner at the A.A.Martinos Center (Massachusetts General Hospital) using gradients strength of up to 300 mT/m and a broad set of diffusion times. We focused on assessing the DW signal prediction in two regions: the genu in the corpus callosum, where the fibres are relatively straight and parallel, and the fornix, where the configuration of fibres is more complex. The challenge participants had access to three-quarters of the whole dataset, and their models were ranked on their ability to predict the remaining unseen quarter of data. In this work, we provide both an overview and a more in-depth description of each evaluated model, report the challenge results, and infer trends about the model characteristics that were associated with high model ranking. This work provides a much needed benchmark for DW-MRI models. The acquired data and model details for signal prediction evaluation are provided online to encourage a larger scale assessment of diffusion models in the future.

This work has been published in [16].

7.1.3. Advanced dMRI signal modeling for tissue microstructure characterization

Participants: Rutger Fick, Demian Wassermann, Rachid Deriche.

Non-invasive estimation of brain white matter microstructure features using dMRI – otherwise known as Microstructure Imaging – has become an increasingly complex and difficult challenge over the last decade. Within the framework of Fick's PhD thesis [13], we contributed to the challenge to recover microstructure tissue parameters by studying the impact of using well-regularized functional basis together with multi-compartment approaches. We focused on the estimation and interpretation of microstructure-related markers, often referred to as *Microstructure Imaging* and we reviewed and compared most state-of-the-art microstructure models in PGSE-based Microstructure Imaging, emphasizing model assumptions and limitations, as well as validating them using spinal cord data with registered ground truth histology. We then presented contributions to 3D q-space imaging and microstructure recovery. We proposed closed-form Laplacian regularization for the recent MAP functional basis, allowing robust estimation of tissue-related q-space indices. We also applied this approach to Human Connectome Project data, where we used it as a preprocessing for other microstructure models. Finally, we compared tissue biomarkers in a ex-vivo study of Alzheimer rats at different ages. Last but not least, we contributed to representing the qt-space- varying over 3D q-space and diffusion time. Overall, we significantly contributed to the challenge of better understanding microstructure-related features of the brain's white matter.

This work has been published in [13].

7.1.4. White matter tractography guided by anatomical and microstructural priors

Participants: Gabriel Girard [SCIL, Sherbrooke University, CA], Maxime Descoteaux [SCIL, Sherbrooke University, CA], Demian Wassermann, Rachid Deriche.

In this work, performed within the framework of G. Girard's PhD thesis [81], we mainly focused in developing beyond the state-of-the-art and well grounded tractography solutions to recover the brain structural connectivity: We started reporting biases from tractography reconstruction and suggested to use anatomical priors, derived from a high resolution T1-weighted image to reduce these biases and to embed additional spatial information of the brain tissues in the tractography to guide tractography. We showed that optimizing tractography parameters, stopping and seeding strategies can reduce the biases in position, shape, size and length of the streamline distribution. Overall, we very nicely succeeded to show that this idea was able to significantly improve the tractography by reducing the rate of false positives produced and provides a more quantitative characterization of the WM structure. Going further, we then proposed to embed more intrinsic microstructural information in the reconstruction process and remarkably succeeded to show the great added value brought to tractography by the addition of intrinsic microstructural information such as the mean axonal diameter information estimated from the orientation of maximal diffusion probability. This is an original and important step forward in microstructure informed tractography, paving the way to a new generation of algorithms able to deal with intricate configurations of white matter fibres and providing quantitative brain connectivity analysis.

This work has been published in [13] and its part related to AxTract, the micro-informed tractography algorithm, in [19].

7.1.5. Rational invariants of ternary forms under the orthogonal group

Participants: Paul Görlach, Evelyne Hubert, Théodore Papadopoulo, Rachid Deriche.

In [79], [80], [95] we started to explore the theory of tensor invariants as a mathematical framework for computing new biomarkers for HARDI. We pursued this work and, in collaboration with the project-team GALAAD/AROMATH, we succeeded to develop a complete set of rational invariants for ternary quartics [44]. Being rational, they are very close to the polynomial invariants developed in [80] but they constitute a complete set of invariants. They are also good tools to understand better the algebraic invariants of [95] and some others based on spherical harmonics decomposition [61]. We determined a generating set of rational invariants of minimal cardinality for the action of the orthogonal group O3 on the space $R[x, y, z]_{2d}$ of ternary forms of even degree 2d. The construction relies on two key ingredients: On one hand, the Slice Lemma allows us to reduce the problem to dermining the invariants for the action on a subspace of the finite subgroup B3 of signed permutations. On the other hand, our construction relies in a fundamental way on specific bases of harmonic polynomials. These bases provide maps with prescribed B3-equivariance properties. Our explicit construction of these bases should be relevant well beyond the scope of this work. The expression of the B3-invariants can then be given in a compact form as the composition of two equivariant maps. Instead of providing (cumbersome) explicit expressions for the O3-invariants, we provide efficient algorithms for their evaluation and rewriting. We also use the constructed B3-invariants to determine the O3-orbit locus and provide an algorithm for the inverse problem of finding an element in $R[x, y, z]_{2d}$ with prescribed values for its invariants. These are the computational issues relevant in brain imaging.

This work has been sumitted and is currently under review. A preprint is available in [44].

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

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

This work has been published in [17]

7.1.7. Computational diffusion & perfusion MRI in brain imaging

Participants: Marco Pizzolato, Rachid Deriche.

Diffusion and Perfusion Magnetic Resonance Imaging (dMRI & pMRI) represent two modalities that allow sensing important and different but complementary aspects of brain imaging. This work performed within the framework of M. Pizzolato's PhD thesis presents a theoretical and methodological investigation on the MRI modalities based on diffusion-weighted (DW) and dynamic susceptibility contrast (DSC) images. For both modalities, the contributions of the thesis are related to the development of new methods to improve quality, processing, and exploitation of the obtained signals. With respect to contributions in diffusion MRI, the nature of the complex DW signal is investigated to explore a new potential contrast related to tissue microstructure. In addition, the complex signal is exploited to correct a bias induced by acquisition noise of DW images, thus improving the estimation of structural scalar metrics. With respect to contributions in perfusion MRI, the DSC signal processing is revisited in order to account for the bias due to bolus dispersion. This phenomenon prevents the correct estimation of perfusion metrics but, at the same time, can give important insights about the pathological condition of the brain tissue. The contributions of the thesis are presented within a theoretical and methodological framework, validated on both synthetic and real images.

This work has been published in [15].

7.1.8. Solving the Inclination Sign Ambiguity in Three Dimensional Polarized Light Imaging with a PDE-Based Method

Participants: Abib 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 human postmortem brain or heart at a submillimeter 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 published in [27]

7.1.9. *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], Romain Valabregue [ICM, CENIR, Paris], Richard Levy [ICM, CENIR, Paris], Isabelle Arnulf [ICM, CENIR, Paris], Stéphane Lehericy [ICM, CENIR, Paris], Rutger Fick, Demian Wassermann, 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. Using new techniques to boost signal-to-noise ration and biomarker extraction in multi-shell dMRI [13], we have studied, in collaboration with the Brain and Spine Institute (ICM, Paris) the Klein-Levin syndrome (KLS) [45]. Our results highlight the presence of structural changes correlated to the apathy score i n the anterior portion of the CC during episodes, a region where fibers project onto the medial orbitofrontal cortex. As, these prefrontal regions are involved in motivation processes, this suggests that apathy in KLS could result from difficul ties to provide the affective/motivational value of a given behavioral context.

This work has been published in [45].

7.2. Unveiling brain activity using M/EEG

7.2.1. *Dictionary learning for M/EEG processing*

Participants: Maureen Clerc, Sebastian Hitziger, Théodore Papadopoulo.

Signals obtained from magneto- or electroencephalography (M/EEG) are very noisy and inherently multi-dimensional, i.e. provide a vector of measurements at each single time instant. To cope with noise, researchers traditionally acquire measurements over multiple repetitions (trials) and average them to classify various patterns of activity. This is not optimal because of trial-to-trial variability (waveform variations, jitters). The jitter-adaptive dictionary learning method (JADL) has been developed [82] to better handle for this variability, with a particular emphasis on jitters. It was generalized to handle variability both in jitter and in duration, in a method called Adaptive Waveform Learning [8]. These methods [83] are data-driven and learn a dictionary (prototype signals) from a set of signals, but are limited to a single channel, which restricts their capacity to work with very noisy multichannel data such as M/EEG. An extension to multidimensional signals has been developped in [96] and [41].

7.2.2. *Accounting for conductivity in M/EEG leadfields*

Participants: Maureen Clerc, Juliette Leblond [APICS project-team], Kostiantyn Maksymenko, Jean-Paul Marmorat [APICS project-team], Théodore Papadopoulo, Christos Papageorgakis [APICS project-team].

We aim at improving the EEG forward/inverse problem by better modelling the skull conductivity. Indeed, it has been shown that the complex conductivity profile of the skull has a major influence on the accuracy of the EEG forward/inverse problems.

- The skull conductivity is usually considered homogeneous, but the skull is actually made of several types of bone: hard (compacta) and soft (spongiosa) which may have different conductivity characteristics. By adapting a template to MR images of individual subjects, the influence of the spongiosa on source localization can be demonstrated [97]. Estimating the conductivity values of the skull compartments is an important problem, for which theoretical results on uniqueness and robustness have been obtained [64], [63], [26].
- Such studies show the need of easily obtaining EEG leadfields with various conductivity values. Recomputing a new leadfield for every different set of conductivities is expensive. We have thus developped a technique inspired by “reduced bases” which approximates the set of leadfields over a domain of conductivities using a low number of "base leadfields" [40]. The approach offers mathematical guarantees on the approximation level and provides an efficient methodological ground for attempting to compute both sources and conductivities in the EEG inverse problem.

7.2.3. Cochlear implant stimulation models

Participants: Maureen Clerc, Kai Dang, Dan Gnansia [Oticon Medical], Nicolas Guevara [CHU de Nice].

Our expertise on building forward models in bioelectromagnetism has led to a collaboration with Oticon Medical, a cochlear implant manufacturer. Through Dang’s PhD thesis [12], we developed computational models of cochlear implant stimulation, which can account for the anatomical shape of the inner ear, the shape of the implanted electrode, and the stimulation mode, for instance common ground or multi-mode grounding [67], [66]. The OpenMEEG software was extended to cope with zero-conductivity regions (e.g. the silicon electrode holder). The cochlear implant Boundary Element model was coupled with a lumped capacitor and constant phase element model, allowing time-domain simulation. Thorough validation campaigns were conducted, in vitro (notably using a 3D printer) and in situ (in human specimens).

7.3. Combining spatio-temporal CNS imaging modalities

7.3.1. Groupwise structural parcellation of the whole cortex: A logistic random effects model based approach

Participants: Guillermo Gallardo, William Wells [Harvard Medical School, Boston, MA, USA], Demian Wassermann, Rachid Deriche.

Current theories hold that brain function is highly related to 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 of the cortex. 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 [6].

7.3.2. Spatial regularization based on dMRI to solve EEG/MEG inverse problem

Participants: Brahim Belaoucha, Théodore Papadopoulo.

In this work, we present a new approach to reconstruct dipole magnitudes of a distributed source model for magnetoencephalographic (MEG) and electroencephalographic (EEG). This approach is based on the structural homogeneity of the cortical regions which are obtained using diffusion MRI (dMRI). First, we parcellate the cortical surface into functional regions using structural information. Then, we use a weighting matrix that relates the dipoles' magnitudes of sources inside these functional regions. The weights are based on the region's structural homogeneity. Results of the simulated and real MEG measurement are presented and compared to classical source reconstruction methods.

This work has been published in [29], [11].

7.3.3. Large brain effective network from EEG/MEG data and dMR information

Participants: Brahim Belaoucha, Théodore Papadopoulo.

In this research, we aim at reconstructing the information flow in the brain for a given task. More than simple activations, we look at their relationship in time, so at networks constituted by nodes obtained from the parcellations of [55] and edges coming from tractographies obtained by dMRI. In [56] a multivariate auto-regressive model has been used to model the interactions between brain areas. Those areas are obtained using the methods depicted in paragraph 1. Then a putative network is built using connexions obtained by tractography augmented by cortico-cortical connexions (horizontal connexions between neighbor areas) which are not seen by dMRI. A two stage algorithm estimates the coefficients of the autoregressive matrices [57]. Those matrices are constrained to be sparse, so that the non-zero coefficients can be used to estimate the effective network that was activated during the task. The method was validated using simulated data and applied to real MEG and EEG datasets.

This work has been published in [28], [11].

7.3.4. Inference and Visualization of Information Flow in the Visual Pathway using dMRI and EEG

Participants: Samuel Deslauriers-Gauthier, Jean-Marc Lina [ETS - Ecole de Technologie Supérieure, Montréal, CA], Russel Buttler [SCIL, Sherbrooke University, CA], Pierre-Michel Bernier [SCIL, Sherbrooke University, CA], Kevin Whittingstall [SCIL, Sherbrooke University, CA], Maxime Descoteaux [SCIL, Sherbrooke University, CA], Rachid Deriche.

We propose a method to visualize information flow in the visual pathway following a visual stimulus. Our method estimates structural connections using diffusion magnetic resonance imaging and functional connections using electroencephalography. First, a Bayesian network which represents the cortical regions of the brain and their connections is built from the structural connections. Next, the functional information is added as evidence into the network and the posterior probability of activation is inferred using a maximum entropy on the mean approach. Finally, projecting these posterior probabilities back onto streamlines generates a visual depiction of pathways used in the network. We first show the effect of noise in a simulated phantom dataset. We then present the results obtained from left and right visual stimuli which show expected information flow traveling from eyes to the lateral geniculate nucleus and to the visual cortex. Information flow visualiza-tion along white matter pathways has potential to explore the brain dynamics in novel ways.

This work has been published in [37].

7.3.5. Information Flow in the White Matter During a Motor Task: A Structural Connectivity Driven Approach

Participants: Guillermo Gallardo, Demian Wassermann, Maxine Descoteaux [SCIL, Sherbrooke University, CA], Samuel Deslauriers-Gauthier, Rachid Deriche.

Cognitive tasks emerge from the interaction of functionally specialized cortical regions . These interactions are supported by information flow through white matter fiber bundles connecting distant cortical regions. Estimating the information flow through white matter fiber bundles would therefore provide valuable information into the necessary cortical interactions to realize a task. In this work, we build a Bayesian network representing cortical regions and their connections using a structural connectivity driven parcellation derived from diffusion MRI (dMRI). We then introduce Magnetoencephalography (MEG) measurements as evidence into this network to infer the information flow between cortical regions. We show, for the first time, results on the interaction between the precentral, postcentral and occipital regions during a hand-movement task.

This work has been published in [39].

7.4. Brain Computer Interfaces

7.4.1. Multimodal BCI

Participants: Maureen Clerc, Lorraine Perronnet [Visages project-team], Saugat Bhattacharyya [Camin team].

We are conducting research in Multimodal BCI:

- In collaboration with Camin team in Montpellier, we are investigating the use of feedback using Functional electrical stimulation (FES) of limb muscles [58] for Motor Imagery and also studying the influence of the FES on brain signals.
- A study comparing unimodal and bimodal EEG-fMRI neurofeedback for 10 healthy volunteers showed that EEG-fMRI leads to stronger activations than EEG alone [24].

7.4.2. Automatizing calibration

Participants: Maureen Clerc, Nathalie Gayraud, Alain Rakotomamonjy [Université de Rouen].

One of the drawbacks of BCI is the time required for setup and calibration before its use. Instead of fine-tuning the BCI by collecting labeled data by asking the user to perform tasks without any purpose nor feedback, we propose to fine-tune the BCI after the user has started using it. This requires an initial - suboptimal - classifier, which we propose to build through “transfer learning” by re-using labeled data acquired from other subjects and other sessions. We have investigated two main directions for this:

- **Riemannian geometry of covariance matrices**. Covariance matrices of EEG signals are interesting features for BCI. Their information geometry has led to impressive transfer learning performance, as testified by their excellent ranking in several competitions. We are studying the advantages of these features and how they can be used to build separability markers within datasets [74].
- **Optimal transport theory**. A new strand of research is to use optimal transport methods for domain adaptation. The idea is to reuse the classifiers built from existing labeled datasets by transporting the new unlabeled data onto the domain of the existing data [34].

7.4.3. Translational research

Participants: Maureen Clerc, Claude Desnuelle [CHU de Nice], Violaine Guy [CHU de Nice], Théodore Papadopoulo, Marie-Hélène Soriani [CHU de Nice].

The P300-speller is a widespread BCI paradigm for communication, studied in many laboratories. Our involvement in this paradigm was triggered by the Nice University Hospital ALS reference center. Having evaluated with them existing P300-spellers, which were found difficult to get to work properly, we decided to develop our own P300-speller based on OpenViBE in collaboration with Inserm Lyon [65], [104]. Among its distinctive features: optimal stopping of flashes, principled choice of letter groups [103] and word completion and prediction. We demonstrated the feasibility of our “Coadapt P300 speller” in collaboration with Nice University Hospital during a clinical study with 20 ALS patients who participated in 3 sessions each [99], [20].

In order to bring this type of communication BCI closer to patients, we developed a user-friendly software, bci-vizapp, with far greater portability with respect to hardware (OS, screen and amplifier).

Our work aroused the interest of patient associations, in particular “Espoir Charcot” who helped a patient hospitalized in Chambéry acquire a consumer-grade (Emotiv-EPOC) EEG in order to use the P300-speller. He eventually succeeded in using the system, with the help of a local engineer, but notably without our physical presence at any stage. This represents an important first step for us in translational research.

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, 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 [67]. 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, through the introduction of artificial habitats for the predatores or through the introduction of biological control agents in deterministic [13] or stochastic fashion. This was the main topic of Nicolas Bajeux's PhD thesis [11].

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 study of the durability of plant resistance to root-knot nematodes [28], [41].

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 [57] and implemented on various models [39]. 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. This work was part of Stefano Casagranda's PhD thesis [12] 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 ABC-like method, less computationally expensive than standard Bayesian fitting procedures such as ABC [6]. 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 several parameter sets compatible with the data and reflecting the variability among individuals. So we based our fitting criterion on viral indicators rather than the whole viremia dynamics [44]. This work was part of Natacha Go's post-doctorate, supported by the MIHMES project, in collaboration with the Roslin Institute, Edinburgh, UK. It benefited from the resources and support of NEF computation cluster.

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

7.1.2. Metabolic and genomic models

Participants: Jean-Luc Gouzé, Madalena Chaves, Olivier Bernard, Valentina Baldazzi, Stefano Casagranda, Francis Mairet, Ivan Egorov, Sofia Almeida, Claudia Lopez Zazueta, Lucie Chambon, Luis Gomes Pereira, Eleni Firippi, Ignacio Lopez Munoz.

7.1.2.1. Hybrid models analysis

Applying differential dynamic logic to biological networks. In [26] we have explored the framework of differential dynamic logic for the analysis of hybrid systems and, in particular, piecewise linear models of biological networks (collaboration with D. Figueiredo and M.A. Martins from the University of Aveiro, Portugal).

Attractor computation using interconnected Boolean networks. Following the work in [10] and [58], 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 [9]. We prove that this orbit is unique under some conditions on the parameters.

7.1.2.2. Continuous models analysis

Reduced models for the mammalian cell cycle and clock. In the context of project ANR ICycle, we have focused on identifying and analysing the main mechanisms underlying the cell cycle and the circadian clock in mammalian cells. A reduced two-dimensional model of the cell cycle is described [38]; 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 is in collaboration with F. Delaunay and part of the PhD thesis of Sofia Almeida.

Interconnection of reduced models of the mammalian cell cycle and clock. Also in the context of project ANR ICycle, we have studied several possibilities for the interconnection between these two mammalian oscillators, using the reduced model already described in [38] and two different possible oscillatory circuits of low dimension. This work is part of the Master's thesis of Eleni Firippi.

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 [45]. 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 [17]. We also study other models of the global cellular machinery, and growth models ([22]). This is part of the PhD thesis of Stefano Casagranda, and done in collaboration with Inria IBIS project-team, in particular with D. Ropers.

Analysis and reduction of a model of sugar metabolism in peach fruit. Predicting genotype-to-phenotype relationships under contrasting environments is a big challenge for plant biology and breeding. A model of sugar metabolism in peach fruit has been recently developed and applied to 10 peach varieties [25]. The aim of this ongoing work is to reduce model's size and complexity to allow for calibration on a whole progeny of 106 genotypes and for further application to virtual breeding (collaboration with B. Quilot-Turion and Mohamed Memmah (INRA Avignon) and part of the PhD thesis of Hussein Kanso).

Analysis of an integrated cell division-endoreduplication and expansion model. The development of a new organ depends on cell-cyle progression and cell expansion, but the interaction and coordination between these processes is still unclear. An integrated model of fruit development has been developed and used to investigate the regulation of cell expansion capabilities. To this aim, different control schemes are tested by means of specific model variants and simulation results compared to observed data in tomato [14].

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) [5]. We developed different versions of the problem [43], [36], and consider a new problem where the aim is to optimize the production of a product (ANR projects Reset and Maximic).

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 [32].

7.1.2.4. Large scale metabolic modeling

Metabolic modeling generally assumes balanced growth, *i.e.* that there is no accumulation of intermediate compound, and that the metabolism is rapidly at quasi steady state. We have proposed a new approach called DRUM where this hypothesis is relaxed by splitting the metabolic network into subnetworks and assuming that some compounds can accumulate between the subnetworks [2], [49]. This approach was successfully applied to several cases where the strong variations in light or nutrient resources induce a strong accumulation in the microalgal cells which could not be represented by the state of the art approaches [48]. More recently we have expended this approach to the modeling of diauxic growth for heterotrophic or mixotrophic microalgae [15].

7.1.2.5. Slow-Fast analysis of metabolic models

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

7.2. Fields of application

7.2.1. Bioenergy

7.2.1.1. Modeling microalgae production

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

Experimental developments

Running experiments in controlled dynamical environments. The experimental platform made of continuous photobioreactors driven by a set of automaton controlled by the ODIN software is a powerful and unique tool which gave rise to a quantity of very original experiments. Such platform improved knowledge of several biological processes such as lipid accumulation or cell cycle under light fluctuation, etc. [55],[19].

This experimental platform was used to control the long term stress applied to a population of microalgae. This Darwinian selection procedure generated two new strains after more than 6 months in the so called selectiostats. A strain with $+92\%$ lipids was obtained, another more transparent resulting in $+92\%$ enhancement in productivity [18].

Other experiments were carried out to reproduce the light signal percept by a cell in a raceway pond [60], derived from hydrodynamical studies [64]. 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 [59]. Experiments with coloured light demonstrated that the growth rate results from the absorbed light, whatever its wavelength.

On top of this, we carried out outdoor pilot experiments with solar light. We tested the impact of various temperatures, resulting from different shadowing configurations on microalgal growth rate [56],[40]. This is the topic of Bruno Assis Pessi's master thesis.

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

Metabolism of carbon storage and lipid production. A metabolic model has been set up and validated for the microalgae *Isochrysis luthea*, on the basis of the DRUM framework , in order to simulate autotophic, heterotropic and mixotrophic growth, and to determine how to reduce substrate inhibition [15]. The model was extended for other substrates such as glucose or glycerol. A simplified model was developped by I. Lopez to represent the dynamics of polar lipids, especially when faced to a high oxygen concentration.

Modeling the coupling between hydrodynamics and biology. In collaboration with the Inria ANGE team, a model coupling the hydrodynamics of the raceway (based on a new multilayer discretisation of Navier-Stokes equations) with microalgae growth was developed [51]. 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. The statistical analysis of both theoretical properties of probability densities for perfectly mixed systems and output of Lagrangian simulations demonstrate the accurate reconstruction of the trajectories. As a consequence, more relevant experimental protocols have been proposed to more realistically design simplified light signal for experiments.

Modeling photosynthetic biofilms. Several models have been developed to represent the growth of microalgae within a biofilm. A first structured physiological model uses mixture theory to represent the microalgae growth, based on the consideration of intracellular reserves triggering the processes of growth, respiration and excretion. We consider separately the intracellular storage carbon (lipids and carbohydrates) and the functional part of microalgae [29]. Another approach accounts for the dynamics of the light harvesting systems when cells are submitted to rapid successions of light and dark phases. A simpler model was developed and used to identify the optimal working mode of a process based on photosynthetic biofilm growing on a conveyor belt.

Modeling microalgae production processes. The integration of different models developed within BIOCORE [52] was performed to represent the dynamics of microalgae growth and lipid production in raceway systems.

Using these approaches, we have developed a model which predicts lipid production in raceway systems under varying light, nutrients and temperature [72]. A simplified version of this model, describing microalgal growth under varying light and temperature conditions predicts microalgal productivity in the perspective of large scale biofuel production [23].

In the framework of the ANR project Purple Sun, we developed a thermal 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). We have shown in [40] that a control strategy based on shadowing with solar panel can significantly improve productivity, especially during the early growth stage of the culture.

A procedure for rapid outdoor model calibration, from lab data, has been proposed and applied to the microalgae *Dunaliella salina* [56].

Modeling thermal adaptation in microalgae. We have studied several models of microalgae growth to different temperatures [27]. In particular, we have detailed the impact of higher temperatures on cell mortality [20]. Experiments have been carried out in collaboration with A.-C. Baudoux (Biological Station of Roscoff) in order to study growth of various species of the microalgae genus *Micromonas* at different temperatures. After calibration of our models, we have shown that the pattern of temperature response is strongly related to the site where cells were isolated. We derived a relationship to extrapolate the growth response from isolation location. With this approach, we proved that the oceanwide diversity of *Micromonas* species is very similar to the oceanwide diversity of the phytoplankton. We have used Adaptive Dynamics theory to understand how temperature drives evolution in microalgae. We could then predict the evolution of this biodiversity in a warming ocean and show that phytoplankton must be able to adapt within 1000 generation to avoid a drastic reduction in biodiversity.

Modeling viral infection in microalgae. Experiments have been carried out in collaboration with A.-C. Baudoux (Biological Station of Roscoff) in order to study the impact of viral infections on the development of populations of *Micromonas* at different temperatures. This work revealed a qualitative change in viral infection when temperature increases. A model was developed to account for the infection of a *Micromonas* population, with population of susceptible, infected and also free viruses. The model turned out to accurately reproduce the infection experiments at various temperatures, and the reduction of virus production above a certain temperature [24].

7.2.1.2. Control and Optimization of microalgae production

Optimization of the bioenergy production systems. A model predictive control approach was run based on simple microalgae models coupled with thermal physical models. Optimal operation in continuous mode for outdoor cultivation was determined when allowing variable culture depth. Assuming known weather forecasts considerably improved the control efficiency [23].

Interactions between species. We had formerly proposed an adaptive controller which regulates the light at the bottom of the reactor [70]. 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 [69]. 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 studied. We modelled the adaptive dynamics for a population submitted to a variable temperature [62]. 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 [18].

Finaly, optimal strategies when selecting the strain of interest within a set of n species competing for the same substrate has been proposed [16].

7.2.2. Biological depollution

7.2.2.1. Control and optimization of bioprocesses for depollution

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

Although bioprocesses involve an important biodiversity, the design of bioprocess control laws are generally based on single-species models. In [68], 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 monospecific 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, Carlos Martinez Von Dossow.

The coupling between a microalgal pond and an anaerobic digester is a promising alternative for sustainable energy production and wastewater treatment by transforming carbon dioxide into methane using light energy. The ANR Phycover project is aiming at evaluating the potential of this process [74].

We have proposed several models to account for the biodiversity in the microalgal pond and for the interaction between the various species. These models were validated with data from the Saur company. More specifically, we have included in the miroalgae model the impact of the strong turbidity, and derived a theory to better understand the photolimitation dynamics especially when accounting for the photo-inhibition in the illuminated periphery of the reactor. Optimal control strategies playing with the dilution rate, shadowing or modifying depth were then studied [40].

7.2.2.3. Life Cycle Assessment

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

Environmental impact assessment. In the sequel of the pioneering life cycle assessment (LCA) work of [65], we continued to identify the obstacles and limitations which should receive specific research efforts to make microalgae production environmentally sustainable.
We studied a new paradigm to improve the energy balance by combining biofuel production with photovoltaic electricity. This motivated the design of the purple sun ANR-project where electricity is produced by semi transparent photovoltaic panels [50] under which photosynthetic microalgae are growing. The LCA of a greenhouse with, at the same time, photovoltaic panels and low emissivity glasses is studied. Depending on the period of the year, changing the species can both improve productivity and reduce environmental footprint.

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

7.2.3. Design of ecologically friendly plant production systems

7.2.3.1. Controlling plant arthropod pests

Participants: Frédéric Grognard, Ludovic Mailleret, Suzanne Touzeau, Nicolas Bajeux, Bapan Ghosh.

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 [66], [73], 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 [13]. Extension of this result have been performed to take into account stochasticity by develeoping a master equation for the combined continuous-stochastic process and a purely stocastic model. This last part of N. Bajeux's PhD thesis mycitePhD:bajeux was performed in collaboration with Vincent Calcagno (ISA).

Characteristics of space and the behavior and population dynamics of parasitoids. We studied the influence of space on the spread of biological control agents through computer simulations and laboratory experiments on *Trichogramma*. This is the topic of Marjorie Haond's PhD thesis (ISA, 2015-). In particular, we showed both theoretically and experimentally how habitat richness [63] 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).

Model of coffee berry borer dynamics. We built a first model describing the coffee berry borer dynamics, in order to design efficient and sustainable control strategies, including alternative methods to pesticides (cropping practices, trapping, biological control). This single-season model is based on the insect life-cycle and includes the berry availability during a cropping season. Local and global stability results, the latter using Lyapunov functions, were obtained for both the pest-free and the endemic equilibria. Furthermore, this model was extended to integrate the berry maturation age. The well-posedness of the resulting PDE model was shown. This research pertains to Yves Fotso Fotso's PhD thesis, who visited BIOCORE during 4 months in 2017 in the framework of the EPITAG associate team.

7.2.3.2. Controlling plant pathogens

Participants: Frédéric Grognard, Ludovic Mailleret, Suzanne Touzeau, Julien Guégan, Yves Fotso-Fotso, Israel Tankam-Chedjou.

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

Experiments were conducted in INRA Avignon, 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 [31]. Also, the Quantitative Trait Loci (QTL) controlling viruses effective population sizes (linked to genetic drift) have been identified for two different viruses, showing the genetic origin of these parameters and the presence of general and virus specific QTLs [34]. This 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 [28], [41]. This research pertains to Samuel Nilusmas' PhD thesis.

We developed and partly calibrated a (spatio-)temporal epidemiological model of the phoma stem canker of oilseed rape, to design sustainable resistance deployment strategies. Ongoing work includes the completion of this study and the development of a user-friendly simulation tool. It will be achieved through the MoGeR project, in collaboration with BIOGER (INRA Grignon) and partners from technical institutes and cooperatives. It benefits from the resources and support of NEF computation cluster.

Model of nematodes-plantain roots dynamics. We developed and analysed a seasonal model describing the interactions between nematodes and plantain roots, to design efficient and sustainable control strategies, including alternative methods to pesticides (cropping practices, resistant or tolerant banana cultivars, biological control). It is a doubly hybrid system, so as to take into account the plantain root growth. A slow-fast dynamics approximation was used to obtain local stability results for the pest-free equilibrium and exact solutions around this equilibrium. Conditions were derived for nematode extinction, depending in particular on the delay between cropping seasons. This research pertains to Israël Tankam Chedjou's PhD thesis, who visited BIOCORE during 4 months in 2017 in the framework of the EPITAG associate team.

Mate limitation and cyclic epidemics. We studied the effect of mate limitation in parasites which perform both sexual and asexual reproduction in the same host. Since mate limitation implies positive density dependence at low population density, we modeled the dynamics of such species with both density-dependent (sexual) and density-independent (asexual) transmission rates. A first simple SIR model incorporating these two types of transmission from the infected compartment, suggested that combining sexual and asexual spore production can generate persistently cyclic epidemics [30].

7.2.3.3. Optimality/games in population dynamics

Participants: Frédéric Grognard, Ludovic Mailleret, Pierre Bernhard, Ivan Egorov, Pierre-Olivier Lamare.

Optimal resource allocation. Mycelium growth and sporulation are considered for phytopathogenic fungi. For biotrophic fungi, a flow of resource is uptaken by the fungus without killing its host; in that case, life history traits (latency-sporulation strategy) have been computed based on a simple model considering a single spore initiating the mycelium, several spores in competition and applying optimal resource allocation [42], and several spores in competition through a dynamic game. The solution of this dynamic game has been shown to be the equilibrium of two-trait adaptive dynamics in Julien Guégan's internship. Also, the obtained sporulation strategy has been put in a PDE model to evaluate how the characteristics of the fungus evolve along a colonization gradient. This work, in the framework of the ANR Funfit project, is done with Fabien Halkett of INRA Nancy.

Dynamic games as a model of animal foraging. P. Bernhard has continued his investigations of dynamic games with randomly arriving players as a model of animal foraging and of competition in open markets. He has written the chapter "Robust Control and Dynamic Games"in the Handbook of Dynamic Games Theory [54].

7.3. Patents

Two patents were proposed for improving growth of microalgae with green light [53] and for enhancing the thermal niche after long term thermal stress in a continuous reactor [47].

BIOVISION Team

7. New Results

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

7.1.1. Using virtual reality to helping low-vision people read depending on their pathology

Participants: Marco Benzi [Université Côte d'Azur (France)], Stéphanie Baillif [Centre hospitalier Pasteur 2 (service d'ophtalmologie, Nice, France)], Annick Martin ["27Delvalle" (Centre d'Innovation Santé de la ville de Nice, France)], Eric Castet [Aix-Marseille Université (CNRS, Laboratoire de Psychologie Cognitive, Marseille, France)], Fabio Solari [University of Genoa (DIBRIS, Genoa, Italy)], Manuela Chessa [University of Genoa (DIBRIS, Genoa, Italy)].

By stimulating imagination, reading can be considered as the first immersive media that we are experimenting in our life. We read for leisure, to learn or to be informed. Nowadays, we read not only on printed books or newspaper but on a variety of electronic platforms (computers, tablets, phones), thus extending the possibilities to read. However, reading poses problems for almost everyone with low-vision and it is amongst the strongest need reported by patients [55], [65]. Electronic equipments such as CCTV have offered new possibilities for the patients to tune their prefered display and many studies have been done to understand the impact of most parameters in reading performance [50], [70], [42], [49], [65]. However, display is still highly limited by the small field of view offered by CCTVs, the navigation issues, and the fact that they are constrained to sit at their desk in order to read, thus providing a limited comfort to patients. Our goal is to investigate how virtual reality could be used to overcome these limitations and study new reading aid strategies depending on patients' pathologies.

This project received funding from Université Côte d'Azur (France), in the "Pré-maturation" call which finances actions that transform existing proof of concept into an operational laboratory prototype allowing either the realization of "robust" demonstrators or the complete experimental validation of concept (see Sec. 9.1.1).

7.1.2. Real-time image enhancement in virtual reality applications for low-vision people

Participants: Manuela Chessa [University of Genoa (DIBRIS, Genoa, Italy)], Alberto Patino [University of Genoa (DIBRIS, Genoa, Italy)], Horacio Rostro [University of Guanajuato (Guanajuato, Mexico)], Eric Castet [Aix-Marseille Université (CNRS, Laboratoire de Psychologie Cognitive, Marseille, France)], Fabio Solari [University of Genoa (DIBRIS, Genoa, Italy)], Pierre Kornprobst.

In the last years, virtual reality technology has experienced a boost in affordability, and an increasing number of applications have emerged proposing new immersive 360 degrees visual content. To make this content accessible for low-vision people, one should adopt the same strategies as in traditional displays, i.e., use dedicated image enhancement methods to facilitate their interpretation. This work introduces a virtual reality application for mobile devices that implements real-time content enhancement. It is implemented as a visual search task in a set of static 360 degrees environments: the immersed user can manipulate the parameters of the enhancement algorithm in a intuitive way, using an external controller. In particular, we focus on the transform proposed by Peli et al [69], which is based on an adaptive filter that controls the local contrast as a function of the local mean luminance of an image. Such a transform has been shown to improve recognition tasks in patients with moderate visual loss, central scotoma or cataracts. Our application is, to our knowledge, the first attempt to evaluate the impact of this image enhancement in an immersive virtual reality environment. In particular, our system allows the real time tuning of the transform, and provides all the quantitative data to analyse a posteriori users' behaviour and how parameters may impact their performance. Designed as a game, it is perceived as more enjoyable than traditional ophthalmologic experiments. More generally, this application could be a way for low-vision people to adjust vision enhancements to their needs in everyday virtual reality applications, also for entertainment purposes

This work was presented at the Vision conference [27].

7.1.3. ARVIP: Augmented reality for visually impaired people

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

In Biovision, we want to develop new augmented reality systems for low-vision people, to facilitate scene interpretation by enhancing important scene characteristics. Research and investigations are conducted using automotive industry HW solutions, thanks to a partnership with Bosch Visiontec (Sophia Antipolis, France, see Sec. 8.1.1).

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

7.2.1. Recurrent network dynamics reconciles visual motion segmentation and integration

Participants: N.v. Kartheek Medathati, James Rankin [University of Exeter (Department of Mathematics, Exeter, UK)], Andrew I. Meso [Institut de Neurosciences de la Timone (CNRS and Aix-Marseille Université, France)], Pierre Kornprobst, Guillaume S. Masson [Institut de Neurosciences de la Timone (CNRS and Aix-Marseille Université, France)].

In sensory systems, different computational rules are postulated to be implemented by different neuronal subpopulations characterised by their tuning function. For instance, in primate cortical area MT, different classes of direction-selective cells have been identified and related to either motion integration, segmentation or transparency. Still, how such different tuning properties are constructed is unclear. The dominant theoretical viewpoint based on linear-nonlinear feedforward cascade does not account for their complex temporal dynamics and their versatility when facing different input statistics. Here, we demonstrate that a recurrent network model of visual motion processing can reconcile these different properties. Using a ring network, we show how excitatory and inhibitory interactions can implement different computational rules such as vector averaging, winner-take-all or superposition. The model also captures ordered temporal transitions between these behaviours. In particular, depending on the inhibition regime the ring network can switch from motion integration to motion segmentation, thus being able to compute either a single pattern motion or to superpose multiple inputs as in motion transparency. We thus demonstrate that recurrent architectures can adaptively give rise to different cortical computational regimes depending upon the input statistics, thus reconciling the twin blows of sensory processing: integration and segmentation.

This work was published in [20]

7.2.2. Retinal waves

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

Retinal waves are bursts of activity occurring spontaneously in the developing retina of vertebrate species, contributing to the shaping of the visual system organization: retina circuitry shaping, retinotopy, eye segregation [77], [56], [72], [57]. They stop a few weeks after birth. Wave activity begins in the early development, long before the retina is responsive to light. It was recently found that they can be reinitiated pharmacologically in the adult mammalian retina [54]. This could have deep consequences on therapy for several degenerative retinal diseases. The mechanism of their generation, in imature, or adult retinas, remains however incompletely understood [78].

We have proposed a model for stage II retinal waves - induced by bursting Starburst Amacrine Cells (SACs) coupled by acetylcholine - with 2 objectives: (i) being sufficiently close to biophysics to explain and propose experiments and (ii) affording a mathematical analysis. From a bifurcations analysis we have highlighted several relevant biophysical parameters controlling waves generation, mainly regulating potassium and calcium dynamics. We thus explain how SACs in different species exhibit a large variability in their bursting periods with a common mechanism. We have proposed a testable experimental prediction providing a possible link of the evolution of voltage-dependent potassium channels along development with their role on the excitability properties of SACs. We have reproduced experimental findings (statistical characteristics of waves size, duration and frequency of appearance) and analyzed how the evolution of cholinergic conductance due to the maturation of nicotinic receptors dramatically changes the retinal wave characteristics. We have also shown that the nonlinear dynamics generates heterogeneous local spatial structures inside which retinal waves propagate. This induces a wide variability in waves characteristics even though the network is perfectly homogeneous.

This work has been presented in [36], [34], [24], [25], [38], [37]

7.2.3. Pan-retinal characterisation of light responses from ganglion cells in the developing mouse retina

Participants: Gerrit Hilgen [Institute of Neuroscience (ION, Newcastle, UK)], Sahar Pirmoradian [Institute for Adaptive and Neural Computation (ANC, School of Informatics University of Edinburgh, UK)], Daniela Pamplona [ENSTA ParisTech, Autonomous Systems and Robotics (Paris, France)], Pierre Kornprobst, Bruno Cessac, Matthias H. Hennig [Institute for Adaptive and Neural Computation (ANC, School of Informatics University of Edinburgh, UK)], Evelyne Sernagor [Institute of Neuroscience (ION, 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 behaviour, 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 has been published in [19].

7.2.4. Trajectory anticipation, from retina to V1

Participants: Selma Souihel, Bruno Cessac.

Global motion processing is a major computational task of biological visual systems. When an object moves across the visual field, the sequence of visited positions is strongly correlated in space and time, forming a trajectory. These correlated images generate a sequence of local activation of the feedforward stream. At the present stage of knowledge, it is still unclear how the early visual system processes motion trajectories. Motion integration, anticipation and prediction would be jointly achieved through the interactions between feed-forward, lateral and feedback propagations within a common spatial reference frame, the retinotopic maps. Addressing this problem is particularly challenging, as it requires to probe these sequences of events at multiple scales (from individual cells to large networks) and multiple stages (retina, primary visual cortex (V1).

In the context of the ANR Trajectory we are working on such an integrated approach. We aim at modelling the population responses at two key stages of visual motion encoding: the retina and V1 based on simultaneous micro- and mesoscopic recordings made by our partners Institut de Neurosciences de la Timone (CNRS and Aix-Marseille Université, France) and Institut de la Vision (Paris, France), and design a simulator of retinal output feeding V1. This study is a step toward understanding mechanisms of motion coding and anticipation with strong impact on our understanding of the visual system.

We have implemented in our retina simulator, PRANAS, gain control mechanisms allowing to reproduce motion anticipation for simple motions. We developed a simple decoding algorithm that reconstructs the stimulus using firing rates, with the goal of comparing the performance of the different models of gain control. We have also designed a biologically inspired model of connectivity, mimicking short and long range connections between ganglion cells via amacrine cells. This has allowed us to compare the pairwise correlations between ganglion cells, under the influence of a moving object both, in vivo and in silico. These results have been presented in [40], [41], [39]

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

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

Retinal spike response to stimuli is constrained, on one hand by short range correlations (receptive field overlap) and on the other hand by lateral connectivity (cells connectivity). This last effect is difficult to handle from statistics because it requires to consider spatio-temporal correlations with a time delay long enough to take into account the time of propagation along synapses. Although MaxEnt models are useful to fit optimal model (maximizing entropy) under the constraints of reproducing observed correlations, they do address spatio-temporal correlations in their classical form (Ising or higher order interactions but without time delay). Binning in such models somewhat integrates propagation effects, but in an implicit form, and increasing binning severely bias data. To resolve this issue we have considered spatio-temporal MaxEnt model formerly developed e.g. by Vasquez et al. [75]. The price to pay, however is a huge set of parameters that must be fitted to experimental data to explain the observed spiking patterns statistics. There is no a priori knowledge of which parameters are relevant and which ones are contributing to overfitting. We propose here a method of dimension reduction, i.e. a projection on a relevant subset of parameters, relying on the so-called Susceptibility matrix closely related to the Fisher information. In contrast to standard methods in information geometry though, this matrix handles space and time correlations. We have applied this method for retina data obtained in a diurnal rodent (Octodon degus, having 30% of cones photoreceptors) and a 252-MEA system. Three types of stimuli were used: spatio-temporal uniform light, white noise and a natural movie. We show the role played by time-delayed pairwise interactions in the neural response to stimuli both for close and distant cells. Our conclusion is that, to explain the population spiking statistics we need both short-distance interactions as well as long-distance interactions, meaning that the relevant functional correlations are mediated not only by common input (i.e. receptive field overlap, electrical coupling; spillover) but also by long range connections.

This work has been submitted to Plos Comp Bio.

7.2.6. On the mathematical consequences of binning spike trains

Participants: Bruno Cessac, Arnaud Le Ny [Laboratoire d'Analyse et de Mathématiques Appliquées (LAMA, (Université Paris-Est, France)], Eva Loecherbach [Laboratoire d'Analyse, Géométrie et Modélisation (AGM) and Département de Mathématiques (Cergy-Pontoise, France)].

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 [17].

7.2.7. Linear response of general observables in spiking neuronal network models

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

The activity of a neuronal network, characterized by action potentials (spikes), is constrained by the intrinsic properties of neurons and their interactions. When a neuronal network is submitted to external stimuli, the statistics of spikes changes, and it is difficult to disentangle the influence of the stimuli from the intrinsic dynamics. Using the formalism of Gibbs distributions, which are a generalization of Maximum Entropy distributions to non-stationary distributions, and generalization of Markov chains to infinite memory, we analyze this problem in a specific model (Conductance-based Integrate-and-Fire), where the neuronal dynamics depends on the history of spikes of the network. We derive a linear response formula allowing to quantify the influence of a weak amplitude external stimuli on the average value of arbitrary observables. This formula clearly disentangles the effect of the stimuli, intrinsic neuronal dynamics, and network connectivity. Upon some approximations, it reduces to a convolution, allowing to recover a standard formulation in computational neuroscience.

This work has been submitted to Journal of Mathematical Neurosciences [33].

7.2.8. A bio-inspired synergistic virtual retina model for tone mapping

Participants: Marco Benzi, Maria-Jose Escobar [Universidad Tecnico Federico Santa María (Electronics Engineering Department, Valparaíso, Chile)], Pierre Kornprobst.

Real-world radiance values span several orders of magnitudes which have to be processed by artificial systems in order to capture visual scenes with a high visual sensitivity. Interestingly, it has been found that similar processing happens in biological systems, starting at the retina level. So our motivation in this paper is to develop a new video tone mapping operator (TMO) based on a synergistic model of the retina. We start from the so-called Virtual Retina model [76], which has been developed in computational neuroscience. We show how to enrich this model with new features to use it as a TMO, such as color management, luminance adaptation at photoreceptor level and readout from a heterogeneous population activity. Our method works for video but can also be applied to static images (by repeating images in time). It has been carefully evaluated on standard benchmarks in the static case, giving comparable results to the state-of-the-art using default parameters, while offering user control for finer tuning. Results on HDR videos are also promising, specifically w.r.t. temporal luminance coherency. As a whole, this paper shows a promising way to address computational photography challenges by exploiting the current research in neuroscience about retina processing.

This work was published in [15].

CAMIN Team

6. New Results

6.1. Modeling and identification of the sensory-motor system

6.1.1. 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 gait events such as stride length or dorsiflexion speed at heel on. 29 subjects were included in this experimental protocol. Equipped with motion capture targets on which an inertial sensor is set, subjects had to perform an experimental path on a gait carpet. EMG recordings were also performed to monitor and evaluate fatigue. Algorithms were developped for computing 3D trajectory (6), dorsiflexion angles at mid-swing or before heel strike. Results shows an RMS error of 5.8° at heel on and 6.6° at mid-swing compared to motion capture data [20]. François Feuvrier has defended his medicine thesis on this topic on December 14th 2017.

6.2. Model based optimal multipolar stimulation without a priori knowledge of nerve structure: application to vagus nerve stimulation

Participants: Mélissa Dali, Olivier Rossel, David Guiraud.

Neural electrical stimulation, applied to the peripheral nervous system for motor functions restoration or neuromodulation, is a thriving technology, especially implanted stimulation using cuff electrodes positioned around a peripheral nerve. The main obstacle to the development of stimulation systems is the difficulty in obtaining the independent stimulation or inhibition of specific target functions (i.e. functional selectivity). The parameters involved in selectivity are not always intuitive and the number of degrees of freedom (choice of electrode, number of contacts, pulse shape etc.) is substantial. Thus, testing all these hypotheses in a clinical context is not conceivable. This choice of parameters can be guided using prior numerical simulations predicting the effect of electrical stimulation on the neural tissue. Numerous studies developed new strategies to achieve selectivity based on modeling results that have been validated a posteriori by experimental works. We presented a general method based on a spatiotemporal model to optimize and assess multipolar neural electrical stimulation without a priori knowledge of the nerve structure. The model consists of two independent components: a lead field matrix (LFM) and an activation model. It represents the transfer function from the applied current to the extracellular voltage present on the nodes of Ranvier along each axon. The determination of fibers activation is used to optimize the spatial layout for the selective activation of specific fibers or nerve areas. Optimization is not only based on selectivity but also on robustness and efficiency of the stimulation settings.

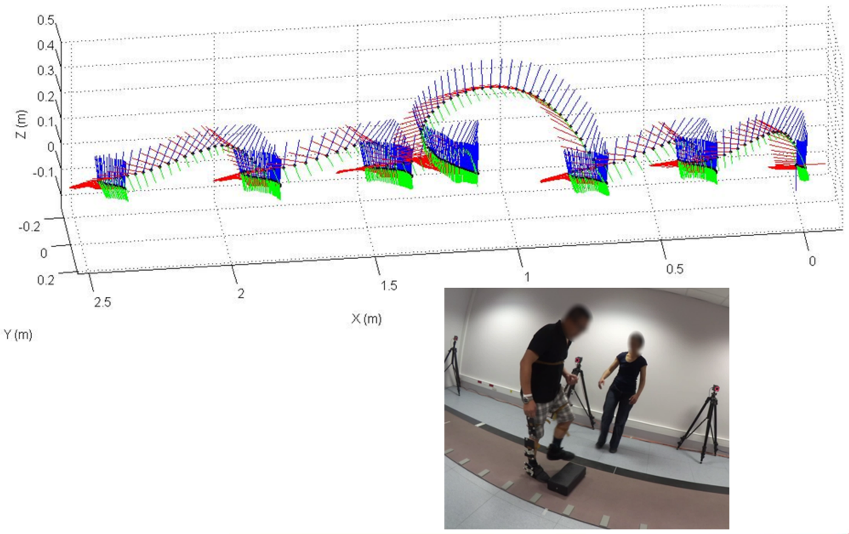


Figure 6. 3D trajectory reconstruction from inertial sensors

The results show that state-of-the- art solutions are part of the optimized solutions but new ones can emerge depending on the trade-off between the criteria and the targeted area. We successfully assessed the solutions in-vivo to selectively induce a decrease in cardiac rhythm through vagus nerve stimulation. Experiments on animal model allowed us to evaluate the effectiveness and genericness of the method. These encouraging results suggest that this approach will have broader applications that would benefit from multicontact cuff electrodes to elicit very accurate and selective responses. This work was performed as part of a larger project on vagus nerve stimulation (INTENSE project) in which one of the applications focused on the treatment of cardiac disorders. The main objective was to selectively activate a specific population of nerve fibers to improve therapy and decrease side effects. Within the framework of the INTENSE project, the second application investigated vagus nerve stimulation as a therapy for morbid obesity. Activation of target axons related to gastric functions requires a significant amount of charge injection. Several studies suggest that non-rectangular waveforms can activate axons of the peripheral nervous system with a reduced amount of charge compared to the reference rectangular pulse shape. Our last contribution focuses on the experimental study and the modeling of these complex waveforms. The modeling approach, if performed properly and while bearing in mind its limits, provides a relevant and even indispensable analysis tool for the clinical adjustment of neuroprostheses.

6.3. Alterations of EEG rhythms and dynamics during motor preparation following wide-awake brain surgery

Participants: Anthony Boyer, Sofiane Ramdani [LIRMM], Hugues Duffau [CHU Montpellier], Bénédicte Poulin-Charronnat [Université de Bourgogne], David Guiraud, François Bonnetblanc.

Awake brain surgery of 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. Recently, we focused on postoperative

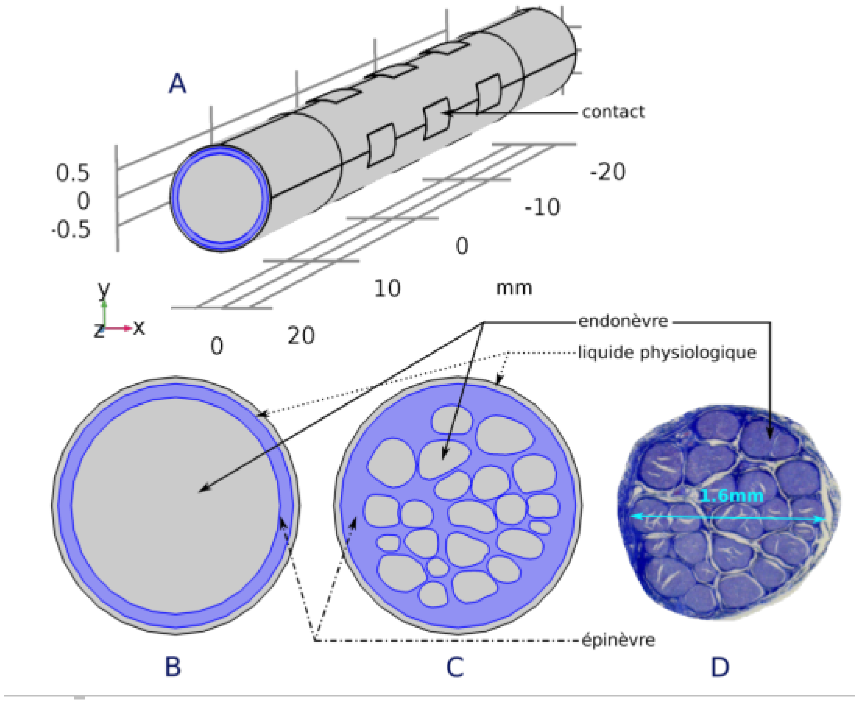


Figure 7. Generic nerve model (A,B) and realistic nerve model (C) based on histological data

brain dynamics of patients, who underwent wide-awake surgery for Low grade gliomas (LGG). We analysed EEG data of 5 patients, who perfomed an ecological visuomanual task, comparing them to a control group of 8 healthy subjects (fig. 8). We used the motor preparation period to extract power features and phase space features to better characterise changes in EEG signal following surgery and subsequent functional reorganisation. The preparation period was chosen for its stationarity allowing analyses, which were not applicable during the ERP period. Our results clearly identify changes in postoperative brain dynamics of patients, who underwent wide-awake surgery. Both spectral and recurrence quantification analyses suggested imbalances between the injured and healthy hemispheres for patients, whether in terms of spectral power density or temporal structure of EEG signal. These investigations performed on the motor preparation period also provided important information regarding longitudinal recovery of brain dynamics. Although all patients in our study had very different tumours, both in size and location, it is interesting to note that the 2 patients, who underwent the experimental protocol respectively 9 and 12 months after surgery, showed more moderate alterations of spectral content and signal complexity independently of the lesion size. This may be seen as an indicator for EEG signal standardization in time and presumably a resumption of brain dynamics. These findings have potential clinical rehabilitation implications.

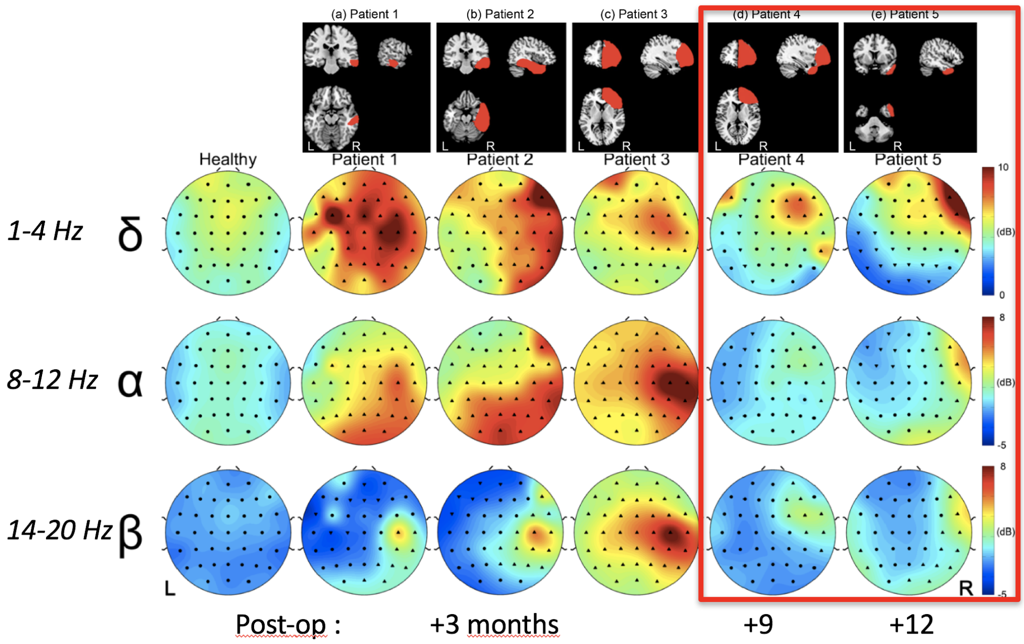


Figure 8. Topographical maps of spectral power: Maps illustrating the spatial distribution of the spectral power contained in a given frequency band over the scalp. We selected bands which showed significant peaks of spectral power for patients in comparison with control group (i.e. δ band: 1 - 4Hz, α/μ band: 9 - 12Hz and β band: 14 - 20Hz) and we then calculated the average power at each electrode for each band. Electrode locations are represented by a set of symbols: ● symbol is used when the corresponding spectral power falls within the 95% confidence interval estimated from healthy subjects. ▲ and ▼ symbols are respectively used when the power is either greater or smaller than the 95% confidence interval. α/μ band

6.4. Electrophysiological brain mapping: measuring evoked potentials induced by electrical stimulation and its physiological spreading in the human brain.

Participants: Marion Vincent, François Bonnetblanc, David Guiraud, Hugues Duffau [CHU Montpellier], Emmanuel Mandonnet [CHU Lariboisière, APHP], Anthony Boyer.

Being able to change or inhibit the activity of a region or population of neurons in the brain is an essential approach in fundamental neuroscience, as it helps the researcher to determine the functional role of neurons. This approach is also important at a more applied level, for brain function mapping during neurosurgical procedures. It is well known that electrical stimulation (ES) affects neural activity by modifying the voltage gradient along the neuronal cell inducing depolarization or hyperpolarization of the membrane. When a current flows in tissues around neuronal cells, it can change their membrane potential and trigger an action potential. However, this general principle can be applied in vivo via several different settings and much is unknown about which neural elements are excited or inhibited locally and how this local perturbation spreads within the brain through physiological pathways [35]. We are now able to record different types of electrophysiological potentials that are evoked by ES in the human brain and we developed some basic methodological considerations required for their correct assessment [26] (fig.9). With our methodology, three different types of evoked potentials can now be measured during brain surgery in the operative room: – Cortical evoked-potential (also called direct cortical response, DCR), when recording the cortex at the stimulation site, – Cortico-axono-cortical evoked-potential, i.e. recording the cortex at a distant site from the stimulating site. These potentials are elicited by physiological propagation through white matter associative pathways from the locally stimulated area towards the distal area, – Axono-cortical evoked potentials, when the cortex is distally recorded from a stimulation site within the white matter. These evoked potentials are technically difficult to observe. Their recording imposes important methodological considerations about the way they can be triggered and measured. In particular, proposed some factors potentially determining the generation of true cortico-axono-cortical evoked potentials, spreading from one stimulated cortical area to another distant one and passing through the white matter pathways. Correctly measuring evoked potentials in the human brain induced by electrical stimulation is important in the clinical domain especially in the neurosurgical context. It remains challenging because of many pitfalls that can occur at the methodological level and few teams in the world are currently able to efficiently record these evoked potentials. Nevertheless, they can give strong real-time in vivo insights into the functional state and connectivity of a patient's brain. In the next years measuring intraoperatively the evoked potentials with ES in the brain will be a new method for mapping the brain in vivo and in real time and taking into account the specificity of each patient's brain.

6.5. Diagnosis evaluation of acute ischemic stroke using new technics

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

Cerebral infarctions can now be treated with new techniques using intravenous thrombolysis and thrombectomy. Their proven efficacy is directly correlated to the time lapse between the start of symptoms and the initiation of treatment. Currently, a definitive diagnosis can only be made once the patient has performed a radiological imaging (CT scan or MRI) on a medical center equipped with these expensive devices, thus enabling the medical team to initiate the appropriate treatment. Transit times during the pre-hospitalization phase before diagnosis are therefore often longer and have the greatest negative impact on the patient's prognosis. In collaboration with the interventional neuroradiology department of Gui de Chauliac Hospital, I2FH and Euromov, the EleVANT project is aiming to prospectively evaluate new techniques to assess a diagnosis of acute cerebral ischaemia. This low cost technology could be used in a mobile way for the very early diagnosis of cerebral infarction and thus reduce treatment delays, opening the way to a new generation of diagnostic tools. The concept consist on evaluating the cerebral near-infrared spectroscopy (NIRS) response to different stimulus, and to evaluate its lateralization. Recently, we tested our device on healthy volunteers. Method: Left

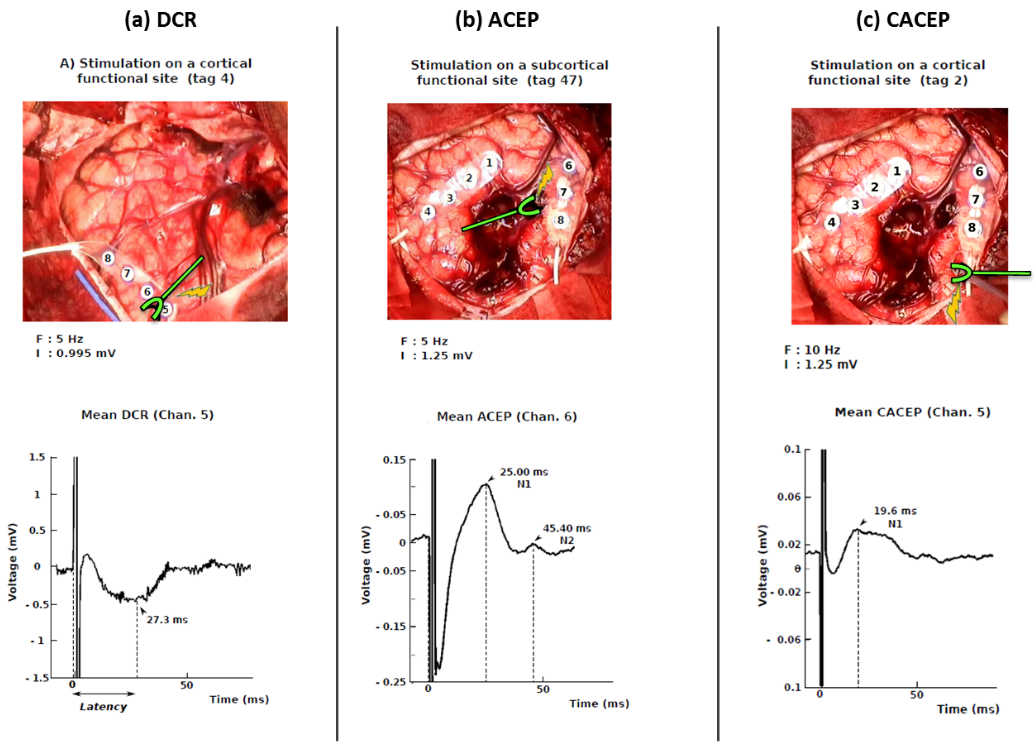


Figure 9. Example of mean evoked potentials induced by DES. (a) Direct cortical responses (DCR) present one primary peak around 27 ms after the stimulation onset. They were measured on 4 patients on cortical sites distant of less than 2 cm from the cortical stimulation site. (b) Axono-cortical evoked potentials (ACEP) presented a primary peak around 25 ms after DES, followed by a second peak 20 ms later. DES is applied subcortically, around 1.7 cm away from the recording site. ACEP were osberved on 2 patients. (c) Cortico-axono-cortical evoked potentials (CACEP) were oberved in 1 patient. Cortical DES induced a one-peak waveform 14 to 35 ms after the artefact onset. CACEP were recorded on cortical site more than 2 cm away from the stimulation site.

and right hemisphere reactivity index are recorded by NIRS and normalized (Figure 10). Result: The experiment present a suitable feasibility and repeatability. In healthy subjects, a good response to the stimulus is recorded, and no significant differences between hemispheres are observed. The confidence level is acceptable since the amplitude response in above the standard deviation level.

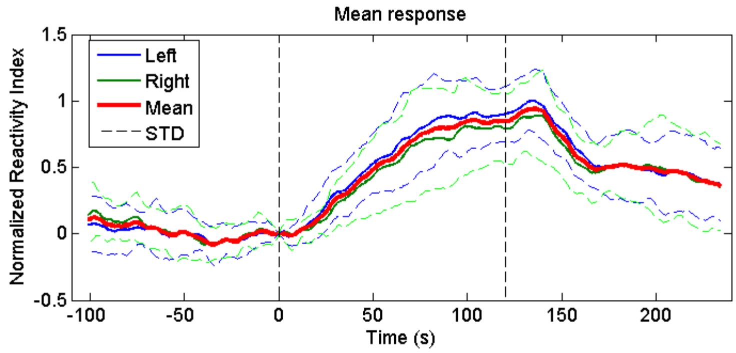


Figure 10. NIRS reactivity Index in response to a stimulus (bounded by the dashed lines)

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

6.6. A study on Natural user feedback in BCI with peripheral sensory stimulation toward efficient motor learning

Participants: Saugat Bhattacharyya, Maureen Clerc, Mitsuhiro Hayashibe.

Brain-computer Interfacing (BCI) measures the neural activity of the brain to create a direct communication channel to peripheral devices in form of robots, prosthesis, wheelchair or a computer controlled by the user, independent of the peripheral nerves and muscles. To improve the performance of the BCI operation and provide a feedback to the user as an indication of his/her achievement in terms of voluntary brain modulation, a feedback in form of visual, auditory or (vibro-)tactile medium can be provided to the user during training.

One can employ Functional Electrical Stimulation (FES) targeting specific muscle group as a feedback modality in BCI research. Functional Electrical Stimulation (FES) is often applied during rehabilitation to directly engage muscles of the affected side of the body. FES is capable of reconstructing certain daily life skills for physically challenged patients by directly stimulating the targeted muscles group. Thus, it is quite natural to combine FES rehabilitation with BCI systems, where the FES can activate the sensory channel to provide a maximal inflow in the brain and the BCI would provide an efferent outflow of motor commands to close the motor loop. Thus, we aim at studying the effect of electrical stimulation (ES) on the motor imagery EEG and to implement the usage of ES as a natural feedback to BCI. The purpose was to extract all relevant information from the current EEG dataset acquired during BCI experiment with FES based neuro-feedback and to compare the results to the classical visual neuro-feedback paradigm.

The EEG data in this study were recorded from 14 right-handed participants (11 male and 3 female) with a mean age of 28 years and standard deviation of 9 years. The experiments took place at Inria Montpellier and Inria Sophia Antipolis centers. In this experiment, we abide by the norms of the local Inria ethical committee. The participants sat in front of a display placed at eye level and performed the following cued motor imagery tasks: left hand movement, right hand movement, left foot movement and right foot movement. The participants were randomly divided into two groups: one group was provided with only visual feedback (VIS) and the other group was relayed with only FES as feedback during the motor imagery tasks. This step was taken in the experimentation so that the groups were not influenced by both feebacks and were trained on only one feedback. The VIS feedback group received the feedback in form of a uni-directional bar whereas the FES feedback group received the feedback in form of electrical stimulation on their respective limbs. The group with FES feedback performed two different sets of experiment, which are: 1) the participant performed the motor imagery tasks while receiving electrical stimulation as feedback, which we term as *FES-Active (ACT)* sessions, and 2) the participant performed no motor imagery tasks (relaxation condition) and received the electrical stimulation as a stimuli, which we term as *FES-Passive (PAS)* sessions.

The raw EEG data was first filtered using a notch filter to remove the 50Hz noise from the signal. Then, a 4th order Butterworth filter was applied to the signal. Then, the mean of the signal was removed followed by a spatial filtering using common average referencing technique. Finally, the continuous EEG data were segmented into smaller samples (Epochs) from -1s to 4s, where 0 indicates the onset of the motor imagery task (left hand, right hand, right foot). After filtering and epoching the EEG data, the EEG epochs are spatially filtered using common spatial patterns (CSP) algorithm. Then, the log-variance of 4 discriminating CSP filters (2 for either classes) were selected as features. These features are then used as inputs to a linear discriminating analysis (LDA) classifier to derive the output of the current motor task imagined by the participant. We provide the average classification result across all subjects for three (ACT and VIS) and two sessions (PAS) in Fig.11 . As noted from the figure, the performance of the decoder improves after every session for the VIS and ACT sessions. This can be attributed to the increase in learning occurring to the participant during the progression of the experiment. As the subject was performing no mental tasks during the PAS session, thus, no such improvement on the classification performance is noticed. On the contrary, a decrease in the performance is noted after the second session.

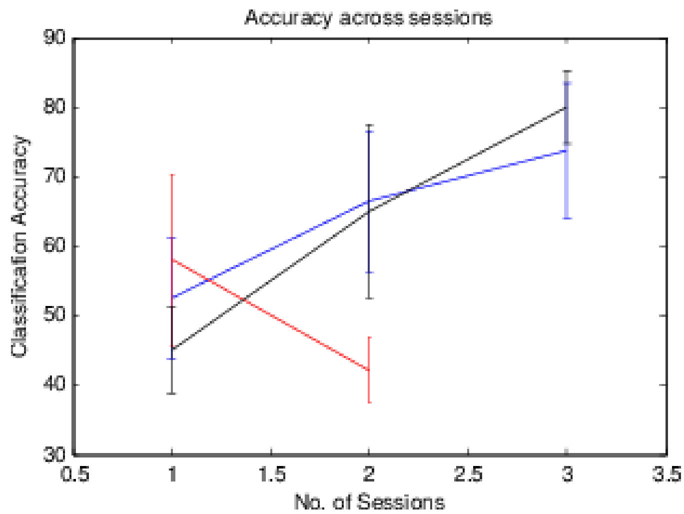


Figure 11. Classification result across all subjects for subsequent sessions.

To further investigate the learning occurring across trials, we have calculated the band power of the epochs at the mu-band (8-12Hz) and the central-beta band (16-25 Hz) at Cz electrode (Fig.12). To calculate the power we have employed Welchs' periodogram at an overlap of 75% and a window size of 250ms. Finally, the average is calculated over all windows of the given trial to determine its power. As seen from the example in Fig.12 , ACT and VIS conditions show a monotonic increase of power which can be quantified as an indication of learning occurring in the participant across the trial.

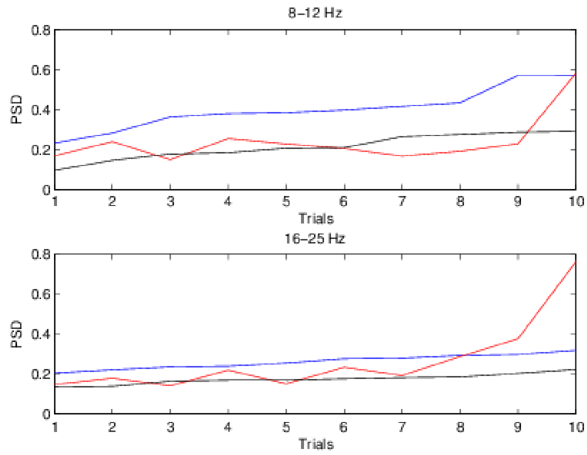


Figure 12. The distribution of power from the first to the tenth correctly classified trial during left hand imagery. Blue is for ACT condition, Red is for PAS and Black is for VIS condition.

6.7. Formal validation for critical digital 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 (based on Interpreted Time Petri Nets). 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., considering the execution of the model on the target).

One solution has been studied in the PhD thesis of H. Leroux [34], which lays the foundations of translation rules from the designed model to the analyzed model integrating part of implementation and execution characteristics. 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.

However, if the formal model, the Interpreted Time Petri Net in this case (ITPN), is inherently asynchronous, it is nevertheless executed synchronously on the target. In fact, the usual analysis approaches are not adapted in the sense that they construct state graphs that do not conform to the real state evolution within the target. In order to gain confidence in the validity of the results of the formal analysis, we carried on, through the PhD thesis of I. Merzoug, capturing the so-called non-functional characteristics to reify them on the model and finally to consider their impact through a dedicated analysis approach. In other words, we improved the expressiveness of the model and the relevance of the analysis, considering aspects such as clock synchronization, effective parallelism, the risk of blocking induced by the expression of an event (condition) and a time window of occurrence, without omitting the management of exceptions.

To deal with all these aspects, we have proposed a new method of analysis for Synchronously executed ITPN (SITPN), transforming them into an equivalent formalism that could be analyzed ([29]). This formalism is associated with a new formal semantics integrating all the particular aspects of the execution. We also propose and implement a dedicated state space construction algorithm: the Synchronous Behavior Graph (an example being given on Fig. 13 and Fig. 14). Our work has been applied to an industrial case, more precisely to the validation of the behavior of the digital part of our neuro-stimulator.

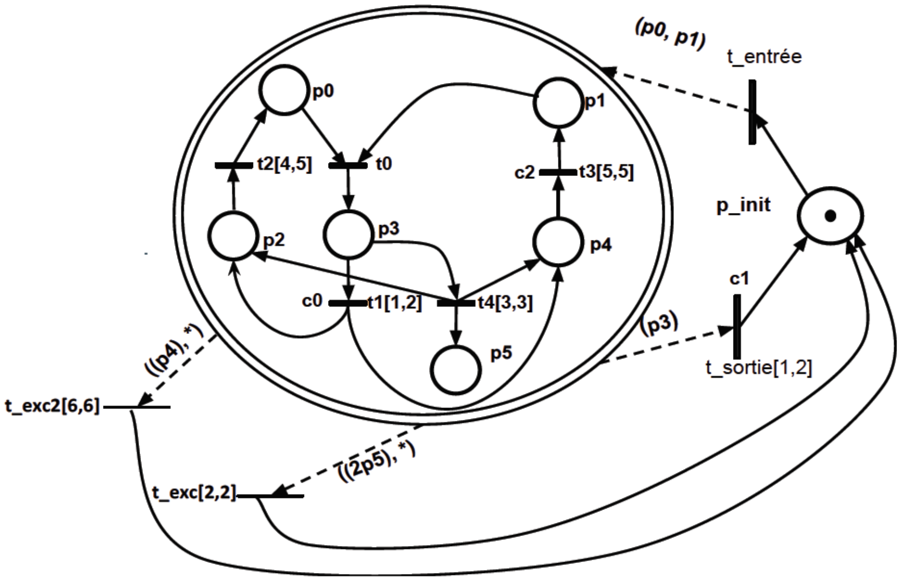


Figure 13. Example of SITPN model with state aggregation and exception handling

6.8. Respiratory detection and monitoring

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

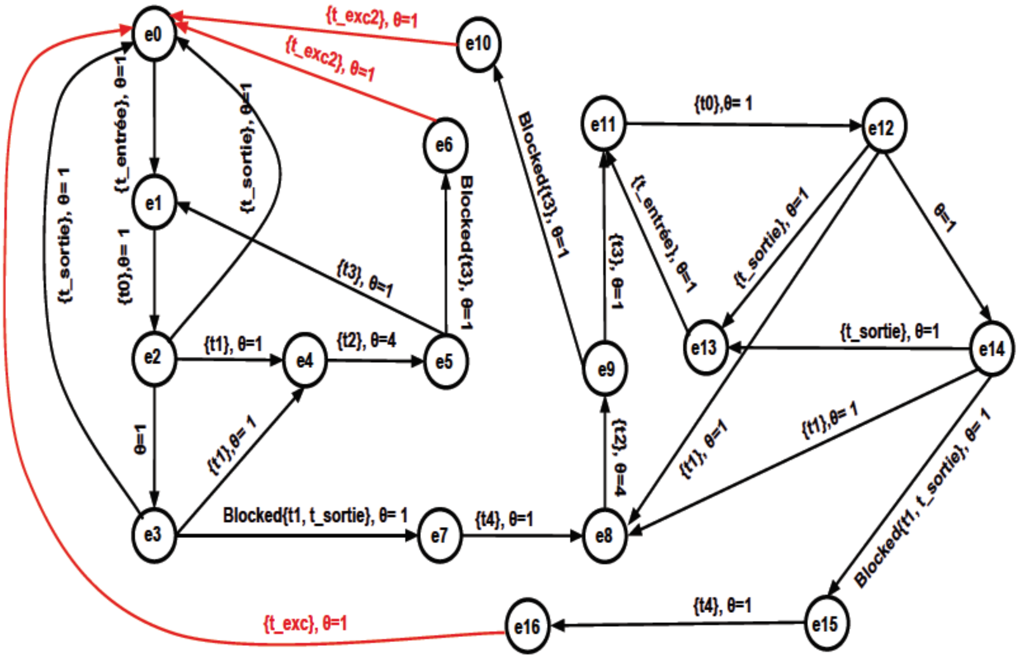
This work is conducted within a CIFRE PhD thesis. The general subject is the respiration induced by implanted stimulation for the tetraplegic and syndrome of Ondine. In France, every year, there is approximately 90 new spinal cord injuries who have a ventilatory dependence due to a high cervical involvement.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

We have developped a first solution bases on a microphone. The signal is processed in order to determine the spectral power between 400Hz and 600Hz (the band of respiratory sounds) and a threshold detection applied to detect respiration.

Preliminary recordings on healthy individuals have been perfomed. Advance signal processing techniques are now under study.

6.9. Evoked EMG correlation with muscle torque

Participants: Adriana Mendes, Mitsuhiro Hayashibe, David Guiraud.



e0: p_init, **B**{}, {t_entrée[1,1]}	**e3:** p3, **B**{}, {t1[1,1], t4[2,2], t_sortie[1,1]}	**e6:** p0,p4, **B**{t3}, {t_exc2[1,1]}	**e9:** p0,p4,p5, **B**{}, {t3[1,1], t_exc2[2,2]}	**e12:** p3,p5,**B**{}, {t1[1,2], t4[3,3], t_sortie[1,2]}	**p15:** p3, p5 **B**{t1, t_sortie}, {t4[1,1]}
e1: p0,p1,**B**{}, {t0[1,1]}	**e4:** p2,p4, **B**{}, {t2[4,4], t3[5,5], t_exc2[6,6]}	**p7:** p3, **B**{t1,t_sortie}, {t4[1,1]}	**e10:** p0,p4, p5 **B**{t3}, {t_exc2[1,1]}	**e13:** p_init,p5 **B**{}, {t_entrée[1,1]}	**p16:** p3, p4, p5(2) **B**{}, {t_exc[1,1]}
e2: p3, **B**{}, {t1[1,2], t4[3,3], t_sortie[1,2]}	**e5:** p0,p4, **B**{}, {t3[1,1], t_exc2[2,2]}	**e8:** p2,p4,p5 **B**{}, {t2[4,4], t3[5,5], t_exc2[6,6]}	**e11**:p0,p1,p5, **B**{}, {t0[1,1]}	**e14:** p3,p5, **B**{}, {t1[1,1], t4[2,2], t_sortie[1,1]}	

Figure 14. Synchronous Behavior Graph of the model given Figure 13

During the internship, we developed software, based on algorithms available in literature, that allow to recover M-Wave induced by surface FES. The algorithm detects the onset of the artifact, the Otsu method is used to determine the length of the contaminated data and finally, the M-wave is interpolated through Cubic Hermite extensions. The results can be seen on Figure 15 where the M-wave, fully reconstructed can then be quantified. We thus verified that the classical torque-EMG relationship can be recovered using MAV, RMS or P2P and the results show a very good correlation. Finally we successfully developed a realtime version of the processing and tested it through a closed loop control of the FES through EMG measurements. The technology used was completely wireless (Delsys for the EMG and Vivaltis for the stimulation). One journal paper is under writing in collaboration with the Technological University of Compiègne.

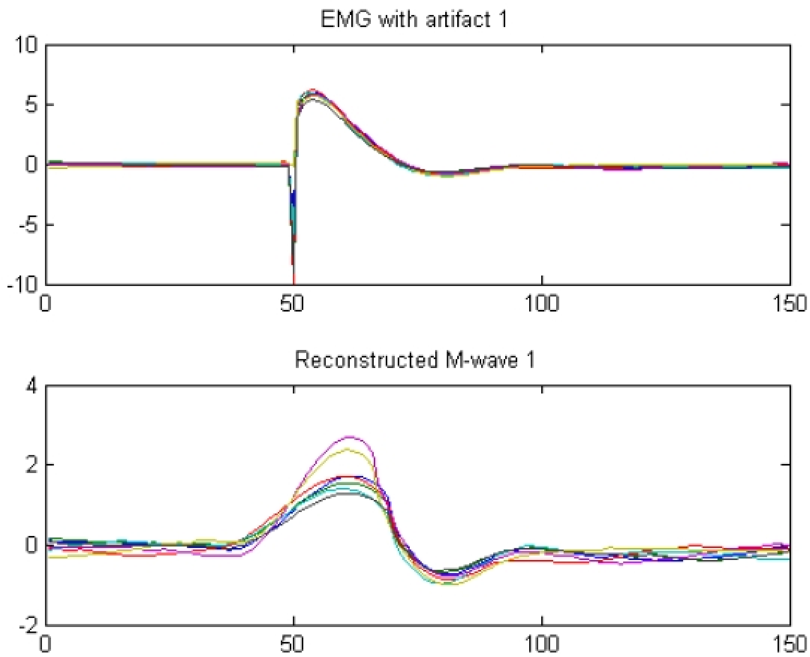


Figure 15. Reconstructed M-Wave

6.10. Pivot transfer assistance in SCI subjects

Participants: Lucas Fonseca [Univ. Brasilia], Antonio Padilha Lanari Bo [Univ. Brasilia], Ana Claudia Lopes [SARA hosp], Christine Azevedo Coste, Emerson Fachin Martins [Univ. Brasilia], Claudia Ochoa-Diaz [Univ. Brasilia].

Spinal cord injured (SCI) patients that have no lower limb motor function perform several transfers during a day. Those transfers are from and to a wheelchair, a car, a hygienic chair, among other situations. These repetitive motions can cause overload on their upper limbs over time. Functional Electrical Stimulation may be used to induce contraction on knee extensors, providing additional support at the joint level during transfer [33]. However, the design of the interface with which to control the onset of stimulation is challenging. The use of some automated system is beneficial, particularly since the user is using both hands to perform the transfer. Therefore, the precise moment of activation is important because, if erroneous, it can cause the user's loss of balance. In the context of CACAO associate team with Brasilia University, a system with which the users themselves were activating the stimulation with triggers in gloves was used to collect kinematic data from SCI patients during Sitting Pivot Transfers (16). The results show that the trunk angle can be used along a threshold for a reliable assistance device [28].

Figure 16. Experimental set-up. The gloves embed pressure sensors. It is possible to see the markers over the subject body, which are captured by the motion capture system.

6.11. Real-time control and scheduling for stimulation systems

Participants: Daniel Simon, David Andreu, Ronan Le Guillou, Benoît Sijobert.

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 [15].

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. Such simulator can be used for the design, testing and preliminary validation of new technologies and implementation. The initial design, working with a simple model of a knee, is currently extended with the dynamic model of a human hand (Figure 17).

A portable controller has been prototyped to run control loops using stimulation and sensing probes. ([32]). It is architectured around a Raspberry Pi3B single board computer, and provides USB ports towards sensing probes from HiKoB and stimulation units from Vivaltis. It uses a dedicated RT_PREEMPT linux kernel to make the system real-time control compliant (Figure 18).

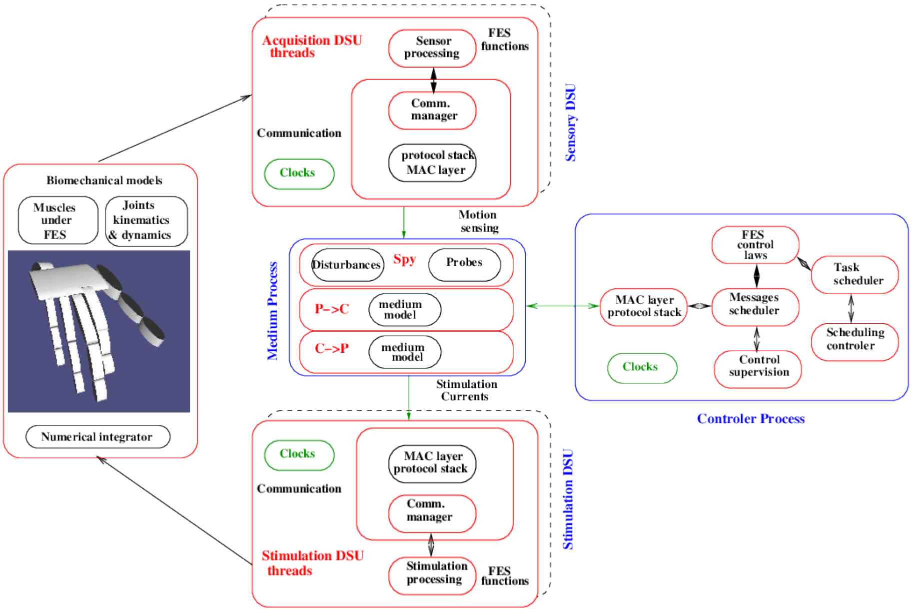


Figure 17. Hybrid simulation of a hand under FES

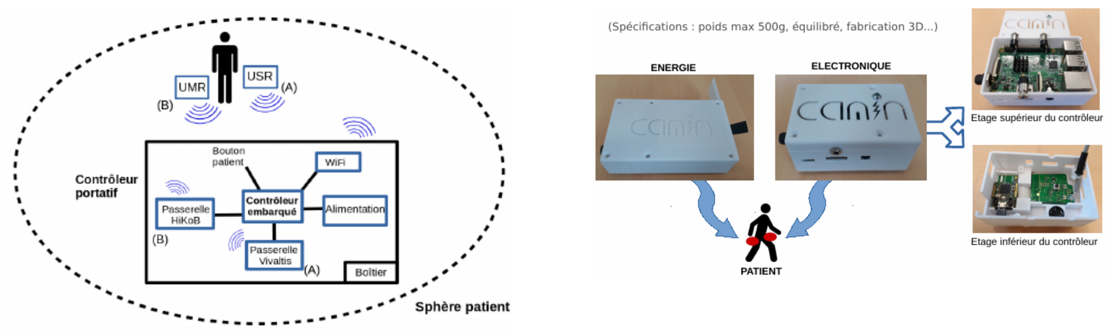


Figure 18. Portable stimulation controller architecture and components

Beyond software-in-the-loop simulation, the controller has been firstly tested connected with the previously developed simulation models to perform a hardware-in-the-loop simulation system and further experiment control/computing co-design algorithms ([25]). Gateways has been developed to connect the Vivaltis and HiKoB probes, together with a small graphical end-user interface. The whole embedded system has been succesfully validated for future applications through a pertinent real-time metrology.

6.12. Sensory feedback for phantom limb pain modulation

Participants: Arthur Hiairrassary, David Andreu, Christine Azevedo Coste, Thomas Guiho, David Guiraud.

In the EPIONE european project, the partners UM and MXM-OBELIA are responsible for the design and manufacturing of the STIMEP stimulator (see figure 1) and in charge of all the software and the experimental follow-up.

During the first round, we were able to quantify the state of each contact of each electrode to prevent misinterpretation of feedback sensation. Indeed, if the patient does not feel anything while stimulating, impedance check may show that it is due to a contact failure and not to a lack of nerve response.

This estimation was done during the “Contacts Check” functionality embedded in the STIMEP. At the same time, a more detailed measure was stored in the STIMEP (but only reachable off-line for further investigation).

For instance, the following figure shows the number of valid contacts during the clinical phase of the 4 TIME-4H electrodes computed by the “Contacts Check” functionality. The electrodes stand almost OK up to February-March on this example (2-3 months) then failures begin to occur.

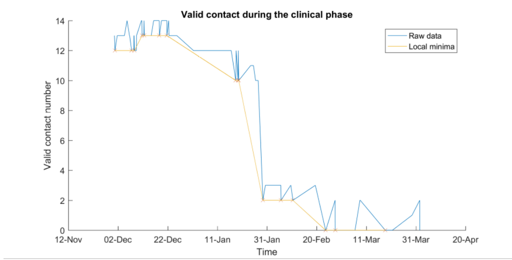


Figure 19. a) the STIMEP b) Ulnar nerve – Proximal electrode

However, these data were not detailed enough so we decided to develop an easy to use software able to control automatically in the same time the STIMEP and the acquisition card (NI-6218). It performed voltage and current measurements to follow and to assess the complex impedance evolution of the TIME-4H in vivo. This software, named “Synergy Acquire” (Figure 3), was used by the clinic of Roma with the second patient.

Synergy Acquire performs safe, really quick stimulation and measurement on an electrode (around 1 minute, less than 5 minutes for the 4 TIME-4H, figure 4), which allow a very regular follow-up (2-3 times by week) by the practitioners. Data were logged, sent to us, processed and then sent back to UCSC for checking. This work is related to clinical trials follow-up. In conclusion, within this project that ended in August, we developed software (following 62304 class B regulation), test in animals, used in humans and we processed all the data

6.13. Spin-off Neurinnov

Participants: David Andreu, David Guiraud, Olivier Climent, Milan Demarcq, Guillaume Souquet.

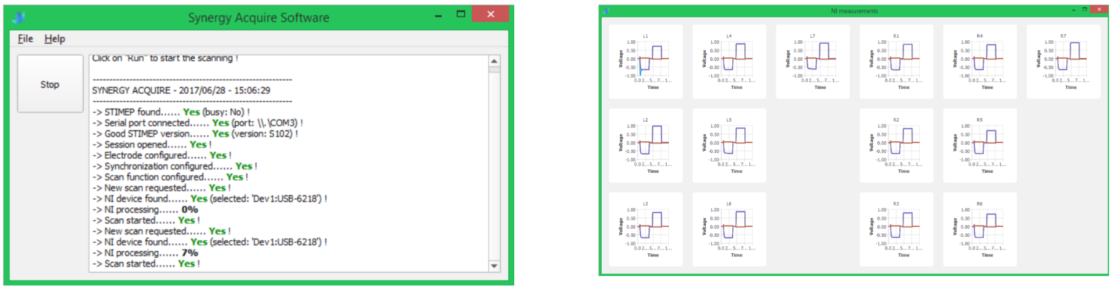


Figure 20. a) Synergy Acquire b) Results of the voltage and current measurements

Thanks to the support of the Inria-DGDT, the spin-off Neurinnov has started the industrialization of the innovative technology developed in CAMIN, a new generation of active implantable medical device (AIMD). Neurinnov has been awarded with the i-Lab 2017 prize by the French Minister of Research and Innovation, that encourage the most innovative and promising startups in France. Moreover, Neurinnov is accredited by the Business Incubation Center of Montpellier and incubated by the Languedoc-Roussillon Incubation Center.

Industrialization means on the one hand the development of an industrial version of the technology with all the regulatory documents required by the Technical Documents part of the CE certification, and on the other hand the setting up of our own system of quality management in accordance with ISO 13485. Since the beginning the spin-off has to consider regulatory aspects, of which the quality management system (QMS). A QMS is a set of policies, processes and procedures designed to help an organization to consistently provide safe and effective medical devices, and to comply with customer and regulatory requirements. Thus the team worked on defining processes and associated procedures regarding for instance the design, the development and the verification of our stimulation device.

The design and verification of the two parts of our AIMD (stimulator), namely the digital part (FPGA) and the analogue part (ASIC), were carried out in accordance with the defined procedure and applicable standards.

The core of the stimulators developed in the CAMIN team are based on an Application Specific Integrated Circuit (ASIC). It includes both the analog part with the generation of 12 current sources that are able to drive a pulticontact electrode. The global ASIC architecture fully implements our patent and allows to spread the current from a unique current source over the 12 outputs through ratios programming. This unique feature is a consequence of researches about the multicontact selective stimulation through neural cuffs. In the new 0.18μ new design, the analog part was entirely revised to enhance power consumption and global analogue features. On the digital aprt the concept of virtual electrode was fully implemented within this ASIC (named CORAIL) to embed all the low level programming parts dedicated to the spreding of the current. It enhances the safety but also the efficacy of the code developed to control this ASIC as it virtualize the concept of ratios. Moreover CORAIL stores the Virtual Electrode so that the needed bandwidth but also the transfer time between CORAIL and the hiigh level control is much lowered compared to the previous version we developed. We tested and implemented this original digital part in collaboration with the micro-electronics department at LIRMM and SL3J company. A first version of the ASIC was made and is under investigation to prepare the next version.

The digital part of the device embeds a set of functionalities (described section 5.1.1) allowing the stimulator to be programmable, communicating and fully controllable remotely. The formal design and verification of this digital part is based on the HILECOP software developed within CAMIN (see sections 5.1.1 and 6.7). All constituent components have been developed, verified and documented in accordance with the defined procedure.

In addition, Neurinnov has focused on setting up the necessary industrial collaborations on the one hand to complement its device (e.g., electrodes, connectors) and on the other hand to manufacture it.

CASTOR Project-Team

7. New Results

7.1. Mathematical theory of reduced MHD models

Participant: Hervé Guillard.

One of the fundamental model used for fusion plasma simulations 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 dominating magnetic field 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 last year 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. This work continues with a tentative to relax the large aspect ratio assumption that is not verified in modern machines.

7.2. 2D C^1 triangular elements

Participants: Hervé Guillard, Ali Elarif.

In order to avoid some mesh singularities that arise when using quadrangular elements for complex geometries and flux aligned meshes, the use of triangular elements is a possible option that we have studied in the past years [30]. In particular, we have developped the geometric tools necessary for the construction of Powell-Sabin splines and have applied these methods for the approximation of some simple hyperbolic PDE systems (namely the Euler equation of fluid dynamics). The PhD thesis of Ali Elarif that has begun in october 2017 is devoted to the study of the applicability of these methods to more complex PDE models encountered in plasma physics and to an extension towards other triangular C^1 elements (Clough-Tocher elements).

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

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

We have studied numerically an extension designed for turbulent flows of the shallow water model. The model is able to describe the oscillatory nature of turbulent hydraulic jumps and as such correct the deficiency of the classical shallow water equations. The model equations, originally developed for horizontal flow or flows occurring over small constant slopes, are straightforwardly extended here for modeling flows over non-constant slopes and numerically solved by a second-order well-balanced finite volume scheme. Further, a new set of exact solutions to the extended model equations are derived and several numerical tests are performed to validate the numerical scheme and its ability to predict the oscillatory nature of hydraulic jumps under different conditions. The comparisons with experiments performed at Tainan University are very satisfactory given the simplicity of the model [27].

7.4. Block-structured meshes

Participants: Hervé Guillard, Alexis Loyer, Adrien Loseille [Gamma3 team, Inria Saclay], Jalal Lakhlili [IPP Garching], Ahmed Ratnani [IPP Garching].

Due to the highly anisotropic character of strongly magnetized plasmas, a crucial point for numerical simulations is the construction of meshes that are aligned on the magnetic flux surfaces computed by Grad-Shafranov equilibrium solvers. In this work, we study an original method for the construction of flux aligned grids that respect the magnetic equilibrium topology and that can be applied to block-structured meshes using C^1 finite element methods (Hermite-Bézier/Cubic spline). This method relies on the analysis of the singularities of the magnetic flux function and the construction of the Reeb graph that allows the segmentation of the physical domain into sub-domains that can be mapped to a reference square domain. Once this domain decomposition has been done, the mapping of the sub-domain to reference patches can be done using integration along the streamlines of the flux function[23], [34]. This work is performed in the framework of the EoCoE European project (see section 8.2.1.2).

7.5. FEM-BEM coupling methods for Tokamak plasma axisymmetric free-boundary equilibrium computations in unbounded domains

Participants: Blaise Faugeras, Holger Heumann.

Incorporating boundary conditions at infinity into simulations on bounded computational domains is a repeatedly occurring problem in scientific computing. The combination of finite element methods (FEM) and boundary element methods (BEM) is the obvious instrument, and we adapt here for the first time the two standard FEM-BEM coupling approaches to the free-boundary equilibrium problem: the Johnson–Nédélec coupling and the Bielak–MacCamy coupling. We recall also the classical approach for fusion applications, dubbed according to its first appearance von-Hagenow–Lackner coupling and present the less used alternative introduced by Albanese, Blum and de Barbieri. We show that the von-Hagenow–Lackner coupling suffers from undesirable non-optimal convergence properties, that suggest that other coupling schemes, in particular Johnson–Nédélec or Albanese–Blum–de Barbieri are more appropriate for non-linear equilibrium problems. Moreover, we show that any of such coupling methods requires Newton-like iteration schemes for solving the corresponding non-linear discrete algebraic systems.

7.6. Optimal control of a coupled partial and ordinary differential equations system for the assimilation of polarimetry Stokes vector measurements in tokamak free-boundary equilibrium reconstruction with application to ITER

Participant: Blaise Faugeras.

The modelization of polarimetry Faraday rotation measurements commonly used in tokamak plasma equilibrium reconstruction codes is an approximation to the Stokes model. This approximation is not valid for the foreseen ITER scenarios where high current and electron density plasma regimes are expected. In this work a method enabling the consistent resolution of the inverse equilibrium reconstruction problem in the framework of non-linear free-boundary equilibrium coupled to the Stokes model equation for polarimetry is provided. Using optimal control theory we derive the optimality system for this inverse problem. A sequential quadratic programming (SQP) method is proposed for its numerical resolution. Numerical experiments with noisy synthetic measurements in the ITER tokamak configuration for two test cases, the second of which is an H-mode plasma, show that the method is efficient and that the accuracy of the identification of the unknown profile functions is improved compared to the use of classical Faraday measurements.
In the framework of JET Task T17-15, the method has been implemented in the new code NICE and equilibrium reconstruction studies using real JET measurements are currently being performed.

7.7. Equilibrium reconstruction with Equinox at JET

Participant: Blaise Faugeras.

Within the framework of JET Task T17-02 an update of the real-time equilibrium reconstruction code Equinox at JET in view of its coupling with the transport code Raptor has been performed. Mainly the computation of all the averaged geometric quantities which enter the transport equation have been added.

7.8. Equilibrium reconstruction within the framework of the European Integrated Tokamak Modelling WPCD project

Participants: Blaise Faugeras, Cédric Boulbe.

We have been involved in a benchmark study between the equilibrium reconstruction codes VACTH-EQUINOX, EQUAL and LIUQE on TCV equilibriums [EPS paper R. Coelho et al] The benchmark study lead us to include new functionalities to VACTH-EQUINOX such as the possibility to have an upper X-point. The adaptation of VACTH-EQUINOX to IMAS (Integrated Modelling & Analysis Suite), the ITER standard using IDS (Interface Data Structure) as data type, has been carried on. Equilibrium reconstructions using IMAS have been performed on real JET measurements and on the first recently available WEST measurements.

7.9. Coupling free boundary equilibrium code and magnetic controller on IMAS

Participants: Cedric Boulbe, Jakub Urban.

During the previous years, the free boundary equilibrium code CEDRES++ has been coupled to the transport solver ETS and a magnetic simulink controler using the Integrated Tokamak Modelling infrastructure (Project Eurofusion WPCD - Work Package Code Development). In 2017, we have started to port this tool on IMAS which is the integrated modelling infrastructure developped by ITER. CEDRES++ has been adapted to IMAS and has been coupled to a magnetic controller in the framework of the Eurofusion WPCD project. This activity has been a pilot project to test the C++ tools provided on IMAS.

7.10. An Automated Approach to Plasma Breakdown Design

Participants: Holger Heumann, Eric Nardon.

Plasma breakdown in a tokamak requires a large toroidal electric field E_ϕ and a low poloidal magnetic field B_p, i.e. a so-called *field null region*. The latter should remain as extended as possible for a sufficient duration (typically a few tens of ms), all the more if one operates at low E_ϕ (e.g. in ITER where $E_\phi = 0.3V/m$). Finding appropriate settings (i.e. premagnetization coils currents and voltage waveforms) to produce and maintain a good field null region is not a trivial task, in particular in the presence of highly conducting passive structures which make the problem dynamic. WEST is a good example of this situation, due to two toroidally continuous copper plates which have been added for vertical stabilization: indeed, the current in the plates ramps up fast when E_ϕ is applied, which tends to degrade the field null region.
Our automated approach to determining appropriate breakdown settings relies on a precise electromagnetic model of the machine (including the iron core) and solves a constrained optimization problem, where the objective function to be minimized quantifies the design goal: the averaged magnitude of B_p. After discretization we end up with *finite dimensional* convex constrained optimization problem, that can be solved efficiently with Sequential Quadratic Programming. The approach follows the lines of optimal control methods for plasma equilibria in [35] and [36].
The automated approach was already beneficial for obtaining first breakdowns in WEST during the initial launch in December 2016. The data collected during these breakdowns allowed for improving the electromagnetic model and the simulations reproduce now very well magnetic measurements and the shapes observed on the fast camera during the experiments.

7.11. A high order method for the approximation of integrals over simplicity defined hypersurfaces

Participants: Lukas Drescher, Holger Heumann, Kersten Schmidt.

We introduced a novel method to compute approximations of integrals over implicitly defined hypersurfaces. The new method is based on a weak formulation in L2(0,1) that uses the coarea formula to circumvent an explicit integration over the hypersurfaces. As such it is possible to use standard quadrature rules in the spirit of hp/spectral finite element methods, and the expensive computation of explicit hypersurface parametrizations is avoided. We derived error estimates showing that high order convergence can be achieved provided the integrand and the hypersurface defining function are sufficiently smooth.

7.12. FEMs on Composite Meshes for Tuning Plasma Equilibria in Tokamaks

Participants: Holger Heumann, Francesca Rapetti, Xiao Song.

We rely on a combination of different finite element methods on composite meshes, for the simulation of axisymmetric plasma equilibria in tokamaks. One mesh with Cartesian quadrilaterals covers the burning chamber and one mesh with triangles discretizes the region outside the chamber. The two meshes overlap in a narrow region around the chamber. This approach gives the flexibility to achieve easily and at low cost higher order regularity for the approximation of the flux function in the area that is covered by the plasma, while preserving accurate meshing of the geometric details in the exterior. The continuity of the numerical solution across the boundary of each subdomain is enforced by a mortar-like projection. Higher order regularity is very beneficial to improve computational tools for tokamak research. In [13], we showed 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 the present work we show how the composite meshes and higher regular finite element functions allow to single out snowflake configurations, that play an important role to mitigate heat load in divertors. Implementations and numerical test were carried out in FEEQS.M

7.13. Automating the design of tokamak experiment scenarios

Participants: Jacques Blum, Holger Heumann, Xiao Song.

The real-time control of plasma position, shape and current in a tokamak has to be ensured by the Poloidal Field (PF) system. A standard strategy is to feedback-control the currents in the PF coils in order to match reference currents, the latter being a combination of FeedForward (FF) and FeedBack (FB) terms. While the FB part allows a precise control, it can work only near the target and therefore the FF part is essential to “guide” the system, i.e. to approximately reach the target while remaining clear from hardware limits. An essential part of tokamak scenario design is therefore the construction of these FF waveforms. A tool for automatic FF waveforms optimisation (the inverse evolutive mode of the Free-Boundary Equilibrium [FBE] solver FEEQS.M) has been developed recently in the frame of a collaboration with IRFM, CEA. This tool reduces drastically the amount of human work needed to design optimized scenarios compatible with hardware limits. Xiao Song has performed first applications and validations of this tool on present and future machines such as WEST and ITER. This preliminary work focused on the choice of the cost-function and compared different choices for the same type of discharge. A second key aspect of this work was the treatment of inequality constraints via penalisation terms.

7.14. Higher order FEM for Free-Boundary Equilibrium in FEEQS

Participant: Holger Heumann.

We extended FEEQS.M to work with higher order finite element functions (polynomials of degree 1, ... 11, or Powell-Sabin spline finite element functions). This feature is currently available only for the static modes. The free-boundary aspect is addressed by a subdivision approach, that needs to be improved in the future, to increase the accuracy.

7.15. The two temperature MHD model

Participants: Hervé Guillard, Afeintou Sangam, Elise Estibals.

The dynamics of plasma charged particles can be described by a two-fluid MHD model. This description considers a plasma as a mixture of ions fluid and electrons flow that are coupled by exchanged terms such as momentum transfer terms, ion and electron heating terms due to collisions, supplemented by the Maxwell's equations. This system is quite intricate so that it is usually reduced to more tractable models. We first derive the two-temperature model, the ideal and resistive MHD equations from the two-fluid MHD system, and show that they correspond to asymptotic regimes for weakly and strongly magnetized plasmas. We then propose a finite volume approximation to compute the solutions of these models in unstructured tessellations used to appropriate mesh the toroidal geometry of the tokamak, where flows the plasma. The formulation of the magnetic field as Euler potential ensures the divergence free constraint in cheap manner, while a relaxation scheme for the two temperature allows an accurate computation of the electron and ion temperatures.

7.16. Spectral element schemes for dispersive equations

Participants: Sebastian Minjeaud, Richard Pasquetti.

S. Minjeaud and R. Pasquetti have addressed the Korteweg-de Vries equation as an interesting model of high order PDE, in order to 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 the lower invariants, on the basis of a (only) H^1-conformal Galerkin approximation, namely the Spectral Element Method (SEM). The proposed approach relies on the introduction of additional variables that can be trivially eliminated, because the SEM mass matrix is diagonal, thus allowing to define discrete high order differentiation operators. Highly accurate RK IMEX schemes are used in time, with implicit treatment of the third order term and explicit treatment of the convective one. While the conservation of the mass invariant is natural, the conservation of the energy invariant is enforced by interpolation between embedded IMEX schemes, with preservation of the time discretization accuracy. Applications to several test problems have shown the robustness and accuracy of the proposed method, that is *a priori* easily extensible to other PDEs and to multidimensional problems (See [38]).

7.17. Cubature nodes for spectral element methods on symplicial meshes

Participants: Richard Pasquetti, Francesca Rapetti.

In a recent JCP paper (see [37]), a higher order triangular spectral element method (TSEM) is proposed to address seismic wave field modeling. The main interest of this TSEM is that the mass matrix is diagonal, so that an explicit time marching becomes very cheap. In [16], R. Pasquetti and F. Rapetti have compared this cubature points based method to the Fekete-Gauss one, that makes use of Fekete points for interpolation and of Gauss points for quadrature. Moreover, they have proposed an extension of this cubature TSEM to address elliptic PDEs with non homogeneous Neumann or Robin boundary conditions. More recently, the cubature TSEM has been experimented with isoparametric mappings to consider the case of non polygonal computational domains. In any cases it turns out that the cubature TSEM compares well with the Fekete-Gauss one.

7.18. Validation of the Full MHD with Bohm Boundary conditions

Participants: Boniface Nkonga, Guido Huijsmans, Ashish Bhole.

We have implemented Bohm mach condition using penalty boundary integral over open field lines. We have added temperature dependent viscosity and parallel conductivity, Bohm condition on energy flux. The JET configuration has been considered with success to reach the equilibrium with Bohm conditions on the divertor. However, the solution needs to be improved at the separatrix close to the boundary by a proper numerical stabilization. These structures disappear with constant resistivity. First n=10 ballooning mode in JET has been considered and need to be compared to the reduced MHD results. In order to proceed to these comparisons, a model for the reduced model has been derived including modeling of the viscosity. Validations on circular geometries are on going.

7.19. Non-linear MHD simulations of QH-mode DIII-D plasmas : ITER high Q scenarios

Participants: Feng Liu, Guido Huijsmans, Alberto Loarte, Boniface Nkonga.

In nonlinear MHD simulations of DIII-D QH-mode plasmas it has been found that low n kink/peeling modes (KPMs) are unstable and grow to a saturated kink-peeling mode. The features of the dominant saturated KPMs, which are localized toroidally by non-linear coupling of harmonics, such as mode frequencies, density fluctuations and their effect on pedestal particle and energy transport, are in good agreement with the observations of the Edge Harmonic Oscillation (EHO) typically present in DIII-D QH-mode experiments. The non-linear evolution of MHD modes including both kink-peeling modes and ballooning modes, is investigated through MHD simulations by varying the pedestal current and pressure relative to the initial conditions of DIII-D QH-mode plasma. The edge current and pressure at the pedestal are key parameters for the plasma either saturating to a QH-mode regime or a ballooning mode dominant regime. The influence of E×B flow and its shear on the QH-mode plasma has been investigated. E×B flow shear has a strong stabilization effect on the medium to high-n modes but is destabilizing for the n=2 mode. The QH-mode extrapolation results of an ITER Q=10 plasma show that the pedestal currents are large enough to destabilize n=1-5 kink/peeling modes, leading to a stationary saturated kink-peeling mode.

7.20. Sharpening diffuse interfaces with compressible fluids on unstructured meshes

Participants: Alexandre Chiapolino, Richard Saurel, Boniface Nkonga.

Diffuse interface methods with compressible fluids, considered through hyperbolic multiphase flow models, have demonstrated their capability to solve a wide range of complex flow situations in severe conditions (both high and low speeds). These formulations can deal with the presence of shock waves, chemical and physical transformations, such as cavitation and detonation. Compared to existing approaches able to consider compressible materials and interfaces, these methods are conservative with respect to mixture mass, momentum, energy and are entropy preserving. Thanks to these properties they are very robust. However, in many situations, typically in low transient conditions, numerical diffusion at material interfaces is excessive. Several approaches have been developed to lower this weakness. In the present contribution, a specific flux limiter is proposed and inserted into conventional MUSCL type schemes, in the frame of the diffuse interface formulation of Saurel et al. (2009). With this limiter, interfaces are captured with almost two mesh points at any time, showing significant improvement in interface representation. The method works on both structured and unstructured meshes and its implementation in existing codes is simple. Computational examples showing method capabilities and accuracy are presented.

COATI Project-Team

7. New Results

7.1. Network Design and Management

Participants: Christelle Caillouet, David Coudert, Frédéric Giroire, Frédéric Havet, Nicolas Huin, Joanna Moulierac, Nicolas Nisse, Stéphane Pérennes, Andrea Tomassilli.

Network design is a very wide subject which concerns all kinds of networks. In telecommunications, networks can be either physical (backbone, access, wireless, ...) or virtual (logical). The objective is to design a network able to route a (given, estimated, dynamic, ...) traffic under some constraints (e.g. capacity) and with some quality-of-service (QoS) requirements. Usually the traffic is expressed as a family of requests with parameters attached to them. In order to satisfy these requests, we need to find one (or many) paths between their end nodes. The set of paths is chosen according to the technology, the protocol or the QoS constraints.

We mainly focus on four topics: Firstly, we study the new network paradigms, Software-Defined Networks (SDN) and Network Function Virtualization (NFV). On the contrary to legacy networks, in SDN, a centralized controller is in charge of the control plane and takes the routing decisions for the switches and routers based on the network conditions. This new technology brings new constraints and therefore new algorithmic problems such as the problem of limited space in the switches to store the forwarding rules. We then tackle the problem of placement of virtualized resources. We validated our algorithms on a real SDN platform [0]. Secondly, we consider different scenarios regarding wireless networks, in particular, wireless backhaul networks, linear access networks for transportation systems, and connected Unmanned Aerial Vehicules (UAVs). Third, we tackle routing in the Internet. Last, we study live streaming in distributed systems.

7.1.1. *Software Defined Networks (SDN)*

Software-defined Networks (SDN), 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.

7.1.1.1. Minnie: an SDN World with Few Compressed Forwarding Rules

While SDN brings flexibility to 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. Also, we investigate in [37] 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 entries 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 the 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 the Application-Specific Integrated Circuits (ASICs).

Hence, both simulations and experimental results suggest that MINNIE can be safely deployed in real networks, providing compression ratios between 70% and 99%.

[0] Testbed with SDN hardware, in particular a switch HP 5412 with 96 ports, hosted at I3S laboratory. A complete fat-tree architecture with 16 servers can be built on the testbed.

7.1.1.2. *Bringing Energy Aware Routing closer to Reality with SDN Hybrid Networks*

Energy aware routing aims at reducing the energy consumption of ISP networks. The idea is to adapt routing to the traffic load in order to turn off some hardware. However, it implies to make dynamic changes to routing configurations which is almost impossible with legacy protocols. The SDN paradigm bears the promise of allowing a dynamic optimization with its centralized controller.

In [49], [59], we propose SENAtoR, an algorithm to enable energy aware routing in a scenario of progressive migration from legacy to SDN hardware. Since in real life, turning off network equipments is a delicate task as it can lead to packet losses, SENAtoR provides also several features to safely enable energy saving services: tunneling for fast rerouting, smooth node disabling and detection of both traffic spikes and link failures.

We validate our solution by extensive simulations and by experimentation. We show that MINNIE can be progressively deployed in a network using the SDN paradigm. It allows to reduce the energy consumption of ISP networks by 5 to 35% depending on the penetration of SDN hardware, while diminishing the packet loss rate compared to legacy protocols.

7.1.1.3. *Network Function Virtualization (NFV) and Service Function Chains*

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. The challenge is then to efficiently provision the service chain requests, while finding the best compromise between the bandwidth requirements, the number of locations for hosting Virtual Network Functions (VNFs), and the number of chain occurrences.

In [48], we propose two ILP (Integer Linear Programming) models for routing service chain requests, one of them with a decomposition modeling. We conduct extensive numerical experiments, and show we can solve exactly the routing of service chain requests in a few minutes for networks with up to 50 nodes, and traffic requests between all pairs of nodes. We investigate the best compromise between the bandwidth requirements and the number of VNF nodes.

In [50], 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.

7.1.2. Wireless networks

We study optimization problems on various kinds of wireless networks.

7.1.2.1. *Computing and maximizing the exact reliability of wireless backhaul 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. We provide in [45] 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 at each leaf in the tree a valid routing for the network is evaluated. Any such tree provides bounds on the reliability, and the algorithm improves these bounds by branching in the tree. We also consider the problem of determining the topology and configuration of a backhaul network that maximizes reliability subject to a limited budget. We provide an algorithm that exploits properties of the conditional probability tree used to calculate reliability of a given network design, and we evaluate its computational efficiency.

7.1.2.2. *Analysis of the Failure Tolerance of Linear Access Networks*

In [28], 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 terms, we analyze the probability for a user to experience a disconnection longer than a given time interval (t^*)

such that all on-going communications between the vehicle and the infrastructure network are disrupted. We provide an approximation formula considering two scenarios (intercity bus and train). We then carry out a sensitivity analysis and supply a guide for operators when choosing the parameters of the networks. Last, we show that such systems are viable, as they attain a very low probability of long disconnections with a very low maintenance cost.

7.1.2.3. Efficient Deployment of Connected Unmanned Aerial Vehicles for Optimal Target Coverage

Anytime and anywhere network access can be provided by Unmanned Aerial Vehicles (UAV) with air-to-ground and air-to-air communications using directional antennas for targets located on the ground. Deploying these Unmanned Aerial Vehicles to cover targets is a complex problem since each target should be covered, while minimizing (i) the deployment cost and (ii) the UAV altitudes to ensure good communication quality. We also consider connectivity between the UAVs and a base station in order to collect and send information to the targets, which is not considered in many similar studies. In [40], we provide an efficient optimal program to solve this problem and show the trade-off analysis due to conflicting objectives. We propose a fair trade-off optimal solution and also evaluate the cost of adding connectivity to the UAV deployment.

7.1.3. Routing in the Internet

7.1.3.1. Routing at Large Scale: Advances and Challenges for Complex Networks

A wide range of social, technological and communication systems can be described as complex networks. Scale-free networks are one of the well-known classes of complex networks in which nodes degree follow a power-law distribution. The design of scalable, adaptive and resilient routing schemes in such networks is very challenging. In [38], we present an overview of required routing functionality, categorize the potential design dimensions of routing protocols among existing routing schemes and analyze experimental results and analytical studies performed so far to identify the main trends/trade-offs and draw main conclusions. Besides traditional schemes such as hierarchical/shortest-path path-vector routing, the article pays attention to advances in compact routing and geometric routing since they are known to significantly improve the scalability in terms of memory space. The identified trade-offs and the outcomes of this overview enable more careful conclusions regarding the (in-)suitability of different routing schemes to large-scale complex networks and provide a guideline for future routing research. This article concludes the European Project FP7 STREP EULER (2010-2014).

7.1.3.2. Grid spanners with low forwarding index for energy efficient networks

A routing R of a connected graph G is a collection that contains simple paths connecting every ordered pair of vertices in G. The *edge-forwarding index with respect to* R (or simply the forwarding index with respect to R) $\pi(G,R)$ of G is the maximum number of paths in R passing through any edge of G. The *forwarding index*$\pi(G)$ of G is the minimum $\pi(G,R)$ over all routings R's of G. This parameter has been studied for different graph classes. Motivated by energy efficiency, we look in [30] for different numbers of edges, at the best spanning graphs of a square grid, namely those with a low forwarding index.

7.1.4. Live streaming in distributed systems

Peer to peer networks are an efficient way to carry out video live streaming as the forwarding load is distributed among peers. These systems can be of two types: unstructured and structured. In unstructured overlays, the peers obtain the video in an opportunistic way. The advantage is that such systems handle churn well. However, they are less bandwidth efficient than structured overlays, and the control overhead has a non-negligible impact on the performance. In structured overlays, the diffusion of the video is made via an explicit diffusion tree. The advantage is that the peer bandwidth can be optimally exploited. The drawback is that the departure of peers may break the diffusion tree.

In [29], we propose and analyze a simple local algorithm to balance a tree. In this distributed repair algorithm, each node carries out local operations based on its degree and on the subtree sizes of its children. In a synchronous setting, we first prove that starting from any n-node tree our process converges to a balanced binary tree in $O(n^2)$ rounds. We then describe a more restrictive model, adding a small extra information to each node, under which we adapt our algorithm to converge in $\Theta(n \log n)$ rounds.

In [58], we propose new simple distributed repair protocols for video live streaming structured systems. We show, through simulations with real traces, that structured systems can be very efficient and robust to failures, even for high churn and when peers have very heterogeneous upload bandwidth capabilities.

7.2. Graph Algorithms

Participants: Julien Bensmail, Nathann Cohen, David Coudert, Guillaume Ducoffe, Valentin Garnero, Frédéric Giroire, Frédéric Havet, Fionn Mc Inerney, Nicolas Nisse, Stéphane Pérennes, Rémi Watrigant.

COATI is interested in the algorithmic aspects of Graph Theory. In general we try to find the most efficient algorithms to solve various problems of Graph Theory and telecommunication networks. We use Graph Theory to model various network problems. We study their complexity and then we investigate the structural properties of graphs that make these problems hard or easy.

7.2.1. Complexity of graph problems

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.

7.2.1.1. Parameterized complexity of polynomial optimization problems (FPT in P)

Parameterized complexity theory has enabled a refined classification of the difficulty of NP-hard optimization problems on graphs with respect to key structural properties, and so to a better understanding of their true difficulties. More recently, hardness results for problems in P were established under reasonable complexity theoretic assumptions such as: Strong Exponential Time Hypothesis (SETH), 3SUM and All-Pairs Shortest-Paths (APSP). According to these assumptions, many graph theoretic problems do not admit truly subquadratic algorithms, nor even truly subcubic algorithms (Williams and Williams, FOCS 2010 [82] and Abboud *et al.* SODA 2015 [70]). A central technique used to tackle the difficulty of the above mentioned problems is fixed-parameter algorithms for polynomial-time problems with *polynomial dependency* in the fixed parameter (P-FPT). This technique was rigorously formalized by Giannopoulou et al. (IPEC 2015) [75], [76]. Following that, it was continued by Abboud *et al.* (SODA 2016) [71], by Husfeldt (IPEC 2016) [78] and Fomin *et al.* (SODA 2017) [74], using the treewidth as a parameter. Applying this technique to *clique-width*, another important graph parameter, remained to be done.

In [55] we study several graph theoretic problems for which hardness results exist such as *cycle problems* (triangle detection, triangle counting, girth), *distance problems* (diameter, eccentricities, Gromov hyperbolicity, betweenness centrality) and *maximum matching*. We provide hardness results and fully polynomial FPT algorithms, using clique-width and some of its upper-bounds as parameters (split-width, modular-width and P_4-sparseness). We believe that our most important result is an $\mathcal{O}(k^4 \cdot n + m)$-time algorithm for computing a maximum matching where k is either the modular-width or the P_4-sparseness. The latter generalizes many algorithms that have been introduced so far for specific subclasses such as cographs, P_4-lite graphs, P_4-extendible graphs and P_4-tidy graphs. Our algorithms are based on preprocessing methods using modular decomposition, split decomposition and primeval decomposition. Thus they can also be generalized to some graph classes with unbounded clique-width.

7.2.1.2. Finding cut-vertices in the square roots of a graph

The square of a given graph $H = (V, E)$ is obtained from H by adding an edge between every two vertices at distance two in H. Given a graph class $\mathcal{H}$, the $\mathcal{H}$-SQUARE ROOT PROBLEM asks for the recognition of the squares of graphs in $\mathcal{H}$. In [56], [46], we answer positively to an open question of Golovach *et al.* (IWOCA'16) [77] by showing that the squares of *cactus-block graphs* can be recognized in polynomial time. Our proof is based on new relationships between the decomposition of a graph by cut-vertices and the decomposition of its square by clique cutsets. More precisely, we prove that the closed neighbourhoods of cut-vertices in H induce maximal subgraphs of $G = H^2$ with no clique-cutset. Furthermore, based on this relationship, we can compute from a given graph G the block-cut tree of a desired square root (if any). Although the latter tree is not uniquely defined, we show surprisingly that it can only differ marginally between two different roots. Our approach not only gives the first polynomial-time algorithm for the $\mathcal{H}$-SQUARE ROOT PROBLEM for several graph classes $\mathcal{H}$, but it also provides a unifying framework for the recognition of the squares of trees, block graphs and cactus graphs — among others.

7.2.1.3. 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.

In [44], we answer open questions of Verbeek and Suri [81] on the relationships between Gromov hyperbolicity and the optimal stretch of graph embeddings in Hyperbolic space. Then, based on the relationships between hyperbolicity and Cops and Robber games, we turn necessary conditions for a graph to be Cop-win into sufficient conditions for a graph to have a large hyperbolicity (and so, no low-stretch embedding in Hyperbolic space). In doing so we derive lower-bounds on the hyperbolicity in various graph classes – such as Cayley graphs, distance-regular graphs and generalized polygons, to name a few. It partly fills in a gap in the literature on Gromov hyperbolicity, for which few lower-bound techniques are known.

In [23] we study practical improvements for the computation of hyperbolicity in large graphs. Precisely, we investigate relations between the hyperbolicity of a graph G and the hyperbolicity of its *atoms*, that are the subgraphs output by the clique-decomposition invented by Tarjan [80] and Leimer [79]. We prove that the maximum hyperbolicity taken over the atoms is at most one unit off from the hyperbolicity of G and the bound is sharp. We also give an algorithm to slightly modify the atoms, called the "substitution method", which is at no extra cost than computing the clique-decomposition, and so that the maximum hyperbolicity taken over the resulting graphs is *exactly* the hyperbolicity of the input graph G. Experimental evaluation on collaboration networks and biological networks shows that our method provides significant computation time savings. Finally, on a more theoretical side, we deduce from our results the first *linear-time* algorithm for computing the hyperbolicity of an outerplanar graph.

7.2.1.4. Computing metric hulls in graphs

Convexity in graphs generalises the classical convexity in Euclidean spaces. The *hull-number* of a graph is the minimum number k such that there exists a set of k vertices whose convex hull is the graph. Computing the hull-number is NP-hard even in very restricted graph classes such as partial cubes (isometric subgraphs of hypercubes). One challenging question in this area is the status of the parameterized complexity of this problem. We further investigate the complexity of a more general problem.

In [60], we prove that, given a closure function the smallest preimage of a closed set can be calculated in polynomial time in the number of closed sets. This confirms a conjecture of Albenque and Knauer and implies that there is a polynomial time algorithm to compute the convex hull-number of a graph, when all its convex subgraphs are given as input. We then show that computing if the smallest preimage of a closed set is logarithmic in the size of the ground set is LOGSNP-complete if only the ground set is given. A special instance of this problem is computing the dimension of a poset given its linear extension graph, that was conjectured to be in P.

The intent to show that the latter problem is LOGSNP-complete leads to several interesting questions and to the definition of the isometric hull, i.e., a smallest isometric subgraph containing a given set of vertices S. While for $|S| = 2$ an isometric hull is just a shortest path, we show that computing the isometric hull of a set of vertices is NP-complete even if $|S| = 3$. Finally, we consider the problem of computing the isometric hull-number of a graph and show that computing it is Σ_2^P-complete.

7.2.1.5. Application to bioinformatics

For a (possibly infinite) fixed family of graphs F, we say that a graph G overlays F on a hypergraph H if $V(H)$ is equal to $V(G)$ and the subgraph of G induced by every hyperedge of H contains some member of F as a spanning subgraph. While it is easy to see that the complete graph on $|V(H)|$ overlays F on a hypergraph H whenever the problem admits a solution, the Minimum F-Overlay problem asks for such a graph with the minimum number of edges. This problem allows to generalize some natural problems which may arise in practice. For instance, if the family F contains all connected graphs, then Minimum F-Overlay corresponds to the Minimum Connectivity Inference problem (also known as Subset Interconnection Design problem) introduced for the low-resolution reconstruction of macro-molecular assembly in structural biology, a problem that has been studied jointly by COATI and ABS [72], [73], or for the design of networks. In [41], we show a strong dichotomy result regarding the polynomial vs. NP-hard status with respect to the considered family F. Roughly speaking, we show that the easy cases one can think of (e.g. when edge-less graphs of the right sizes are in F, or if F contains only cliques) are the only families giving rise to a polynomial problem: all others are NP-complete. We then investigate the parameterized complexity of the problem and give similar sufficient conditions on F that give rise to W[1]-hard, W[2]-hard or FPT problems when the parameter is the size of the solution. This yields an FPT/W[1]-hard dichotomy for a relaxed problem, where every hyperedge of H must contain some member of F as a (non necessarily spanning) subgraph.

7.2.1.6. Matchings for the recovery of disrupted airline operations

In an informal collaboration with Amadeus' members (A. Salch and V. Weber), we have studied the following problem. When an aircraft is approaching an airport, it gets a short time interval (called *slot*) that it can use to land. If the landing of the aircraft is delayed (because of bad weather, or if it arrives late, or if other aircrafts have to land first), it looses its slot and Air traffic controllers have to assign it a new slot. However, slots for landing are a scare resource of the airports and, to avoid that an aircraft waits too much time, Air traffic controllers have to regularly modify the assignment of the slots of the aircrafts. Unfortunately, for legal and economical reasons, Air traffic controllers can modify the slot-assignment only through specific kind of operations. The problem is then the following. Precisely, let $k \geq 1$ be an odd integer, a graph G and a matching M (set of pairwise disjoint edges) of G. What is the maximum size of a matching that can be obtained from M by *using* only augmenting paths of length *at most* k?

By Berge's theorem, finding a *maximum matching* in a graph relies on *the use* of *augmenting paths*. When no further constraint is added (k unbounded), Edmonds' algorithm allows to compute a maximum matching in polynomial time by sequentially augmenting such paths. In [39], we first prove that this problem can be solved in polynomial time for $k \leq 3$ in any graph and that it is *NP*-complete for any fixed $k \geq 5$ in the class of planar bipartite graphs of degree at most 3 and arbitrarily large girth. We then prove that this problem is in *P*, for any k, in several subclasses of trees such as caterpillars or trees with all vertices of degree at least 3 "far appart". Moreover, this problem can be solved in time $O(n)$ in the class of n-node trees when k and the maximum degree are fixed parameters. Finally, we consider a more constrained problem where only paths of length *exactlyk* can be augmented. We prove that this latter problem becomes *NP*-complete for any fixed $k \geq 3$ and in trees when k is part of the input.

In [51], we perform a deeper analysis of the complexity of this problem for trees. On the positive side, we first show that it can be solved in polynomial time for more classes of trees, namely bounded-degree trees (via a dynamic programming approach), caterpillars and trees where the nodes with degree at least 3 are sufficiently far apart. On the negative side, we show that, when only paths of length *exactlyk* can be augmented, the problem becomes *NP*-complete already for $k = 3$, in the class of planar bipartite graphs with maximum degree 3 and arbitrary large girth. We also show that the latter problem is *NP*-complete in trees when k is part of the input.

7.2.2. Graph decompositions and graph searching

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.

7.2.2.1. Minimum size tree-decompositions

We study in [31] the problem of computing a tree-decomposition of a graph with width at most k and minimum number of bags. More precisely, we focus on the following problem: given a fixed $k \geq 1$, what is the complexity of computing a tree-decomposition of width at most k with minimum number of bags in the class of graphs with treewidth at most k? We prove that the problem is NP-complete for any fixed $k \geq 4$ and polynomial for $k \leq 2$; for $k = 3$, we show that it is polynomial in the class of trees and 2-connected outerplanar graphs.

7.2.2.2. Exclusive Graph Searching and pathwidth.

An algorithmic interpretation of tree/path-decomposition is the well known *graph searching* problem, where a team of searchers aims at capturing an intruder in a network, modeled as a graph. All variants of this problem assume that any node can be simultaneously occupied by several searchers. This assumption may be unrealistic, e.g., in the case of searchers modeling physical searchers, or may require each individual node to provide additional resources, e.g., in the case of searchers modeling software agents.

We thus introduce and investigate in [22] *Exclusive Graph Searching*, in which no two or more searchers can occupy the same node at the same time. As for the classical variants of graph searching, we study the minimum number of searchers required to capture the intruder. This number is called the *exclusive search number* of the considered graph. Exclusive graph searching appears to be considerably more complex than classical graph searching, for at least two reasons: (1) it does not satisfy the *monotonicity property*, and (2) it is not *closed under minor*. Moreover, we observe that the exclusive search number of a tree may differ exponentially from the values of classical search numbers (e.g., pathwidth). Nevertheless, we design a polynomial-time algorithm which, given any n-node tree T, computes the exclusive search number of T in time $O(n^3)$. Moreover, for any integer k, we provide a characterization of the trees T with exclusive search number at most k. Finally, we prove that the ratio between the exclusive search number and the pathwidth of a graph is bounded by its maximum degree.

In [32], we study the complexity of this new variant and show that there are graph classes where its complexity differs from the complexity of pathwidth. We show that the problem is NP-hard in planar graphs with maximum degree 3 and it can be solved in linear-time in the class of cographs. We also show that *monotone* Exclusive Graph Searching is NP-complete in split graphs where Pathwidth is known to be solvable in polynomial time. Moreover, we prove that monotone Exclusive Graph Searching is in P in a subclass of star-like graphs where Pathwidth is known to be NP-hard. Hence, the computational complexities of monotone Exclusive Graph Searching and Pathwidth cannot be compared. This is the first variant of Graph Searching for which such a difference is proved.

7.2.2.3. Distributed Graph Searching.

We then study exclusive graph searching in a distributed setting. Consider a set of mobile robots placed on distinct nodes of a discrete, anonymous, and bidirectional ring. Asynchronously, each robot takes a snapshot of the ring, determining the size of the ring and 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. This model of computation is known as *Look-Compute-Move*. The computation depends on the required task. In [25], 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 very weak assumptions. More precisely, we provide a full characterization (except for few pathological cases) of the initial configurations for which Gathering can be solved. The algorithm relies on the necessary assumption of the local-weak multiplicity detection. This means that during the Look phase a robot detects also whether the node it occupies is occupied by other robots, without acquiring the exact number.

For the exclusive searching, we characterize all (except for few pathological cases) aperiodic configurations from which the problem is feasible. We also provide some impossibility results for the case of periodic configurations.

7.2.3. Combinatorial games on graphs

We study several two-player games on graphs. Some of these games allow to model real-life applications. In the case of the Spy-game presented below, we propose a successful new approach by studying fractional relaxation of such games.

7.2.3.1. Localization Game on Geometric and Planar Graphs

Motivated by a localization problem in cellular networks, we introduce in [52] a model based on a pursuit graph game that resembles the famous Cops and Robbers game. It can be considered as a game theoretic variant of the *metric dimension* of a graph. Given a graph G we want to localize a walking agent by checking his distance to as few vertices as possible. We provide upper bounds on the related graph invariant $\zeta(G)$, defined as the least number of cops needed to localize the robber on a graph G, for several classes of graphs (trees, bipartite graphs, etc). Our main result is that, surprisingly, there exists planar graphs of treewidth 2 and unbounded $\zeta(G)$. On a positive side, we prove that $\zeta(G)$ is bounded by the pathwidth of G. We then show that the algorithmic problem of determining $\zeta(G)$ is NP-hard in graphs with diameter at most 2. Finally, we show that at most one cop can approximate (arbitrarily close) the location of the robber in the Euclidean plane.

7.2.3.2. Spy-Game on graphs

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 vertex. 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 the same vertices. The spy has to escape the surveillance of the guards, i.e., must reach a vertex at distance more than $d \in \mathbb{N}$ (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).

In [53], we consider the computational complexity of the problem, showing that it is NP-hard (for every speed s and distance d) and that some variant of it is PSPACE-hard in DAGs. Then, we establish tight tradeoffs between the number of guards, the speed s of the spy and the required distance d when G is a path or a cycle.

In order to determine the smallest number of guards necessary for this task, we analyze in [42], [43], [54] the game through a Linear Programming formulation and the *fractional strategies* it yields for the guards. We then show the equivalence of fractional and integral strategies in trees. This allows us to design a polynomial-time algorithm for computing an optimal strategy in this class of graphs. Using duality in Linear Programming, we also provide non-trivial bounds on the fractional guard-number of grids and torus. We believe that the approach using fractional relaxation and Linear Programming is promising to obtain new results in the field of combinatorial games.

7.2.3.3. Hyperopic Cops and Robbers

We introduce in [68] a new variant of the game of Cops and Robbers played on graphs, where the robber is invisible when located in the neighbor set of a cop. The hyperopic cop number is the corresponding analogue of the cop number, and we investigate bounds and other properties of this parameter. We characterize the cop-win graphs for this variant, along with graphs with the largest possible hyperopic cop number. We analyze the cases of graphs with diameter 2 or at least 3, focusing on when the hyperopic cop number is at most one greater than the cop number. We show that for planar graphs, as with the usual cop number, the hyperopic cop number is at most 3. The hyperopic cop number is considered for countable graphs, and it is shown that for connected chains of graphs, the hyperopic cop density can be any real number in $[0, 1/2]$.

7.3. Graph theory

Participants: Julien Bensmail, Guillaume Ducoffe, Frédéric Havet, William Lochet, Nicolas Nisse, Bruce Reed.

COATI 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 (di)graphs

We study various conditions that ensure a (di)graph to contain certain substructures.

In [17], we study the question of finding a set of k vertex-disjoint cycles (resp. directed cycles) of distinct lengths in a given graph (resp. digraph). In the context of undirected graphs, we prove that, for every $k \geq 1$, every graph with minimum degree at least $\frac{k^2+5k-2}{2}$ has k vertex-disjoint cycles of different lengths, where the degree bound is the best possible. We also consider other cases such as when the graph is triangle-free, or the k cycles are required to have different lengths modulo some value r. In the context of directed graphs, we consider a conjecture of Lichiardopol concerning the least minimum out-degree required for a digraph to have k vertex-disjoint directed cycles of different lengths. We verify this conjecture for tournaments, and, by using the probabilistic method, for some regular digraphs and digraphs of small order.

A $(k_1 + k_2)$-*bispindle* is the union of $k_1 (x, y)$-dipaths and $k_2 (y, x)$-dipaths, all these dipaths being pairwise internally disjoint. Recently, Cohen et al. showed that for every $(1, 1)$-bispindle B, there exists an integer k such that every strongly connected digraph with chromatic number greater than k contains a subdivision of B. In [24], we investigate generalisations of this result by first showing constructions of strongly connected digraphs with large chromatic number without any $(3, 0)$-bispindle or $(2, 2)$-bispindle. Then we show that strongly connected digraphs with large chromatic number contains a $(2, 1)$-bispindle, where at least one of the (x, y)-dipaths and the (y, x)-dipath are long.

Let $\mathcal{H}$ be a family of graphs and let d be large enough. For every d-regular graph G, we study the existence of a spanning $\mathcal{H}$-free subgraph of G with large minimum degree. This problem is well understood if $\mathcal{H}$ does not contain bipartite graphs. In [35] we provide asymptotically tight results for many families of bipartite graphs such as cycles or complete bipartite graphs. To prove these results, we study a locally injective analogue of the question.

An *even pair* (resp. *odd pair*) in a graph is a pair of non-adjacent vertices such that every chordless path between them has even (resp. odd) length. Even and odd pairs are important tools in the study of perfect graphs and were instrumental in the proof of the Strong Perfect Graph Theorem. We suggest that such pairs impose a lot of structure also in arbitrary, not just perfect graphs. To this end, we show in [36] that the presence of even or odd pairs in graphs imply a special structure of the stable set polytope. In fact, we give a polyhedral characterization of even and odd pairs.

7.3.2. Colourings and partitioning (di)graphs

7.3.2.1. Colouring graphs with constraints on connectivity

A graph G has maximal local edge-connectivity k if the maximum number of edge-disjoint paths between every pair of distinct vertices x and y is at most k. We prove in [11] Brooks-type theorems for k-connected graphs with maximal local edge-connectivity k, and for any graph with maximal local edge-connectivity 3. We also consider several related graph classes defined by constraints on connectivity. In particular, we show that there is a polynomial-time algorithm that, given a 3-connected graph G with maximal local connectivity 3, outputs an optimal colouring for G. On the other hand, we prove, for $k \geq 3$, that k-colourability is NP-complete when restricted to minimally k-connected graphs, and 3-colourability is NP-complete when restricted to $(k-1)$-connected graphs with maximal local connectivity k. Finally, we consider a parameterization of k-colourability based on the number of vertices of degree at least $k + 1$, and prove that, even when k is part of the input, the corresponding parameterized problem is FPT.

7.3.2.2. 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.

Towards the 1-2-3-Conjecture, the best-known result to date is due to Kalkowski, Karoński and Pfender, who proved that it holds when relaxed to 5-edge-weightings. Their proof builds upon a weighting algorithm designed by Kalkowski for a total version (where also the vertices are weighted) of the problem. In [67], we present new mechanisms for using Kalkowski's algorithm in the context of the 1-2-3 Conjecture. As a main result we prove that every 5-regular graph admits a 4-edge-weighting that permits to distinguish its adjacent vertices via their incident sums.

In [66], we investigate the consequences on the 1-2-3 Conjecture of requiring a stronger distinction condition. Namely, we consider two adjacent vertices distinguished when their incident sums differ by at least 2. As a guiding line, we conjecture that every graph with no connected component isomorphic to K_2 admits a 5-edge-weighting permitting to distinguish the adjacent vertices in this stronger way. We verify this conjecture for several classes of graphs, including bipartite graphs and cubic graphs. We then consider algorithmic aspects, and show that it is *NP*-complete to determine the smallest k such that a given bipartite graph admits such a k-edge-weighting. In contrast, we show that the same problem can be solved in polynomial time for a given tree.

In [13], we consider the following question, which stands as a directed analogue of the 1-2-3 Conjecture: Given any digraph D with no arc $\overrightarrow{uv}$ verifying $d^+(u) = d^-(v) = 1$, is it possible to weight the arcs of D with weights among $\{1, 2, 3\}$ so that, for every arc $\overrightarrow{uv}$ of D, the sum of incident weights out-going from u is different from the sum of incident weights in-coming to v? We answer positively to this question, and investigate digraphs for which even the weights among $\{1, 2\}$ are sufficient. In relation with the so-called 1-2 Conjecture, we also consider a total version of the problem, which we prove to be false. Our investigations turn to have interesting relations with open questions related to the 1-2-3 Conjecture.

In [21], we study the following question: Is it always possible to injectively assign the weights $1, ..., |E(G)|$ to the edges of any given graph G (with no component isomorphic to K_2) so that every two adjacent vertices of G get distinguished by their sums of incident weights? One may see this question as a combination of the well-known 1-2-3 Conjecture and the Antimagic Labelling Conjecture. We exhibit evidence that this question might be true. Benefiting from the investigations on the Antimagic Labelling Conjecture, we first point out that several classes of graphs, such as regular graphs, indeed admit such assignments. We then show that trees also do, answering a recent conjecture of Arumugam, Premalatha, Bača and Semaničová-Feňovčíková. Towards a general answer to the question above, we then prove that claimed assignments can be constructed for any graph, provided we are allowed to use some number of additional edge weights. For some classes of sparse graphs, namely 2-degenerate graphs and graphs with maximum average degree 3, we show that only a small (constant) number of such additional weights suffices.

7.3.2.3. Variants of vertex- or edge-colouring

A colouring of a graph G is *properly connected* if every two vertices of G are the ends of a properly coloured path. In [57], [47], we study the *complexity* of computing the *proper connection number* (minimum number of colours in a properly connected colouring) for edge and vertex colourings, in undirected and directed graphs, respectively. First we disprove some conjectures of Magnant et al. (2016) on characterizing the strong digraphs with *proper arc connection number* at most two. Then, we prove that deciding whether a given digraph has proper arc connection number at most two is NP-complete. Furthermore, we show that there are infinitely many such digraphs with no even-length dicycle. We initiate the study of proper vertex connectivity in digraphs and we prove similar results as for the arc version. Finally, we present polynomial-time recognition algorithms for *bounded-treewidth* graphs and *bipartite* graphs with *proper edge connection number* at most two.

A graph is *locally irregular* if no two adjacent vertices have the same degree. The *irregular chromatic index*$\chi'_{\mathrm{irr}}(G)$ of a graph G is the smallest number of locally irregular subgraphs needed to edge-decompose G. Not all graphs have such a decomposition, but Baudon, Bensmail, Przybyło, and Woźniak conjectured that if G can be decomposed into locally irregular subgraphs, then $\chi'_{\mathrm{irr}}(G) \leq 3$. In support of this conjecture, Przybyło showed that $\chi'_{\mathrm{irr}}(G) \leq 3$ holds whenever G has minimum degree at least 10^{10}. In [19] we prove that every bipartite graph G which is not an odd length path satisfies $\chi'_{\mathrm{irr}}(G) \leq 10$. This is the first general constant upper bound on the irregular chromatic index of bipartite graphs. Combining this result with Przybyło's result, we show that $\chi'_{\mathrm{irr}}(G) \leq 328$ for every graph G which admits a decomposition into locally irregular subgraphs. Finally, we show that $\chi'_{\mathrm{irr}}(G) \leq 2$ for every 16-edge-connected bipartite graph G.

An (m,n)-coloured mixed graph is a mixed graph with arcs assigned one of m different colours and edges one of n different colours. A homomorphism of an (m,n)-coloured mixed graph G to an (m,n)-coloured mixed graph H is a vertex mapping such that if uv is an arc (edge) of colour c in G, then $f(u)f(v)$ is also an arc (edge) of colour c. The (m,n)-coloured mixed chromatic number, denoted $\chi_{m,n}(G)$, of an (m,n)-coloured mixed graph G is the order of a smallest homomorphic image of G. An (m,n)-clique is an (m,n)-coloured mixed graph C with $\chi_{m,n}(C) = |V(C)|$. In [16], we study the structure of (m,n)-cliques. We show that almost all (m,n)-coloured mixed graphs are (m,n)-cliques, prove bounds for the order of a largest outerplanar and planar (m,n)-clique and resolve an open question concerning the computational complexity of a decision problem related to $(0,2)$-cliques. Additionally, we explore the relationship between $\chi_{1,0}$ and $\chi_{0,2}$.

An edge colouring of a graph G is called acyclic if it is proper and every cycle contains at least three colours. We show in [33] that for every $\varepsilon > 0$, there exists a $g = g(\varepsilon)$ such that if G has maximum degree Δ and girth at least g then G admits an acyclic edge colouring with $(1+\varepsilon)\Delta + O(1)$ colours.

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 in G. Its *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.

A particular interest was dedicated to grids as many processor networks have a grid topology. There are several types of standard regular infinite grids, in particular the hexagonal grids, the square grids, the triangular grids and the king grids. For such graphs G, the problem consists in finding the minimum density $d^*(G)$ of an identifying code of G.

In [26], we study the infinite triangular grid T_k with k rows. We show $d^*(T_1) = d^*(T_2) = 1/2$, $d^*(T_3) = d^*(T_4) = 1/3$, $d^*(T_5) = 3/10$, $d^*(T_6) = 1/3$ and $d^*(T_k) = 1/4 + 1/(4k)$ for all odd $k \geq 7$. In addition, we show that $1/4 + 1/(4k) \leq d^*(T_k) \leq 1/4 + 1/(2k)$ for all even $k \geq 8$.

In [27], we study the density of king grids which are strong product of two paths. We show that for every king grid G, $d^*(G) \geq 2/9$. In addition, we show this bound is attained only for king grids which are strong products of two infinite paths. Given $k \geq 3$, we denote by K_k the (infinite) king strip with k rows. We prove that $d^*(K_3) = 1/3$, $d^*(K_4) = 5/16$, $d^*(K_5) = 4/15$ and $d^*(K_6) = 5/18$. We also prove that $2/9 + 8/81k \leq d^*(K_k) \leq 2/9 + 4/9k$ for every $k \geq 7$.

7.3.4. Miscellaneous

7.3.4.1. A proof of the Barát-Thomassen conjecture

The Barát-Thomassen conjecture asserts that for every tree T on m edges, there exists a constant k_T such that every k_T-edge-connected graph with size divisible by m can be edge-decomposed into copies of T. So far this conjecture has only been verified when T is a path or when T has diameter at most 4. In [18], we prove the full statement of the conjecture.

7.3.4.2. Recursively partitionable graphs

A connected graph G is said to be *arbitrarily partitionable* (AP for short) if for every partition $(n_1, ..., n_p)$ of $|V(G)|$ there exists a partition $(V_1, ..., V_p)$ of $V(G)$ such that each V_i induces a connected subgraph of G on n_i vertices. Some stronger versions of this property were introduced, namely the ones of being *online arbitrarily partitionable* and *recursively arbitrarily partitionable* (OL-AP and R-AP for short, respectively), in which the subgraphs induced by a partition of G must not only be connected but also fulfil additional conditions. In [14], we point out some structural properties of OL-AP and R-AP graphs with connectivity 2. In particular, we show that deleting a cut pair of these graphs results in a graph with a bounded number of components, some of whom have a small number of vertices. We obtain these results by studying a simple class of 2-connected graphs called *balloons*

7.3.4.3. On oriented cliques with respect to push operation

An oriented graph is a directed graph without any directed cycle of length at most 2. An oriented clique is an oriented graph whose non-adjacent vertices are connected by a directed 2-path. To push a vertex v of a directed graph $\overrightarrow{G}$ is to change the orientations of all the arcs incident to v. A push clique is an oriented clique that remains an oriented clique even if one pushes any set of vertices of it. We show in [20] that it is NP-complete to decide if an undirected graph is the underlying graph of a push clique or not. We also prove that a planar push clique can have at most 8 vertices and provide an exhaustive list of planar push cliques.

7.3.4.4. On q-power cycles in cubic graphs

In the context of a conjecture of Erdős and Gyárfás, we consider in [15], for any $q \geq 2$, the existence of q-power cycles (*i.e.* with length a power of q) in cubic graphs. We exhibit constructions showing that, for every $q \geq 3$, there exist arbitrarily large cubic graphs with no q-power cycles. Concerning the remaining case $q = 2$ (which corresponds to the conjecture of Erdős and Gyárfás), we show that there exist arbitrarily large cubic graphs whose only 2-power cycles have length 4 only, or 8 only.

7.3.4.5. How to determine if a random graph with a fixed degree sequence has a giant component

For a fixed degree sequence $\mathcal{D} = (d_1, ..., d_n)$, let $G(\mathcal{D})$ be a uniformly chosen (simple) graph on $\{1, \cdots, n\}$ where the vertex i has degree d_i. In [34] we determine whether $G(\mathcal{D})$ has a giant component with high probability, essentially imposing no conditions on $\mathcal{D}$. We simply insist that the sum of the degrees in $\mathcal{D}$ which are not 2 is at least $\lambda(n)$ for some function λ going to infinity with n. This is a relatively minor technical condition, and when $\mathcal{D}$ does not satisfy it, both the probability that $G(\mathcal{D})$ has a giant component and the probability that $G(\mathcal{D})$ has no giant component are bounded away from 1.

7.3.4.6. A proof of the Erdős-Sands-Sauer-Woodrow conjecture

A very nice result of Barany and Lehel asserts that every finite subset X of R^d can be covered by $f(d) X$-boxes (i.e. each box has two antipodal points in X). As shown by Gyárfás and Pálvőlgyi this result would follow from the following conjecture : If a tournament admits a partition of its arc set into k partial orders, then its domination number is bounded in terms of k. This question is in turn implied by the Erdős-Sands-Sauer-Woodrow conjecture : If the arcs of a tournament T are colored with k colors, there is a set X of at most $g(k)$ vertices such that for every vertex v of T, there is a monochromatic path from X to v. We give in [69] a short proof of this statement. We moreover show that the general Sands-Sauer-Woodrow conjecture (which as a special case implies the stable marriage theorem) is valid for directed graphs with bounded stability number. This conjecture remains however open.

COFFEE Project-Team

6. New Results

6.1. A few words on the results of the year

- Analysis of models with constraints: existence of solutions for a multidimensional model [1].
- Analysis of the convergence of a particle approximation for a traffic flow model with constraints [2].
- Numerical study of a traffic flow model with constraints [3]
- Existence of martingale solutions for the stochastic isentropic Euler model [4]
- New approach to accelerate convergence of Newton's methods applied to highly nonlinear and heterogeneous porous media flow problems [5], [6]
- We provide the numerical analysis of Discrete Duality Finite Volume (DDFV) schemes on general meshes for the (linear) Stokes problem with Neumann boundary conditions (on a fraction of the boundary). We prove well-posedness for a stabilized version of the scheme and we derive some error estimates. Finally, our theoretical results are illustrated with numerical simulations and stabilized and unstabilized schemes are compared. [26]
- A new domain decomposition algorithm to couple a non-isothermal compositional liquid gas Darcy flow and a free gas flow occurring at the interface between the nuclear waste repository and the ventilation galleries. [16], [22]
- A new two-phase Darcy flow model in fractured porous medium with fractures represented as interfaces of co-dimension one coupled to the surrounding matrix. The model accounts accurately for highly discontinuous capillary pressures, for gravity in the fracture width and both for fractures acting as drains or barriers. [7], [18]
- Use of the code ComPASS at BRGM to study the hydrothermal system of Lamentin Bay in Martinique during the PhD thesis of Yannis Labeau from University of Martinique [14], [21]
- New explicit energy-momentum conserving scheme for Hamiltonian systems [28].
- L. Monasse obtained an ANR JCJC grant.
- Through the PhD of J. Llobell, progress have been made to set up new schemes on staggered grids for solving the Euler system of gas dynamics (full Euler equations, MUSCL version on MAC grids, Low Mach regimes).

DATASHAPE Project-Team

7. New Results

7.1. Algorithmic aspects of topological and geometric data analysis

7.1.1. Variance Minimizing Transport Plans for Inter-surface Mapping

Participant: David Cohen-Steiner.

In collaboration with Manish Mandad, Leik Kobbelt (RWTH Aachen), Pierre Alliez (Inria), and Mathieu Desbrun (Caltech).

We introduce an effcient computational method for generating dense and low distortion maps between two arbitrary surfaces of same genus. Instead of relying on semantic correspondences or surface parameterization, we directly optimize a variance-minimizing transport plan between two input surfaces that defines an as-conformal-as-possible inter-surface map satisfying a user-prescribed bound on area distortion. The transport plan is computed via two alternating convex optimizations, and is shown to minimize a generalized Dirichlet energy of both the map and its inverse. Computational efficiency is achieved through a coarse-tone approach in diffusion geometry, with Sinkhorn iterations modified to enforce bounded area distortion. The resulting inter-surface mapping algorithm applies to arbitrary shapes robustly, with little to no user interaction.

7.1.2. Approximating the spectrum of a graph

Participant: David Cohen-Steiner.

In collaboration with Weihao Kong, Gregory Valiant (Stanford), and Christian Sohler (TU Dortmund).

The spectrum of a network or graph $G=(V,E)$ with adjacency matrix A consists of the eigenvalues of the normalized Laplacian $L=I-D^{-1/2}AD^{-1/2}$. This set of eigenvalues encapsulates many aspects of the structure of the graph, including the extent to which the graph posses community structures at multiple scales. We study the problem of approximating the spectrum $\lambda=(\lambda_1,...,\lambda_{|V|})$, $0{\le}\lambda 1,{\le}...,{\le}\lambda|V|{\le}2$ of G in the regime where the graph is too large to explicitly calculate the spectrum. We present a sublinear time algorithm that, given the ability to query a random node in the graph and select a random neighbor of a given node, computes a succinct representation of an approximation $\widetilde{\lambda}$ such that $\|\widetilde{\lambda}-\lambda\|_1\le\varepsilon|V|$. Our algorithm has query complexity and running time $\exp(O(1/\varepsilon))$, independent of the size of the graph, $|V|$. We demonstrate the practical viability of our algorithm on 15 different real-world graphs from the Stanford Large Network Dataset Collection, including social networks, academic collaboration graphs, and road networks. For the smallest of these graphs, we are able to validate the accuracy of our algorithm by explicitly calculating the true spectrum; for the larger graphs, such a calculation is computationally prohibitive. In addition we study the implications of our algorithm to property testing in the bounded degree graph model.

7.1.3. Anisotropic triangulations via discrete Riemannian Voronoi diagrams

Participants: Jean-Daniel Boissonnat, Mathijs Wintraecken.

In collaboration with mael Rouxel-Labbé (GeometryFactory).

The construction of anisotropic triangulations is desirable for various applications, such as the numerical solving of partial differential equations and the representation of surfaces in graphics. To solve this notoriously difficult problem in a practical way, we introduce the discrete Riemannian Voronoi diagram, a discrete structure that approximates the Riemannian Voronoi diagram. This structure has been implemented and was shown to lead to good triangulations in $\mathbb{R}^2$ and on surfaces embedded in $\mathbb{R}^3$ as detailed in our experimental companion paper.

In [23], [32], [34], we study theoretical aspects of our structure. Given a finite set of points $\mathcal{P}$ in a domain Ω equipped with a Riemannian metric, we compare the discrete Riemannian Voronoi diagram of $\mathcal{P}$ to its Riemannian Voronoi diagram. Both diagrams have dual structures called the discrete Riemannian Delaunay and the Riemannian Delaunay complex. We provide conditions that guarantee that these dual structures are identical. It then follows from previous results that the discrete Riemannian Delaunay complex can be embedded in Ω under sufficient conditions, leading to an anisotropic triangulation with curved simplices. Furthermore, we show that, under similar conditions, the simplices of this triangulation can be straightened.

7.1.4. Only distances are required to reconstruct submanifolds

Participants: Jean-Daniel Boissonnat, Ramsay Dyer, Steve Oudot.

In collaboration with Arijit Ghosh (Indian Statistical Institute).

In [14], we give the first algorithm that outputs a faithful reconstruction of a submanifold of Euclidean space without maintaining or even constructing complicated data structures such as Voronoi diagrams or Delaunay complexes. Our algorithm uses the witness complex and relies on the stability of *power protection*, a notion introduced in this paper. The complexity of the algorithm depends exponentially on the intrinsic dimension of the manifold, rather than the dimension of ambient space, and linearly on the dimension of the ambient space. Another interesting feature of this work is that no explicit coordinates of the points in the point sample is needed. The algorithm only needs the *distance matrix* as input, i.e., only distance between points in the point sample as input.

7.1.5. An obstruction to Delaunay triangulations in Riemannian manifolds

Participants: Jean-Daniel Boissonnat, Ramsay Dyer.

In collaboration with Arijit Ghosh (Indian Statistical Institute) and Nikolay Martynchuk (University of Groningen).

Delaunay has shown that the Delaunay complex of a finite set of points P of Euclidean space $\mathbb{R}^m$ triangulates the convex hull of P, provided that P satisfies a mild genericity property. Voronoi diagrams and Delaunay complexes can be defined for arbitrary Riemannian manifolds. However, Delaunay's genericity assumption no longer guarantees that the Delaunay complex will yield a triangulation; stronger assumptions on P are required. A natural one is to assume that P is sufficiently dense. Although results in this direction have been claimed, we show that sample density alone is insufficient to ensure that the Delaunay complex triangulates a manifold of dimension greater than 2 [13].

7.1.6. Local criteria for triangulation of manifolds

Participants: Jean-Daniel Boissonnat, Ramsay Dyer, Mathijs Wintraecken.

In collaboration with Arijit Ghosh (Indian Statistical Institute).

We present criteria for establishing a triangulation of a manifold [40]. Given a manifold M, a simplicial complex $\mathcal{A}$, and a map H from the underlying space of $\mathcal{A}$ to M, our criteria are presented in local coordinate charts for M, and ensure that H is a homeomorphism. These criteria do not require a differentiable structure, or even an explicit metric on M. No Delaunay property of $\mathcal{A}$ is assumed. The result provides a triangulation guarantee for algorithms that construct a simplicial complex by working in local coordinate patches. Because the criteria are easily checked algorithmically, they are expected to be of general use.

7.1.7. Triangulating stratified manifolds I: a reach comparison theorem

Participants: Jean-Daniel Boissonnat, Mathijs Wintraecken.

In [42], we define the reach for submanifolds of Riemannian manifolds, in a way that is similar to the Euclidean case. Given a d-dimensional submanifold $\mathcal{S}$ of a smooth Riemannian manifold $\mathbb{M}$ and a point $p \in \mathbb{M}$ that is not too far from $\mathcal{S}$ we want to give bounds on local feature size of $\exp_p^{-1}(\mathcal{S})$. Here $\exp_p^{-1}$ is the inverse exponential map, a canonical map from the manifold to the tangent space. Bounds on the local feature size of $\exp_p^{-1}(\mathcal{S})$ can be reduced to giving bounds on the reach of $\exp_p^{-1}(\mathcal{B})$, where $\mathcal{B}$ is a geodesic ball, centred at c with radius equal to the reach of $\mathcal{S}$. Equivalently we can give bounds on the reach of $\exp_p^{-1} \circ \exp_c(B_c)$, where now B_c is a ball in the tangent space $T_c\mathbb{M}$, with the same radius. To establish bounds on the reach of $\exp_p^{-1} \circ \exp_c(B_c)$ we use bounds on the metric and on its derivative in Riemann normal coordinates.

This result is a first step towards answering the important question of how to triangulate stratified manifolds.

7.1.8. The reach, metric distortion, geodesic convexity and the variation of tangent spaces

Participants: Jean-Daniel Boissonnat, Mathijs Wintraecken.

In collaboration with André Lieutier (Dassault Système).

In [41], we discuss three results. The first two concern general sets of positive reach: We first characterize the reach by means of a bound on the metric distortion between the distance in the ambient Euclidean space and the set of positive reach. Secondly, we prove that the intersection of a ball with radius less than the reach with the set is geodesically convex, meaning that the shortest path between any two points in the intersection lies itself in the intersection. For our third result we focus on manifolds with positive reach and give a bound on the angle between tangent spaces at two different points in terms of the distance between the points and the reach.

7.1.9. Delaunay triangulation of a random sample of a good sample has linear size

Participants: Jean-Daniel Boissonnat, Kunal Dutta, Marc Glisse.

In collaboration with Olivier Devillers (Inria Nancy Grand Est).

The *randomized incremental construction* (RIC) for building geometric data structures has been analyzed extensively, from the point of view of worst-case distributions. In many practical situations however, we have to face nicer distributions. A natural question that arises is: do the usual RIC algorithms automatically adapt when the point samples are nicely distributed. We answer positively to this question for the case of the Delaunay triangulation of ϵ-nets.

ϵ-nets are a class of nice distributions in which the point set is such that any ball of radius ϵ contains at least one point of the net and two points of the net are distance at least ϵ apart. The Delaunay triangulations of ϵ-nets are proved to have linear size; unfortunately this is not enough to ensure a good time complexity of the randomized incremental construction of the Delaunay triangulation. In [33], [38], we prove that a uniform random sample of a given size that is taken from an ϵ-net has a linear sized Delaunay triangulation in any dimension. This result allows us to prove that the randomized incremental construction needs an expected linear size and an expected $O(n \log n)$ time.

Further, we also prove similar results in the case of non-Euclidean metrics, when the point distribution satisfies a certain *bounded expansion* property; such metrics can occur, for example, when the points are distributed on a low-dimensional manifold in a high-dimensional ambient space.

7.1.10. Kernelization of the Subset General Position problem in Geometry

Participants: Jean-Daniel Boissonnat, Kunal Dutta.

In collaboration with Arijit Ghosh (Indian Statistical Institute) and Sudeshna Kolay (Eindhoven University of Technology).

In [21], we consider variants of the GEOMETRIC SUBSET GENERAL POSITION problem. In defining this problem, a geometric subsystem is specified, like a subsystem of lines, hyperplanes or spheres. The input of the problem is a set of n points in $\mathbb{R}^d$ and a positive integer k. The objective is to find a subset of at least k input points such that this subset is in general position with respect to the specified subsystem. For example, a set of points is in general position with respect to a subsystem of hyperplanes in $\mathbb{R}^d$ if no $d+1$ points lie on the same hyperplane. In this paper, we study the HYPERPLANE SUBSET GENERAL POSITION problem under two parameterizations. When parameterized by k then we exhibit a polynomial kernelization for the problem. When parameterized by $h = n - k$, or the dual parameter, then we exhibit polynomial kernels which are also tight, under standard complexity theoretic assumptions. We can also conclude similar kernelization results for D-POLYNOMIAL SUBSET GENERAL POSITION, where a vector space of polynomials of degree at most d are specified as the underlying subsystem such that the size of the basis for this vector space is b. The objective is to find a set of at least k input points, or in the dual delete at most $h = n - k$ points, such that no $b+1$ points lie on the same polynomial. Notice that this is a generalization of many well-studied geometric variants of the SET COVER problem, such as CIRCLE SUBSET GENERAL POSITION. We also study the general projective variants of these problems. These problems are also related to other geometric problems like SUBSET DELAUNAY TRIANGULATION problem.

7.1.11. Tight Kernels for Covering and Hitting: Point Hyperplane Cover and Polynomial Point Hitting Set

Participants: Jean-Daniel Boissonnat, Kunal Dutta.

In collaboration with Arijit Ghosh (Indian Statistical Institute) and Sudeshna Kolay (Eindhoven University of Technology).

The POINT HYPERPLANE COVER problem in $\mathbb{R}^d$ takes as input a set of n points in $\mathbb{R}^d$ and a positive integer k. The objective is to cover all the given points with a set of at most k hyperplanes. The D-POLYNOMIAL POINTS HITTING SET (D-POLYNOMIAL POINTS HS) problem in $\mathbb{R}^d$ takes as input a family $\mathcal{F}$ of D-degree polynomials from a vector space $\mathcal{R}$ in $\mathbb{R}^d$, and determines whether there is a set of at most k points in $\mathbb{R}^d$ that hit all the polynomials in $\mathcal{F}$. In [22], we exhibit tight kernels where k is the parameter for these problems.

7.1.12. Shallow packings, semialgebraic set systems, Macbeath regions, and polynomial partitioning

Participant: Kunal Dutta.

In collaboration with Arijit Ghosh (Indian Statistical Institute) and Bruno Jartoux (Université Paris-Est, Laboratoire d'Informatique Gaspard-Monge, ESIEE Paris, France) and Nabil H. Mustafa (Université Paris-Est, Laboratoire d'Informatique Gaspard-Monge, ESIEE Paris, France).

The packing lemma of Haussler states that given a set system $(X, \mathbb{R})$ with bounded VC dimension, if every pair of sets in $\mathbb{R}$ have large symmetric difference, then $\mathbb{R}$ cannot contain too many sets. Recently it was generalized to the shallow packing lemma, applying to set systems as a function of their shallow-cell complexity. In [29] we present several new results and applications related to packings:

1. an optimal lower bound for shallow packings,
2. improved bounds on Mnets, providing a combinatorial analogue to Macbeath regions in convex geometry,
3. we observe that Mnets provide a general, more powerful framework from which the state-of-the-art unweighted ϵ-net results follow immediately, and
4. simplifying and generalizing one of the main technical tools in Fox *et al.* (*J. of the EMS*, to appear).

7.1.13. A Simple Proof of Optimal Epsilon Nets

Participant: Kunal Dutta.

In collaboration with Nabil H. Mustafa (Université Paris-Est, Laboratoire d'Informatique Gaspard-Monge, ESIEE Paris, France, and Arijit Ghosh (Indian Statistical Institute)).

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 [20] 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).

7.1.14. On Subgraphs of Bounded Degeneracy in Hypergraphs

Participant: Kunal Dutta.

In collaboration with Arijit Ghosh (Indian Statistical Institute)).

A k-uniform hypergraph is d-degenerate if every induced subgraph has a vertex of degree at most d. In [48], given a k-uniform hypergraph $H = (V(H), E(H))$, we show there exists an induced subgraph of size at least

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

where $c_k = 2^{-\left(1+\frac{1}{k-1}\right)} \left(1 - \frac{1}{k}\right)$ and $d_H(v)$ denotes the degree of vertex v in the hypergraph H. This connects, extends, and generalizes results of Alon-Kahn-Seymour (1987), on d-degenerate sets of graphs, Dutta-Mubayi-Subramanian (2012) on d-degenerate sets of linear hypergraphs, and Srinivasan-Shachnai (2004) on independent sets in hypergraphs to d-degenerate subgraphs of hypergraphs. Our technique also gives optimal lower bounds for a more generalized definition of degeneracy introduced by Zaker (2013). 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. Finally we provide several applications in discrete geometry, extending results of Payne-Wood (2013) and Cardinal-Tóth-Wood (2016). We also address some natural algorithmic questions. The proof of our main theorem combines the *random permutation* technique of Bopanna-Caro-Wei and Beame and Luby, together with a new *local density* argument which may be of independent interest.

7.2. Statistical aspects of topological and geometric data analysis

7.2.1. The DTM-signature for a geometric comparison of metric-measure spaces from samples

Participant: Claire Brécheteau.

In [43], we introduce the notion of DTM-signature, a measure on $\mathbb{R}_+$ that can be associated to any metric-measure space. This signature is based on the distance to a measure (DTM) introduced by Chazal, Cohen-Steiner and Mérigot. It leads to a pseudo-metric between metric-measure spaces, upper-bounded by the Gromov-Wasserstein distance. Under some geometric assumptions, we derive lower bounds for this pseudo-metric. Given two N-samples, we also build an asymptotic statistical test based on the DTM-signature, to reject the hypothesis of equality of the two underlying metric measure spaces, up to a measure-preserving isometry. We give strong theoretical justifications for this test and propose an algorithm for its implementation.

7.2.2. Estimating the Reach of a Manifold

Participants: Eddie Aamari, Frédéric Chazal, Bertrand Michel.

In collaboration with J. Kim, A. Rinaldo, L. Wasserman (Carnegie Mellon University)

Various problems of computational geometry and manifold learning encode geometric regularity through the so-called reach, a generalized convexity parameter. The reach τ_M of a submanifold $M \subset \mathbb{R}^D$ is the maximal offset radius on which the projection onto M is well defined. The quantity τ_M renders a certain minimal scale of M, giving bounds on both maximum curvature and possible bottleneck structures. In [35], we study the geometry of the reach through an approximation perspective. We derive new geometric results on the reach for submanifolds without boundary. An estimator $\widehat{\tau}$ of τ_M is proposed in a framework where tangent spaces are known, and bounds assessing its efficiency are derived. In the case of i.i.d. random point cloud $\mathbb{X}_n$, $\widehat{\tau}(\mathbb{X}_n)$ is showed to achieve uniform expected loss bounds over a $\mathcal{C}^3$-like model. Minimax upper and lower bounds are derived, and we conclude with the extension to a model with unknown tangent spaces.

7.2.3. Robust Topological Inference: Distance To a Measure and Kernel Distance

Participants: Frédéric Chazal, Bertrand Michel.

In collaboration with B. Fasy, F. Lecci, A. Rinaldo, L. Wasserman.

Let P be a distribution with support S. The salient features of S can be quantified with persistent homology, which summarizes topological features of the sublevel sets of the distance function (the distance of any point x to S). Given a sample from P we can infer the persistent homology using an empirical version of the distance function. However, the empirical distance function is highly non-robust to noise and outliers. Even one outlier is deadly. The distance-to-a-measure (DTM) and the kernel distance are smooth functions that provide useful topological information but are robust to noise and outliers. In [17], we derive limiting distributions and confidence sets, and we propose a method for choosing tuning parameters.

7.2.4. Statistical analysis and parameter selection for Mapper

Participants: Steve Oudot, Bertrand Michel, Mathieu Carrière.

In [44] we study the question of the statistical convergence of the 1-dimensional Mapper to its continuous analogue, the Reeb graph. We show that the Mapper is an optimal estimator of the Reeb graph, which gives, as a byproduct, a method to automatically tune its parameters and compute confidence regions on its topological features, such as its loops and flares. This allows to circumvent the issue of testing a large grid of parameters and keeping the most stable ones in the brute-force setting, which is widely used in visualization, clustering and feature selection with the Mapper.

7.2.5. Sliced Wasserstein Kernel for Persistence Diagrams

Participants: Steve Oudot, Mathieu Carrière.

In collaboration with M. Cuturi (ENSAE)

Persistence diagrams (PDs) play a key role in topological data analysis (TDA), in which they are routinely used to describe succinctly complex topological properties of complicated shapes. PDs enjoy strong stability properties and have proven their utility in various learning contexts. They do not, however, live in a space naturally endowed with a Hilbert structure and are usually compared with specific distances, such as the bottleneck distance. To incorporate PDs in a learning pipeline, several kernels have been proposed for PDs with a strong emphasis on the stability of the RKHS distance w.r.t. perturbations of the PDs. In [27], we use the Sliced Wasserstein approximation of the Wasserstein distance to define a new kernel for PDs, which is not only provably stable but also provably discriminative w.r.t. the Wasserstein distance W1∞ between PDs. We also demonstrate its practicality, by developing an approximation technique to reduce kernel computation time, and show that our proposal compares favorably to existing kernels for PDs on several benchmarks.

7.2.6. An introduction to Topological Data Analysis: fundamental and practical aspects for data scientists

Participants: Frédéric Chazal, Bertrand Michel.

Topological Data Analysis (TDA) is a recent and fast growing field providing a set of new topological and geometric tools to infer relevant features for possibly complex data. In [45], we propose a brief introduction, through a few selected recent and state-of-the-art topics, to basic fundamental and practical aspects of TDA for non experts.

7.3. Topological approach for multimodal data processing

7.3.1. On the Stability of Functional Maps and Shape Difference Operators

Participants: Frédéric Chazal, Ruqi Huang, Maks Ovsjanikov.

In this paper, we provide stability guarantees for two frameworks that are based on the notion of functional maps. We consider two types of perturbations in our analysis: one is on the input shapes and the other is on the change in *scale*. In theory, we formulate and justify the robustness that has been observed in practical implementations of those frameworks. Inspired by our theoretical results, we propose a pipeline for constructing shape difference operators on point clouds and show numerically that the results are robust and informative. In particular, we show that both the shape difference operators and the derived areas of highest distortion are stable with respect to changes in shape representation and change of scale. Remarkably, this is in contrast with the well-known instability of the eigenfunctions of the Laplace-Beltrami operator computed on point clouds compared to those obtained on triangle meshes.

7.3.2. Local Equivalence and Intrinsic Metrics Between Reeb Graphs

Participants: Steve Oudot, Mathieu Carrière.

As graphical summaries for topological spaces and maps, Reeb graphs are common objects in the computer graphics or topological data analysis literature. Defining good metrics between these objects has become an important question for applications, where it matters to quantify the extent by which two given Reeb graphs differ. Recent contributions emphasize this aspect, proposing novel distances such as functional distortion or interleaving that are provably more discriminative than the so-called bottleneck distance, being true metrics whereas the latter is only a pseudo-metric. Their main drawback compared to the bottleneck distance is to be comparatively hard (if at all possible) to evaluate. In [28] we take the opposite view on the problem and show that the bottleneck distance is in fact good enough locally, in the sense that it is able to discriminate a Reeb graph from any other Reeb graph in a small enough neighborhood, as efficiently as the other metrics do. This suggests considering the intrinsic metrics induced by these distances, which turn out to be all globally equivalent. This novel viewpoint on the study of Reeb graphs has a potential impact on applications, where one may not only be interested in discriminating between data but also in interpolating between them.

7.3.3. Structure and Stability of the One-Dimensional Mapper

Participants: Steve Oudot, Mathieu Carrière.

Given a continuous function $f : X -> R$ and a cover I of its image by intervals, the Mapper is the nerve of a refinement of the pullback cover $f^{-1}(I)$. 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. In [16] we propose a theoretical framework relating the structure of the Mapper to that 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 I goes to zero.

7.4. Experimental research and software development

7.4.1. Stride detection for pedestrian trajectory reconstruction: a machine learning approach based on geometric patterns

Participants: Frédéric Chazal, Bertrand Michel, Bertrand Beaufils.

In collaboration with M. Grelet (Sysnav)

A strides detection algorithm is proposed using inertial sensors worn on the ankle. This innovative approach based on geometric patterns can detect both normal walking strides and atypical strides such as small steps, side steps and backward walking that existing methods struggle to detect. It is also robust in critical situations, when for example the wearer is sitting and moving the ankle, while most algorithms in the literature would wrongly detect strides.

DIANA Project-Team

6. New Results

6.1. Service Transparency

6.1.1. On active sampling of controlled experiments for QoE modeling

Participants: Muhammad Jawad Khokhar, Nawfal Abbasi Saber, Thierry Spetebroot, Chadi Barakat.

For internet applications, measuring, modeling and predicting the quality experienced by end users as a function of network conditions is challenging. A common approach for building application specific Quality of Experience (QoE) models is to rely on controlled experimentation. For accurate QoE modeling, this approach can result in a large number of experiments to carry out because of the multiplicity of the network features, their large span (e.g., band-width, delay) and the time needed to setup the experiments themselves. However, most often, the space of network features in which experimentations are carried out shows a high degree of uniformity in the training labels of QoE. This uniformity, difficult to predict beforehand, amplifies the training cost with little or no improvement in QoE modeling accuracy. So, in this work, we aim to exploit this uniformity, and propose a methodology based on active learning, to sample the experimental space intelligently, so that the training cost of experimentation is reduced. We prove the feasibility of our methodology by validating it over a particular case of YouTube streaming, where QoE is modeled both in terms of interruptions and stalling duration. This first validation has appeared in [19]. In another paper which is currently under submission, we propose an online version of this methodology together with a set of criterion to stop the experiments when the learner is confident enough.

6.1.2. On the Cost of Measuring Traffic in a Virtualized Environment

Participants: Karyna Gogunska, Chadi Barakat, Guillaume Urvoy-Keller, Dino Lopez Pacheco.

The current trend in application development and deployment is to package applications and services within containers or virtual machines. This results in a blend of virtual and physical resources with complex interconnection network schemas mixing virtual and physical switches along with specific protocols to build virtual networks spanning over several servers. While the complexity of this set-up is hidden by private/public cloud management solutions, e.g. OpenStack, this constitutes a challenge when it comes to monitor and debug performance related issues. In this work, carried out in collaboration with the Signet team of I3S with the support of the UCN@SOPHIA Labex, we introduce the problem of measuring traffic in a virtualized environment and focus on one typical scenario, namely virtual servers interconnected with a virtual switch. For this scenario, we assess the cost of continuously measuring the network traffic activity of the machines. Specifically, we seek to estimate the competition that exists to access the physical resources (CPU, memory, etc.) of the physical substrate between the measurement task and the legacy application activity. The results of this first study are currently under submission.

6.1.3. LISP measurements

Participant: Damien Saucez.

The Locator/Identifier Separation Protocol (LISP) separates classical IP addresses into two categories: one for identifying terminals, the other for routing. To associate identifiers and locators LISP needs a specific mechanism, called mapping system. This technology is still at an early stage but two experimental platforms have already been deployed in the Internet: LISP Beta Network and LISP-Lab. However, only the LISP Beta Network is monitored with LISPmon that partially monitors the mapping system once a day. To accompany the growth of LISP, a dynamic and complete monitoring system is required. Therefore, we propose LISP-Views, a dynamic versatile large scale LISP monitoring architecture. LISP-Views allows to automatically conduct comprehensive and objective measurements. After running LISP-Views in the wild for several months and comparing the monitoring results with LISPmon, we confirm that LISP-Views provides more detailed and accurate information. We observe the different behaviours between every network entity within mapping system, and also explore the current LISP performance for further improvements. A paper on "LISP-Views Monitoring LISP at Large Scale" was published in ITC this year.

6.2. Open Network Architecture

6.2.1. Controller load in SDN networks

Participant: Damien Saucez.

In OpenFlow, a centralized programmable controller installs forwarding rules into switches to implement policies. However, this flexibility comes at the expense of extra overhead in signalling and number of rules to install. The community considered that it was essential to install all rules and strictly respect routing requirements, hence working on making extra fast and large memory switches and controllers. Instead we took an opposite direction and came with a new vision that leverages the SDN concept and considers the network as a black box where tailored rules should be used only for network traffic that really matters while for the rest a good-enough (sub-optimal but cheap) default behaviour should be enough. In the past, we applied this vision to limit the needed memory on network switches in [5]. Lately, we proposed solutions to limit the number of exchanged messages between the switches and the controller. More precisely, in [31], [16] we developed a distributed sampling adaptive algorithm that allows switches to locally decide if they can contact the controller or if instead they should make their own decision locally. Numerical evaluation and emulation in Mininet demonstrate the benefit of the approach. The results were published in the PGMO (Gaspard Monge Program for Optimisation) days, Nov 2017, Paris, France.

6.2.2. 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.

6.2.3. Message Dissemination in Intelligent Transport Systems

Participant: Thierry Turletti.

We proposed D2-ITS, a flexible and extensible framework to dynamically distribute network control to enable message dissemination in Intelligent Transport Systems (ITS). By decoupling the control from the data plane, D2-ITS leverages network programmability to address ITS scalability, delay intolerance and decentralization. It uses a distributed control plane based on a hierarchy of controllers that can dynamically adjust to environment and network conditions in order to satisfy ITS application requirements. We demonstrate the benefits of D2-ITS through a proof-of-concept prototype using the ns-3 simulation platform. Results indicate lower message delivery latency with minimal additional overhead. This work has been presented at the IEEE/ACM Symposium on Distributed Simulation and Real Time Applications (DS-RT) in October 2017 [18].

6.2.4. Peer-assisted Information-Centric Network

Participant: Thierry Turletti.

Information-Centric Networking (ICN) is a promising solution for most of Internet applications where the content represents the core of the application. However, the proposed solutions for the ICN architecture are associated with many complexities including pervasive caching in the Internet and incompatibility with legacy IP networks, so the deployment of ICN in real networks is still an open problem. In this work, we proposed a backward compatible ICN architecture to address the caching issue in particular. The key idea is implementing edge caching in ICN, using a coalition of end clients and edge servers. Our solution can be deployed in IP networks with HTTP requests. We performed a trace-driven simulation for analyzing PICN benefits using IRCache and Berkeley trace files. The results showed that in average, PICN decreases the latency for 78% and increases the content retrieval speed for 69% compared to a direct download from the original web servers. When comparing PICN with a solution based on central proxy servers, we showed that the hit ratio obtained using a small cache size in each PICN client is almost 14% higher than the hit ratio obtained with a central proxy server using an unlimited cache storage. This work has been published in the IEEE Access journal [14].

6.2.5. Streaming using In-Network Coding and Caching

Participant: Thierry Turletti.

With the rapid growth in high-quality video streaming over the Internet, preserving high-level robustness against data loss and low latency, while maintaining higher data transmission rates, is becoming an increasingly important issue for high-quality real-time delay-sensitive streaming. We have proposed a low latency, low loss streaming mechanism, L4C2, specialized for high-quality delay-sensitive streaming. Using L4C2, nodes in a network estimate the acceptable delay and packet loss probability in their uplinks, aiming at retrieving lost data packets from in-network cache and/or coded data packets using in-network coding within an acceptable delay, by extending the Content-Centric Networking (CCN) approach. Further, L4C2 naturally provides multiple path and multicast technologies to efficiently utilize network resources while sharing network resources fairly with competing data flows by adjusting the video quality as necessary. We validate through comprehensive simulations that L4C2 achieves a high success probability of data transmission considering the acceptable one-way delay and outperforms the existing solution. This work has been presented at the IEEE Infocom conference in May 2017 [23].

6.2.6. 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 designed 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 proposed 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 has been used to study the performance of L2BM. This work has been presented at the IEEE ICC conference [24] in May 2017 and an extended version has been published to the IEEE TNSM journal [13].

6.2.7. Placement of Virtual Network Function Chains in 5G

Participants: Osama Arouk, Thierry Turletti.

We proposed a novel algorithm, namely Multi-Objective Placement (MOP), for the efficient placement of Virtualized Network Function (VNF) chains in future 5G systems. Real datasets are used to evaluate the performance of MOP in terms of acceptance ratio and embedding time when placing the time critical radio access network (RAN) functions as a chain. In addition, we rely on a realistic infrastructure topology to assess the performance of MOP with two main objectives: maximizing the number of base stations that could be embedded in the Cloud and load balancing. The results reveal that the acceptance ratio of embedding RAN functions is only 5% less than the one obtained with the optimal solution for the majority of considered scenarios, with a speedup factor of up to 2000 times. This work has been presented at the IEEE CloudNet conference in September 2017 [17].

6.2.8. P4Bricks: Enabling multiprocessing using Linker-based network data plane architecture

Participants: Hardik Soni, Thierry Turletti, Walid Dabbous.

In order to realize NFV-based multicast service as an add-on network capability without having knowledge of implementation level details of other network functions, we proposed a novel data plane architecture, P4Bricks, for modularized control and packet processing in the network... We propose P4Bricks, a system which aims to deploy and execute multiple independently developed and compiled P4 programs on the same reconfigurable hardware device. P4Bricks is based on a Linker component that merges the programmable parsers/deparsers and restructures the logical pipeline of P4 programs by refactoring, decomposing and scheduling the pipelines' tables. It merges P4 programs according to packet processing semantics (parallel or sequential) specified by the network operator and runs the programs on the stages of the same hardware pipeline, thereby enabling multiprocessing. A paper presenting the initial design of our system with an ongoing implementation and studies P4 language's fundamental constructs facilitating merging of independently written programs was submitted to SOSR and publisehd as a research report [37].

6.2.9. Vehicles as a Mobile Cloud: Modelling, Optimization and Performance Analysis

Participants: Luigi Vigneri, Thrasyvoulos Spyropoulos, Chadi Barakat.

The large diffusion of handheld devices is leading to an exponential growth of the mobile traffic demand which is already overloading the core network. To deal with such a problem, several works suggest to store content (files or videos) in small cells or user equipments. In this work, done in collaboration with Eurecom with the support of the UCN@SOPHIA Labex, we push the idea of caching at the edge a step further, and we propose to use public or private transportation as mobile small cells and caches. In fact, vehicles are widespread in modern cities, and the majority of them could be readily equipped with network connectivity and storage. The adoption of such a mobile cloud, which does not suffer from energy constraints (compared to user equipments), reduces installation and maintenance costs (compared to small cells). In our work, a user can opportunistically download chunks of a requested content from nearby vehicles, and be redirected to the cellular network after a deadline (imposed by the operator) or when her playout buffer empties. The main goal of the work is to suggest to an operator how to optimally replicate content to minimize the load on the core network. Our main contributions are: (i) Modelling: We model the above scenario considering heterogeneous content size, generic mobility and a number of other system parameters. (ii) Optimization: We formulate some optimization problems to calculate allocation policies under different models and constraints. (iii) Performance analysis. We build a MATLAB simulator to validate the theoretical findings through real trace-based simulations. We show that, even with low technology penetration, the proposed caching policies are able to offload more than 50 percent of the mobile traffic demand. The results of this work has been published in several papers, and are currently the subject of two submissions to journals. In particular, in [25] we consider the case of per-chunk caching for video streaming, whereas in [26] we consider the case of Quality of Experience-aware caching of files where the Quality of Experience is modeled as the slowdown in the file download time. A thorough presentation of this work and of our contributions can be found in the PhD thesis of Luigi Vigneri defended in July 2017 and available at [12].

6.3. Experimental Evaluation

6.3.1. The Reproducibility'17 workshop

Participant: Damien Saucez.

Recently, the ACM highlighted that the lack of reproducibility tended to be general in computer science and proposed normalised artifact reviewing and badging definitions [0] with the hope that the various ACM communities would perform artifact reviews based on these definition. We organized a special workshop on reproducibility in conjunction with the ACM SIGCOMM 2017 conference to produce a set of recommendations on how to assess the reproducibility of research published in ACM SIGCOMM'related conferences and journals and ways to promote reproducibility. The proceedings of the workshop is available in [27] and we have produced a set of recommendations to the community in [34] with the following conclusions:

The workshop pointed out that there are several hurdles concerning reproducibility, namely the absence of incentives and the bad habit that our community has grown accustomed to. This is evident in the current typical review process which is not adapted to handle reproducibility. Furthermore, there is no general way to share and preserve artifacts (and related documentation), every author does it in their own way.

The workshop focused on the two most important points to be tackled, namely, i) how to provide incentives for reproducible papers and ii) how to share artifacts.

For the first, a promising approach is to put in place a Reproducibility Committee, which will run in parallel with the normal Technical Program Committee of conferences and workshops, which will assess the level of reproducibility of papers accepted for publication by the TPC. Such approach will solve some of the privacy and anonymity issues while reducing the volume of work for the reviewers that volunteer in assessing the reproducibility level.

For the second, a gradual approach has been suggested. The ACM digital library has been suggested as place to start sharing artifacts, which will be also identified via a DOI number. Beside the artifact itself it is important to share all of the meta-information necessary to actually reproduce prior work, as well as a way to provide feedback in order to make the community learn which meta-information is actually important and build guidelines on how to provide such information.

6.3.2. Towards Realistic Software-Defined Wireless Networking Experiments

Participants: Mohamed Naoufal Mahfoudi, Walid Dabbous, Thierry Turletti.

Software-Defined Wireless Networking (SDWN) is an emerging approach based on decoupling radio control functions from the radio data plane through programmatic interfaces. Despite diverse ongoing efforts to realize the vision of SDWN, many questions remain open from multiple perspectives such as means to rapid prototype and experiment candidate software solutions applicable to real world deployments. To this end, emulation of SDWN has the potential to boost research and development efforts by re-using existing protocol and application stacks while mimicking the behavior of real wireless networks. In this work, we provided an in-depth discussion on that matter focusing on the Mininet-WiFi emulator design to fill a gap in the experimental platform space. We showcased the applicability of our emulator in an SDN wireless context by illustrating the support of a number of use cases aiming to address the question on how far we can go in realistic SDWN experiments, including comparisons to the results obtained in a wireless testbed. Finally, we discussed the ability to replay packet-level and radio signal traces captured in the real testbed towards a virtual yet realistic emulation environment in support of SDWN research. This works has been published in a Special Issue on Software Defined Wireless Networks of the Computer Journal [15].

6.3.3. 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 finegrained 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

[0] Artifact Review and Badging, https://www.acm.org/publications/policies/artifact-review-badging, December 2017

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 presented at a IEEE specialized workshop on Network Localization on Navigation [22].

6.3.4. Lessons Learned while Trying to Reproduce the OpenRF Experiment

Participants: Mohamed Naoufal Mahfoudi, Thierry Turletti, Thierry Parmentelat, Walid Dabbous.

Evaluating and comparing performance of wireless systems, like for any other scientific area, requires the ability to reproduce experimental results. In this work, we described the specific issues that we encountered when focusing on reproducing the experiments described in a paper related to wireless systems. We selected the OpenRF paper published in SIGCOMM 2013, a very interesting research work allowing to perform beamforming on commodity WiFi devices. We illustrated how reproducibility is strongly dependent on the used hardware, and why an extensive knowledge of the used hardware and its design is necessary. On the basis of this experience, we proposed some recommendations and lessons for the design of reproducible wireless experiments. This work has been presented at the ACM SIGCOMM 2017 Reproducibility Workshop in August 2017 [21].

6.3.5. Deploying a 5G network in less than 5 minutes

Participants: Mohamed Naoufal Mahfoudi, Thierry Parmentelat, Thierry Turletti, Walid Dabbous.

We proposed a demonstration run on R2lab, an anechoic chamber located at Inria Sophia Antipolis, France. This demonstration consists in deploying a standalone 5G network in less than 5 minutes. All the network components (base station, subscriber management, serving and packet gateways, network traac analyzers) were run automatically using the nepi-ng experiment orchestration tool. Download and upload performance to the Internet from a commercial phone located in the anechoic chamber are shown. This demo has been presented at the ACM SIGCOMM conference in August 2017 [33].

ECUADOR Project-Team

6. New Results

6.1. Towards Algorithmic Differentiation of C++

Participants: Laurent Hascoët, Benoit Dufumier, Frederic Cazals [ABS team, Inria Sophia-Antipolis], Louis Becquey [ABS team, Inria Sophia-Antipolis], Valérie Pascual.

We started the extension of Tapenade for C++. This year's first step is to connect an external C++ parser to the input formalism of Tapenade: IL. IL is an abstract language that contains the usual constructs of imperative languages. For example, the three existing parsers for Tapenade (Fortran, Fortran 95, and C) all produce Tapenade input in the form of an IL tree. Our goal was therefore to select a C++ parser or front-end and to make it produce IL trees. In parallel, our goal was also to identify the new operators, specific to Object-Oriented languages, that we must add to IL to capture C++ codes.

During their summer internship, students Benoit Dufumier from SUPELEC and Louis Becquey from INSA Lyon have drafted a C++ front-end for Tapenade, based on the tool "Clang-LLVM". They also added the new operators required into IL, and started the developments in Tapenade to manage them. At present, Tapenade is still unable to differentiate a C++ code, but it can parse and analyze a few toy C++ codes. Still, the latest release 3.13 of Tapenade does not provide any meaningful result for C++ codes yet. This work is going on.

This work benefited from the expertise in C++ of Frederic Cazals (Inria ABS team). Frederic Cazals jointly supervised both students during their internship, funded by the local Inria programme "masters transverses". The ABS team also provided the first C++ test codes and will eventually provide a large application code for Molecular Dynamics.

6.2. AD of mixed-language codes

Participants: Valérie Pascual, Laurent Hascoët.

The tangent differentiated code of Calculix (Three-Dimensional Structural Finite Element code), has been built and validated. Adjoint Differentiation in in progress. Driven by this application to Calculix, Tapenade is now able to differentiate mixed-language source that uses either the old style conventions or the newer Fortran 2003 primitives for interoperability with C.

Unsurprisingly, an application to such a large code uncovered a few limitations of our AD tool. One was a faulty treatment of C translation units (i.e. files), which is now fixed. C translation units or Fortran modules are two instances of the more general notion of "package" for which we need to develop more generic support in Tapenade.

6.3. 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 to provide reliable adjoint differentiation of C, and for our distant goal of AD of C++. This research is conducted in collaboration with the MCS department of Argonne National Lab. Our partnership is formalized by joint participation in the Inria joint lab JLESC, and partly funded by the Partner University Fund (PUF) of the French embassy in the USA.

Adjoint AD must reproduce in reverse order the control decisions of the original code. In languages such as C, allocation of dynamic memory and pointer management form a significant part of these control decisions. Reproducing memory allocation in reverse means reallocating memory, possibly receiving a different memory chunk. Reproducing pointer addresses in reverse thus 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, the ADMM library has been improved, and its API has been redesigned to be called from both C and Fortran. The architecture of ADMM has also been simplified, removing circular dependencies with other parts of Tapenade. The latest release 3.13 of Tapenade automatically places calls to ADMM where needed, whether the application language is C or Fortran 95. Since ADMM is a C library, the differentiated code in the Fortran case uses the Fortran 2003 standardized interoperability primitives.

In parallel, we improved the Tapenade adjoint of the "ALIF" code. ALIF 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 challenge is the intensive use of dynamic memory in ALIF, following the programming style of its model C++ code ISSM. Although sucessful, the usage of the ADMM library incurred some overhead. We developed a static data-flow analysis to reduce the number of calls to ADMM. This work is discussed in an article published in journal "Optimization Methods and Software"[14]

6.4. Application to large industrial codes

Participants: Valérie Pascual, Laurent Hascoët, Nicole Goutal [EDF-LNHE], Andrea Piacentini [CERFACS-GLOBC], Charlotte Kotas [Oak Ridge National Lab. (Tennessee, USA)].

We support industrial users with their first experiments of Algorithmic Differentiation of large in-house codes.

A previous collaboration with EDF and CERFACS has been continued by a new three-months contract, with the objective of improving the AD adjoint of the hydrodynamic code Mascaret. The tangent and adjoint differentiated codes have been built for the calculation of steady subcritical flow ("Sarap" kernel) with the latest Mascaret Version 8.1. The differentiation process has been simplified and it exploits the latest capacities of Tapenade on Fortran 95. In particular, the differentiated code manages Fortran 95 dynamic memory through our library ADMM. Connection with the C-written ADMM uses the Fortran 2003 standardized interoperability primitives. Validation was conducted on two test cases (named "Garonne" and "Oraison").

We support AD experiments taking place at Oak Ridge National Laboratory, targetted at building the adjoint of a large CFD application called "Rex". After one year of collaboration, we reached a first milestone with a working tangent differentiation of a sequential (i.e. non MPI) version of the code. Differentiation in tangent mode is significantly easier than in adjoint mode. Therefore it is a good practice to differentiate first in tangent mode even when the final goal is to produce gradients, which require adjoint mode. Moreover, a validated tangent code is very helpful to validate and debug an adjoint code. The next step will be extension to the MPI-parallel version of the code. This will exploit and develop the AMPI library, co-developped with Argonne National Lab, for automated differentiation of MPI communication routines.

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 collaboration with university of Montpellier, a novel multirate method using cell agglomeration has been designed and developed in our AIRONUM CFD platform. A series of large-scale test cases show that the new method is much more efficient than an explicit method, while retaining a similar time accuracy over the whole computational domain. The comparison with an implicit scheme shows that the implicit scheme is in most cases one order less accurate due to higher time steps and higher dissipation. For the applications to massively parallel computing, an accurate study has been undertaken in order to analyse the impact of the mesh partitioning on the parallel efficiency. Three options have been considered. The usual partition, minimizing communication under the unique constraint of uniform load over the whole domain is optimal for a part of the algorithm but performs very poorly for the other part. We have also applied the multi-constraint partitioning of Metis which relies on both whole domain balancing and fine-mesh subdomain balancing. This strategy significantly improves the efficiency, but we observed that the balancing of the whole domain phase was not perfect. A third set of experiments relied on a geometrical-based optimal multi-contraint partition which we could apply to most of our geometries and which gave a notable further improvement. An article is submitted to a journal on the basis of the second part of the thesis of Emmanuelle Itam.

6.6. Control of approximation errors

Participants: Eléonore Gauci, Alain Dervieux, Adrien Loseille [Gamma3 team, Inria-Rocquencourt], Frédéric Alauzet [Gamma3 team, Inria-Rocquencourt], Anca Belme [university of Paris 6], Gautier Brèthes [university of Montreal], Alexandre Carabias [Lemma].

Reducing approximation errors as much as possible is a particular kind of optimal control problem. We formulate it exactly this way when we look for the optimal metric of the mesh, which minimizes a user-specified functional (goal-oriented mesh adaptation). In that case, the usual methods of optimal control apply, using adjoint states that can be produced by Algorithmic Differentiation.

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.

During this year, two works, one on the tensorial metric method started during the thesis of Gautier Brèthes [12], and one on mesh adaptation for third order approximation [13], were completed and published in journals.

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) has been submitted to a Journal.

6.7. Turbulence models

Participants: Alain Dervieux, Bruno Koobus, Stephen Wornom, Maria-Vittoria Salvetti [University of Pisa].

Modeling turbulence is an essential aspect of CFD. The purpose of our work in hybrid RANS/LES (Reynolds Averaged Navier-Stokes / Large Eddy Simulation) is to develop new approaches for industrial applications of LES-based analyses. In the applications targetted (aeronautics, hydraulics), the Reynolds number can be as high as several tens of millions, far too high for pure LES models. However, certain regions in the flow can be predicted better with LES than with usual statistical RANS (Reynolds averaged Navier-Stokes) models. These are mainly vortical separated regions as assumed in one of the most popular hybrid models, the hybrid Detached Eddy Simulation model. Here, "hybrid" means that a blending is applied between LES and RANS. An important difference between a real life flow and a wind tunnel or basin is that the turbulence of the flow upstream of each body is not well known.

The development of hybrid models, in particular DES in the litterature, has raised the question of the domain of validity of these models. According to theory, these models should not be applied to flow involving laminar boundary layers (BL). But industrial flows are complex flows and often present regions of laminar BL, regions of fully developed turbulent BL and regions of non-equilibrium vortical BL. It is then mandatory for industrial use that the new hybrid models give a reasonable prediction for all these types of flow. We concentrated on evaluating the behavior of hybrid models for laminar BL and for vortical wakes. While less predictive than pure LES on laminar BL, some hybrid models still give reasonable predictions for rather low Reynolds numbers. 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. This model can be hybridized with a RANS model with some positive outputs. It can also be hybridized with a DDES model with larger benefits. The prediction is better than with RANS and also better than with a pure DDES model. A communication has been presented in the DLES11 conference [15] and an extended article from a conference held last year in Strasbourg has been written (with 2018 results), submitted and accepted for publication in a Springer book entitled “Progress in Hybrid RANS-LES Modelling”(2018).

FOCUS Project-Team

7. New Results

7.1. Service-Oriented Computing

Participants: Mario Bravetti, Maurizio Gabbrielli, Saverio Giallorenzo, Claudio Guidi, Ivan Lanese, Cosimo Laneve, Fabrizio Montesi, Davide Sangiorgi, Gianluigi Zavattaro.

7.1.1. Microservices

Microservices represent an architectural style inspired by service-oriented computing that has recently started gaining popularity. As we have discussed in [37], one of the main advantages of the microservices approach is that it improves scalability of the developed applications. In [43] we have analyzed the impact of microservices on the overall line of research on software architectures, by pointing out specific open problems and future challenges. One of the challenges is concerned with programming languages because microservice systems are currently developed using general-purpose programming languages that do not provide dedicated abstractions for service composition. In [46] we have discussed the limitations of the current practices and we have proposed a novel language-based approach to the engineering of microservices based on the Jolie programming language.

7.1.2. Orchestrations and choreographies

The practice of programming distributed systems is extremely error-prone, due to the complexity in correctly implementing separate components that, put together, enact an agreed protocol. Theoretical and applied research is, therefore, fundamental, to explore new tools to assist the development of such systems. In particular, usage of so-called session types in orchestration languages guarantees correct communication by means of corresponding type system theories. In this context, we carried out studies about: foundations of the classical theory of session types, by providing an encoding into pi-calculus typing [17]; and subtyping in the context of asynchronous communication, showing it to be an undecidable problem [15]. Choreographies are also an important specification tool in that they can be compiled to obtain projected orchestrations that enjoy deadlock freedom by construction. Moreover they allow one to express dynamic behaviours at the level of the whole system, which then reflect on each involved orchestration. In this context, in [16] we studied the theory and implementation of dynamic choreographies and in [45] we showed how to use them for programming microservice-based applications. Finally, we considered applications in the context of Mobility-as-a-Service (MaaS) scenarios, where solutions of different transportation providers are dynamically composed into a single, consistent interface. We devised the prototype of an enabling software platform for MaaS [27] and we studied MaaS security issues [28].

7.2. Models for Reliability

Participant: Ivan Lanese.

7.2.1. Reversibility

We have continued the study of reversibility started in the past years. In particular, in [19], we thoroughly studied causal-consistent reversibility in the coordination language μKlaim [50], a distributed version of Linda [49]. More specifically, we gave an abstract specification of a causal-consistent rollback operator and showed that our semantics satisfies it. The main novelty of μKlaim w.r.t. process calculi studied in past work is that it includes a primitive to read a datum without consuming it, that, from the causality point of view, creates asymmetric dependencies. The same technique could be used to reverse languages with shared memory.

In [24] we studied how to exploit reversibility to improve client-server interactions. In particular, we defined retractable contracts, namely contracts including the possibility of undoing past agreements, which are more expressive than standard session contracts for binary interactions [48], yet preserve their nice properties: compliance and the subcontract relation are both decidable in polynomial time, the dual of a contract always exists and has a simple syntactic characterization. Furthermore we showed that the same contracts can also describe speculative interactions.

7.3. Probabilistic Systems and Resource Control

Participants: Martin Avanzini, Raphaelle Crubillé, Ugo Dal Lago, Francesco Gavazzo, Charles Grellois, Davide Sangiorgi, Valeria Vignudelli.

7.3.1. Probabilistic termination

In Focus, we are interested in studying probabilistic higher-order programming languages and, more generally, the fundamental properties of probabilistic computation when placed in an interactive scenario. One of the most basic (but nevertheless desirable) properties of programs is certainly termination. When probabilistic choice comes into play, termination can be defined in more than one way. As an example, one can stipulate that a probabilistic program terminates if and only if its probability of convergence is 1, this way being *almost surely* terminating. Alternatively, a probabilistic program can be said to be *positively* almost surely terminating if its average runtime is finite. The latter condition easily implies the former. Termination, already undecidable for deterministic (universal) programming languages, remains so in presence of probabilistic choice. Actually, it becomes provably harder, being strictly higher in the arithmetical hierarchy. Probabilistic termination has received quite some attention in recent years, but most contributions are concerned either with its abstract nature, or with verification methodologies for imperative programs. Along 2017, we have initiated the study of probabilistic termination in probabilistic higher-order functional languages. Our contribution in this direction is twofold. On the one hand, we have analysed the impact of endowing a strongly normalising typed lambda calculus, namely Godel's **T**, with various forms of probabilistic choice operators [26]. Unsurprisingly, the obtained systems are all almost surely terminating, but interestingly, only *some* of them are positively so. In particular, binary probabilistic choice and the geometric distribution can have dramatically different effects. Another line of work has to do with types, and in particular with sized types, which we have generalised to a higher-order functional language with higher order recursion and binary probabilistic programs. We showed how the obtained system is sound for almost sure termination [35], but also that it captures interesting examples like various forms of random walks.

7.3.2. Automating complexity analysis of higher-order functional programs

Complexity analysis of higher-order functional programs has been one of the core research directions within Focus since its inception. Progressively, however, our interest has shifted from foundations to automation. The latter is indeed the main research direction we have pursued in 2017. More specifically, we have been trying to overcome the main shortcoming of our software tool HoCA, namely the fact that most analysis techniques it implements are not modular, and are thus bound not to scale. We have looked at sized type systems as a way to do complexity analysis of functional programs by performing type inference on a so-called ticking-transformed version of them [13]. The obtained design methodology has been proved to allow the analysis of programs which could not be handled by HoCA.

7.3.3. Relational reasoning about effectful and concurrent programs

Building on our knowledge on semantic and coinductive techniques for reasoning about higher-order programs, we have studied how to reason relationally when the programs at hand exhibit some form of effect including probabilistic choice, but also algebraic effects. We have first of all concluded our investigation about metric reasoning about terms in a probabilistic lambda calculus. We discovered that in the general case of a fully-fledged probabilistic lambda calculus, any reasonable metric is bound to trivialise to an equivalence [31]. This negative result convinced us that a richer and more refined notion of comparison is needed, on which we are currently investigating. We also looked at how Abramsky's applicative bisimilarity can be generalised to a language with algebraic effects. Since the notion of algebraic effect is abstract, this is best done by injecting concepts from category theory, and in particular those of a monad and of a relator, into the playground. Mild conditions on the latter allow one to generalise the classic proof of congruence for applicative bisimilarity, due to Howe [33], [34]. This way, conductive proof techniques for equivalence can be shown sound with respect to context equivalence for various forms of algebraic effects including probabilistic choice, global state, exceptions, and combinations. One last line of work we have pursued in 2017 has to do with geometry of interaction, a dynamic semantic framework which is known to faithfully model higher-order computation. We have this year managed to show that multitoken machines, a generalisation of geometry of interaction we introduced three years ago, can faithfully model quantum lambda calculi [32], but also process algebras like the π-calculus, through multiport interaction combinators [14].

7.4. Verification Techniques

Participants: Mario Bravetti, Adrien Durier, Daniel Hirschkoff, Ivan Lanese, Cosimo Laneve, Davide Sangiorgi.

We analyze sensible properties of concurrent systems, including deadlock freedom and resource usages, and proof techniques for deriving behavioural equalities and preorders on processes.

7.4.1. Deadlock detection and cloud elasticity

In order to verify sensible properties of concurrent programs we use a technique consisting of (1) extracting information by means of behavioural type systems and (2) analyzing types by means of ad-hoc tools.

In [20] we study deadlock detection for value-passing CCS (and for π calculus). In this paper we analyze complex programs that create networks with arbitrary numbers of nodes. To enable the analysis of such programs, (1) we define an algorithm for detecting deadlocks of a basic model featuring recursion and fresh name generation, and (2) we design a type system that returns behavioural types. We show the soundness of the type system, and develop a type inference algorithm for it.

In [39] we apply the above technique to a language for stateful active objects. This is challenging because active objects use futures to refer to results of pending asynchronous invocations and because these futures can be stored in object fields, passed as method parameters, or returned by invocations. The type system traces the access to object fields by means of effects. For this reason, it is possible to compute behavioural types that express synchronisation patterns in a precise way. The behavioural types are thereafter analysed by a solver that discovers potential deadlocks. The PhD thesis of Vincenzo Mastandrea [11] addresses deadlock detection of stateful active objects.

In [44] we apply the same technique to Java byte-code. In particular [44] gives a practical presentation of JaDA, a static deadlock analyzer for Java that extracts behavioral types and analyzes these types by means of a fixpoint algorithm that reports potential deadlocks in the original Java code. We also present some of the features for customising the analysis: while the main strength of JaDA is to run in a fully automatic way, user interaction is possible and may enhance the accuracy of the results. The whole theory behind JaDa is fully developed in the PhD thesis of Abel Garcia Celestrin [10].

In [18] we address a concurrent language with explicit acquire and release operations on virtual machines. In our language it is possible to delegate other (ad-hoc or third party) concurrent code to release virtual machines (by passing them as arguments of invocations). In this case, we define (i) a type system associating programs with behavioural types that record relevant information for resource usage (creations, releases, and concurrent operations), (ii) a translation function that takes behavioural types and returns cost equations, and (iii) an automatic off-the-shelf solver for the cost equations. A soundness proof of the type system establishes the correctness of our technique with respect to the cost equations. We have experimentally evaluated our technique using a cost analysis solver. The experiments show that our analysis allows us to derive bounds for programs that are better than other techniques, such as those based on amortized analysis.

7.4.2. Most general property-preserving updates

Systems need to be updated to last for a long time in a dynamic environment, and to cope with changing requirements. It is important for updates to preserve the desirable properties of the system under update, while possibly enforcing new ones. We consider a simple yet general update mechanism [25] that replaces a component of the system with a new one. The context, i.e., the rest of the system, remains unchanged. We define contexts and components as Constraint Automata interacting via either asynchronous or synchronous communication, and we express properties using Constraint Automata too. Then we build most general updates which preserve specific properties, considering both a single property and all the properties satisfied by the original system, in a given context or in all possible contexts.

7.4.3. Proof techniques based on unique solutions

In [22], we study bisimilarity, a behavioural equivalence whose success is much due to the associated bisimulation proof method. In particular, we discuss a different proof method, based on unique solution of special forms of inequations called contractions, and inspired by Milner's theorem on unique solution of equations. The method is as powerful as the bisimulation proof method and its up-to context enhancements. The definition of contraction can be transferred onto other behavioural equivalences, possibly contextual and non-coinductive. This enables a coinductive reasoning style on such equivalences, either by applying the method based on unique solution of contractions, or by injecting appropriate contraction preorders into the bisimulation game.

In [38] we develop the above proof method in a different direction: rather than introducing contractions, we remain within equations, and we investigate conditions that guarantee unique solutions, for bisimilarity as well as for other behavioural equivalences such as trace equivalence. We also consider preorders such as trace inclusion. We finally develop abstract formulations of the theorems, on generic Labeled Transition Systems.

7.4.4. Fuzzy logics

In [14] we introduce a framework for detecting anomalies in the clocks of the different components of a network of sensor stations connected with a central server for measuring air quality. We propose a novel approach, supported by a formal representation of the network using fuzzy-timed automata, to precisely represent the expected behaviour of each component of the network. Using fuzzy logic concepts, we can specify admissible mismatches between the clocks.

7.5. Computer Science Education

Participants: Michael Lodi, Simone Martini.

We study why and how to teach computer science principles (nowadays often referred to as "computational thinking", CT), in particular in the context of K-12 education (students aged approximately from 5 to 18). We study philosophical, sociological and historical motivations to teach computer science at all school levels. Furthermore, we study what concepts and skills related to computer science are not barely technical abilities, but have a general value for all students. Finally we try to find/produce/evaluate suitable materials (tools, languages, lesson plans...) to teach these concepts, taking into account: difficulties in learning CS concepts (particularly programming); stereotypes about computer science (particularly gender related issues); teacher training (particularly non specialist teachers).

7.5.1. Computational thinking definition

There is no accepted definition of computational thinking. From one hand we tried to find out the main common elements in the most important proposed definitions, and investigate, in a large sample of K-12 teachers, if they have a correct idea [30] about CT. We found the vast majority of them held misconceptions or partial views about it. We argued these may be consequences of a massive use of the term in school context [23]; we made clear “computational thinking” is not a new subject, but just a name to indicate computer science principles that should be taught to all students [21].

7.5.2. Evaluation of popularization initiatives

We analyzed [29] the sentiment of a large sample of teachers participating in the national project “Programma il Futuro” (Program the Future) - an italian version of Code.org with support materials. The sentiment was largely positive. Among other results, we note reported interest is equally distributed between male and female students in primary school, and shifts towards a higher male interest only from secondary school, suggesting a social influence.

7.5.3. Growth mindset and teacher training

Every person holds an idea (mindset) about intelligence: someone thinks it is a fixed trait, like eye color (fixed mindset), while others think it can grow like muscles (growth mindset). The latter is beneficial for students to have better results, particularly in STEM disciplines, and to not being influenced by stereotypes. Computer science is a subject that can be affected by fixed ideas (“geek gene”) and some (small) studies showed it can induce fixed ideas. Teachers’ mindset directly affects students’ one. We propose [42] a line of research to investigate mindset of pre-service primary school teachers before and after a “creative computing course”, to analyze and, in perspective, to change their specific “computer science mindset”.

7.6. Constraint Programming

Participants: Maurizio Gabbrielli, Liu Tong.

In Focus, we sometimes make use of constraint solvers (e.g., cloud computing, service-oriented computing). Since a few years we have thus began to develop tools based on constraints. This year, besides refining the work on SUNNY (described elsewhere, see also [40]) we have developed a new tool, NightSplitter, a scheduling tool to optimize (sub)group activities [41]. Humans are social animals and usually organize activities in groups. However, they are often willing to split temporarily a bigger group in subgroups to enhance their preferences. NightSplitter is an on-line tool that is able to plan movie and dinner activities for a group of users, possibly splitting them in subgroups to optimally satisfy their preferences. We first have modeled and proved that this problem is NP-complete. We have then used Constraint Programming (CP) or alternatively Simulated Annealing (SA) to solve it. Empirical results show the feasibility of the approach even for big cities where hundreds of users can select among hundreds of movies and thousands of restaurants. (More information on NightSplitter is found in the section on tools.)

GRAPHDECO Project-Team

6. New Results

6.1. Computer-Assisted Design with Heterogeneous Representations

6.1.1. Patterns from Photograph: Reverse-Engineering Developable Products

Participants: Adrien Bousseau.

Developable materials are ubiquitous in design and manufacturing. Unfortunately, general-purpose modeling tools are not suited to modeling 3D objects composed of developable parts. We propose an interactive tool [13] to model such objects from a photograph (Fig. 4). Users of our system load a single picture of the object they wish to model, which they annotate to indicate silhouettes and part boundaries. Assuming that the object is symmetric, we also ask users to provide a few annotations of symmetric correspondences. The object is then automatically reconstructed in 3D. At the core of our method is an algorithm to infer the 2D projection of rulings of a developable surface from the traced silhouettes and boundaries. We impose that the surface normal is constant along each ruling, which is a necessary property for the surface to be developable. We complement these developability constraints with symmetry constraints to lift the curve network in 3D. In addition to a 3D model, we output 2D patterns enabling to fabricate real prototypes of the object on the photo. This makes our method well suited for reverse engineering products made of leather, bent cardboard or metal sheets.

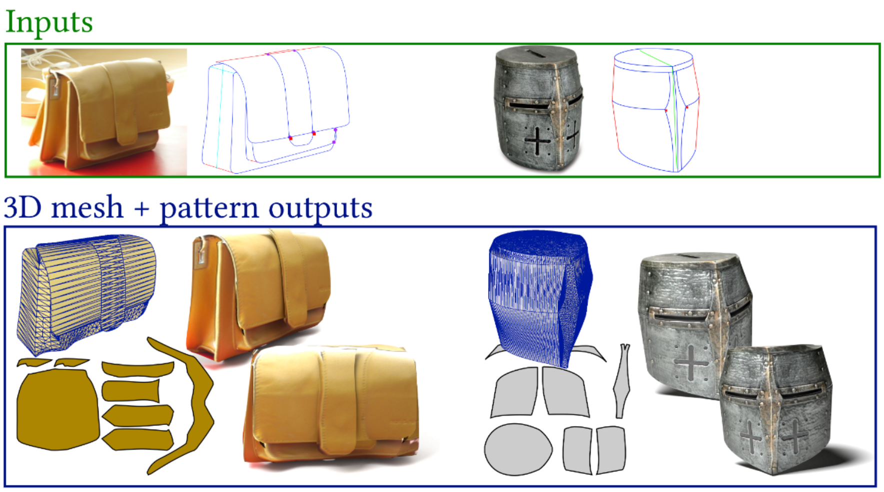


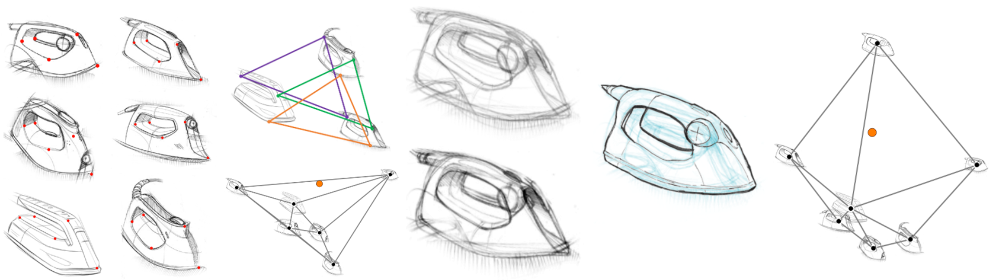
Figure 4. Given an annotated line drawing traced over the photograph of a piecewise-developable object (top), our method produces a 3D model of the visible parts of the object, and of some of the occluded parts inferred by symmetry. Our method guarantees developability of the model, as shown by the flattened patterns (bottom).

This work is a collaboration with Amélie Fondevilla, Damien Rohmer, Stefanie Hahmann and Marie-Paule Cani from the IMAGINE team at Inria Rhône Alpes. The work was published in the special issue of the journal Computers and Graphics (Elsevier), presented at the Shape Modeling International conference.

6.1.2. SketchSoup: Exploratory Ideation Using Design Sketches

Participants: 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 developed SketchSoup [7], a workflow that allows designers to explore the design space induced by such sketches (Fig. 5). We take an unstructured collection of drawings as input, along with a small number of user-provided correspondences as input. We register them using a multi-image matching algorithm, and present them as a 2D interpolation space. By morphing sketches in this space, our approach produces plausible visualizations of shape and viewpoint variations despite the presence of sketch distortions that would prevent standard camera calibration and 3D reconstruction. In addition, our interpolated sketches can serve as inspiration for further drawings, which feed back into the design space as additional image inputs. SketchSoup thus fills a significant gap in the early ideation stage of conceptual design by allowing designers to make better informed choices before proceeding to more expensive 3D modeling and prototyping. From a technical standpoint, we describe an end-to-end system that judiciously combines and adapts various image processing techniques to the drawing domain – where the images are dominated not by color, shading and texture, but by sketchy stroke contours.



(a) *Input sketch images* **(b)** *Registration (top) and interpolation space (bottom)* **(c)** *Warping (top) and non-uniform blending (bottom)* **(d)** *Oversketching* **(e)** *Augmenting the interpolation space*

Figure 5. SketchSoup takes an unstructured set of sketches as input, along with a small number of correspondences (shown as red dots)(a), registers the sketches using an iterative match-warp algorithm harnessing matching consistency across images (b, top), and embeds the sketches into a 2D interpolation space based on their shape differences (b, bottom). Users can explore the interpolation space to generate novel sketches, which are generated by warping existing sketches into alignment (c, top), followed by spatially non-uniform blending (c, bottom). These interpolated sketches can serve as underlay to inspire new concepts (d), which can in turn be integrated into the interpolation space to iteratively generate more designs (e).

This work is a collaboration with Rahul Arora and Karan Singh from Toronto University (Canada) and Ishan Darolia and Vinay P. Namboodiri from IIT Kampur (India). The work was published in the journal Computer Graphics Forum and presented at the Eurographics conference.

6.1.3. Photo2ClipArt: Image Abstraction and Vectorization Using Layered Linear Gradients

Participants: Adrien Bousseau, Jean-Dominique Favreau.

We present a method to create vector cliparts from photographs [8]. Our approach aims at reproducing two key properties of cliparts: they should be easily editable, and they should represent image content in a clean, simplified way. We observe that vector artists satisfy both of these properties by modeling cliparts with linear color gradients, which have a small number of parameters and approximate well smooth color variations. In addition, skilled artists produce intricate yet editable artworks by stacking multiple gradients using opaque and semi-transparent layers. Motivated by these observations, our goal is to decompose a bitmap photograph into a stack of layers, each layer containing a vector path filled with a linear color gradient. We cast this problem as an optimization that jointly assigns each pixel to one or more layer and finds the gradient parameters of each layer that best reproduce the input. Since a trivial solution would consist in assigning each pixel to a different, opaque layer, we complement our objective with a simplicity term that favors decompositions made of few, semi-transparent layers. However, this formulation results in a complex combinatorial problem combining discrete unknowns (the pixel assignments) and continuous unknowns (the layer parameters). We propose a Monte Carlo Tree Search algorithm that efficiently explores this solution space by leveraging layering cues at image junctions. We demonstrate the effectiveness of our method by reverse-engineering existing cliparts and by creating original cliparts from studio photographs.

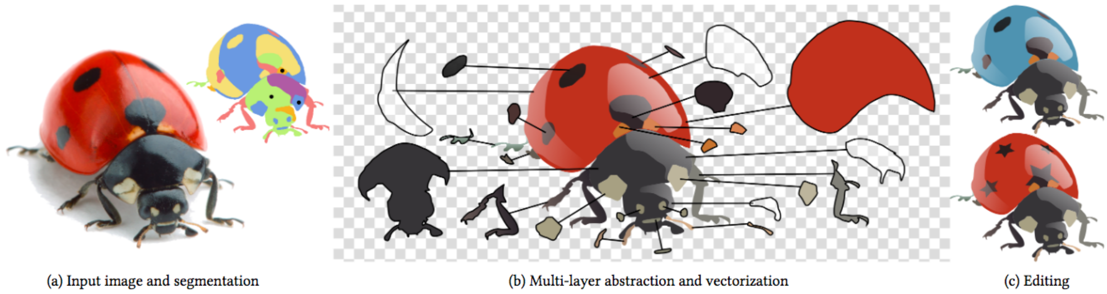


Figure 6. Given a segmented bitmap image as input (a), our method generates an abstract, layered vector clipart, where each layer is filled with an opaque or semi-transparent linear color gradient (b). By expressing the image as a stack of linear color gradients, our vector graphics reproduce the visual style of traditional cliparts and are easy to edit (c). In this example, we turned the lady bug blue (top) and replaced its dots by little stars (bottom). The black dots in the segmentation indicate opaque regions selected by the user to initialize or constrain our algorithm.

This work is a collaboration with Florent Lafarge from the Titane team at Inria Sophia Antipolis. The work was published in the journal ACM Transactions on Graphics and presented at the SIGGRAPH Asia conference.

6.1.4. Data Collection and Analysis of Industrial Design Drawings

Participants: Yulia Gryaditskaya (post-doctoral researcher), Adrien Bousseau (permanent researcher) and Fredo Durand (visiting researcher).

The goal of this project is to collect a dataset of industrial design drawings uniquely matched to a 3D geometry and accompanied by metadata such as each stroke position, time of creation and pressure. We are interested in creation of a classification of lines the designers use and analysis of their relation to the underlying shape. We are further interested in evaluation of correlation between the presence of construction techniques and perspective accuracy of the sketch. We are planning to provide a ground-truth labelling guided by experience of professional designers which will enable development of multiple algorithms, such as sketch beautification and vectorization, style transfer and 3D inference.

This work is a collaboration with Mark Sypesteyn, Jan Willem Hoftijzer and Sylvia Pont from TU Delft, Netherlands.

6.1.5. What You Sketch Is What You Get: 3D Sketching using Multi-View Deep Volumetric Prediction

Participants: Johanna Delanoy, Adrien Bousseau

Drawing is the most direct way for people to express their visual thoughts. However, while humans are extremely good at 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.

6.1.6. Flatenning videos for stylization

Participants: Johanna Delanoy, Adrien Bousseau

Traditional 2D animation exhibits a very specific sense of motion where objects seems to move in a 2D world. Existing stylization methods for videos use the optical flow to ensure temporal consistency of the stylization process. Although the method produces very convincing results, the resulting video often looks like a 3D textured scene instead of a 2D animation. In this project, we propose to transform the input video into a new one with a simplified motion. To achieve this effect, we approximate the motion with 2D rigid patches (rigid motion and scaling): each frame is segmented into rigid motion patches that provide a good approximation of the initial motion. The final sequence exhibits a flattened motion and can be used in any stylization process. This produces a stylized video that has a feeling of 2D motion and is more similar to traditional animation.

This work is a collaboration with Aaron Hertzmann from Adobe Research.

6.2. Graphics with Uncertainty and Heterogeneous Content

6.2.1. Image based rendering of repetitive facades

Participants: Simon Rodriguez, Adrien Bousseau, Frederic Durand, George Drettakis.

Image Based Rendering techniques (IBR) rely on interpolation between multiple views of a scene to generate new viewpoints. One of the main requirements is that the density of input views be high enough to obtain satisfying coverage and resolution, in both preprocessing and rendering. In human-made scenes, repetitive elements can be used to alleviate this limitation when the baseline of input views is sparse. A small number of viewpoints of similar elements can be fused together to extract more information about the scene. We focus on buildings facades, which often exhibit repetitive architectural elements. We propose the following steps: such elements are extracted from input views, and used during pre-processing to generate an approximate geometry of the specific element, and to extract view-dependent effects. These data sources are then combined to perform improved rendering in an IBR context.

6.2.2. Plane-Based Multi-View Inpainting for Image-Based Rendering in Large Scenes

Participants: Julien Philip, George Drettakis.

Image-Based Rendering (IBR) allows high-fidelity free-viewpoint navigation using only a set of photographs and 3D reconstruction as input. It is often necessary or convenient to remove objects from the captured scenes to allow a form of scene editing for IBR. This requires multi-view inpainting of the input images. Previous methods suffer from several major limitations: they do not impose true multi-view coherence, resulting in artifacts such as blur, they do not preserve perspective during inpainting, provide inaccurate depth completion and can only handle scenes with a few tens of images. Our approach addresses these limitations by introducing a new multi-view method that performs inpainting in intermediate, locally common planes. Use of these planes results in correct perspective and multi-view coherence of inpainting results. For efficient treatment of large scenes, we present a fast planar region extraction method operating on small image clusters. We adapt the resolution of inpainting to that required in each input image of the multi-view dataset, and carefully handle image resampling between the input images and rectified planes. Our method can handle up to hundreds of input images, for indoors and outdoors environments.

6.2.3. Thin structures in Image Based Rendering

Participants: Theo Thonat, 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. Thin structures, with their lack of texture and distinctive features, are another important common source of 3D reconstruction errors. 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 setup for IBR applications. We use the assumption that thin structures lie on a 3D surface. We propose a multi-view approach to compute the thin structures images segmentation and its associated alpha matting. Finally, we propose also a new IBR algorithm to render these thin structures.

6.2.4. Handling reflections in Image-Based Rendering

Participants: Theo Thonat, Frederic Durand, George Drettakis.

In order to render new viewpoints, current Image Based Rendering (IBR) techniques use approximate geometry to warp and blend images from close viewpoints. They assume the scene materials are mostly diffuse, and they assume only a direct look at the geometry is enough. These assumptions fail 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 the normals of the reflective surfaces might be not reliable.

6.2.5. Material capture

Participants Valentin Deschaintre, Miika Aittala, Frederic Durand, George Drettakis, Adrien Bousseau.
Convenient material acquisition is a complicated process, current methods are based on strong assumptions or limitations. Acquisition of spatially varying materials complete models is currently limited to specific materials or complex setups requiring multiple pictures with varying light and view positions.

This work aims at acquiring a material's Spatially-Varying BRDF using a single flash picture. We introduce procedural synthetic data generation and deep learning to mitigate the need of material and environment assumptions.

With fewer pictures used in the material acquisition process, comes more ambiguities in the explanation of the lighting behaviour. With one shot acquisition, important effects can be missed or misunderstood because of the lighting or view point. Current "lightweight" methods use various assumptions regarding materials. We use training to learn important ambiguities and how to solve them from the dataset, giving our network the capacity to handle the inherent uncertainty of one picture material acquisition.

6.2.6. Accommodation and Comfort in Head-Mounted Displays

Participants: George-Alex Koulieris, George Drettakis.
Head-mounted displays (HMDs) often cause discomfort and even nausea. Improving comfort is therefore one of the most significant challenges for the design of such systems. We evaluated the effect of different HMD display configurations on discomfort. We did this by designing a device to measure human visual behavior and evaluate viewer comfort. In particular, we focused on one known source of discomfort: the vergence-accommodation (VA) conflict. The VA conflict is the difference between accommodative and vergence response. In HMDs the eyes accommodate to a fixed screen distance while they converge to the simulated distance of the object of interest, requiring the viewer to undo the neural coupling between the two responses. Several methods have been proposed to alleviate the VA conflict, including Depth-of-Field (DoF) rendering, focus-adjustable lenses, and monovision. However, no previous work had investigated whether these solutions actually drive accommodation to the distance of the simulated object. If they did, the VA conflict would disappear, and we would expect comfort to improve. We designed the first device that allows us to measure accommodation in HMDs, and we used it to obtain accommodation measurements and to conduct a discomfort study, see Fig. 7 . The results of the first experiment demonstrated that only the focus-adjustable-lens design drives accommodation effectively, while other solutions do not drive accommodation to the simulated distance

and thus do not resolve the VA conflict. The second experiment measured discomfort. The results validated that the focus-adjustable-lens design improves comfort significantly more than the other solutions.

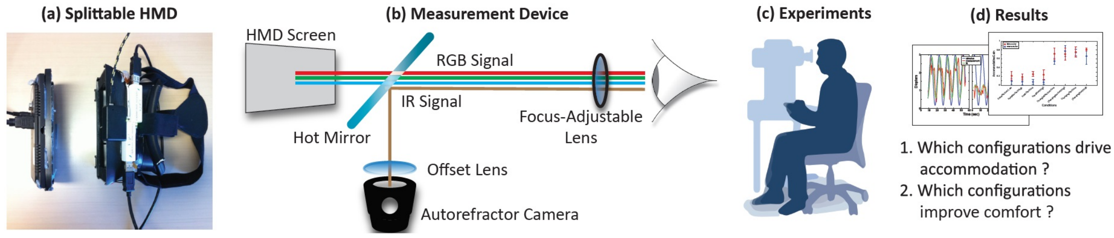


Figure 7. We evaluated the effect of different Head-Mounted Display (HMD) display configurations on discomfort by developing a splittable HMD with focus-adjustable lenses (a) that works with an autorefractor to objectively measure accommodation (b). (c) We run experiments to evaluate the effect of different display configurations. (d) Our results allowed us to answer fundamental questions about each configuration.

This work [11] is a collaboration with Martin S. Banks and Bee Bui from University of California, Berkeley. The work was published in a regular issue of the journal Transactions on Graphics and presented at the ACM SIGGRAPH conference in Los Angeles, USA, 2017.

6.2.7. Focus-tunable and Fixed Lenses and Stereoscopic 3D Displays

Participants: George-Alex Koulieris, George Drettakis.

Stereoscopic 3D (S3D) displays provide an enhanced sense of depth by sending different images to the two eyes. But these displays do not reproduce focus cues (blur and accommodation) correctly. Specifically, the eyes must accommodate to the display screen to create sharp retinal images even when binocular disparity drives the eyes to converge to other distances. This mismatch causes discomfort, reduces performance, and distorts 3D percepts. We developed two techniques designed to reduce vergence-accommodation conflicts and thereby improve comfort, performance, and perception. One uses focus-tunable lenses between the display and viewer's eyes. Lens power is yoked to expected vergence distance creating a stimulus to accommodation that is consistent with the stimulus to vergence. This yoking should reduce the vergence-accommodation mismatch. The other technique uses a fixed lens before one eye and relies on binocularly fused percepts being determined by one eye and then the other, depending on simulated distance. This is meant to drive accommodation with one eye when simulated distance is far and with the other eye when simulated distance is near. We conducted performance tests and discomfort assessments with both techniques and with conventional S3D displays (see Fig. 8). We also measured accommodation. The focus-tunable technique, but not the fixed-lens technique, produced appropriate stimulus-driven accommodation thereby minimizing the vergence-accommodation conflict. Because of this, the tunable technique yielded clear improvements in comfort and performance while the fixed technique did not. The focus-tunable lens technique therefore offers a relatively easy means for reducing the vergence-accommodation conflict and thereby improving viewer experience.

This work is a collaboration with Martin S. Banks from University of California, Berkeley, Paul V. Johnson from Apple, Joohwan Kim, Nvidia, Jared AQ Parnell and Gordon D. Love, Durham University, UK. The work was published in the proceedings of SPIE and presented at SPIE Opto 2017 conference, San Francisco, USA.

6.2.8. Applications of Visual Perception to Virtual Reality Rendering

Participants: George-Alex Koulieris

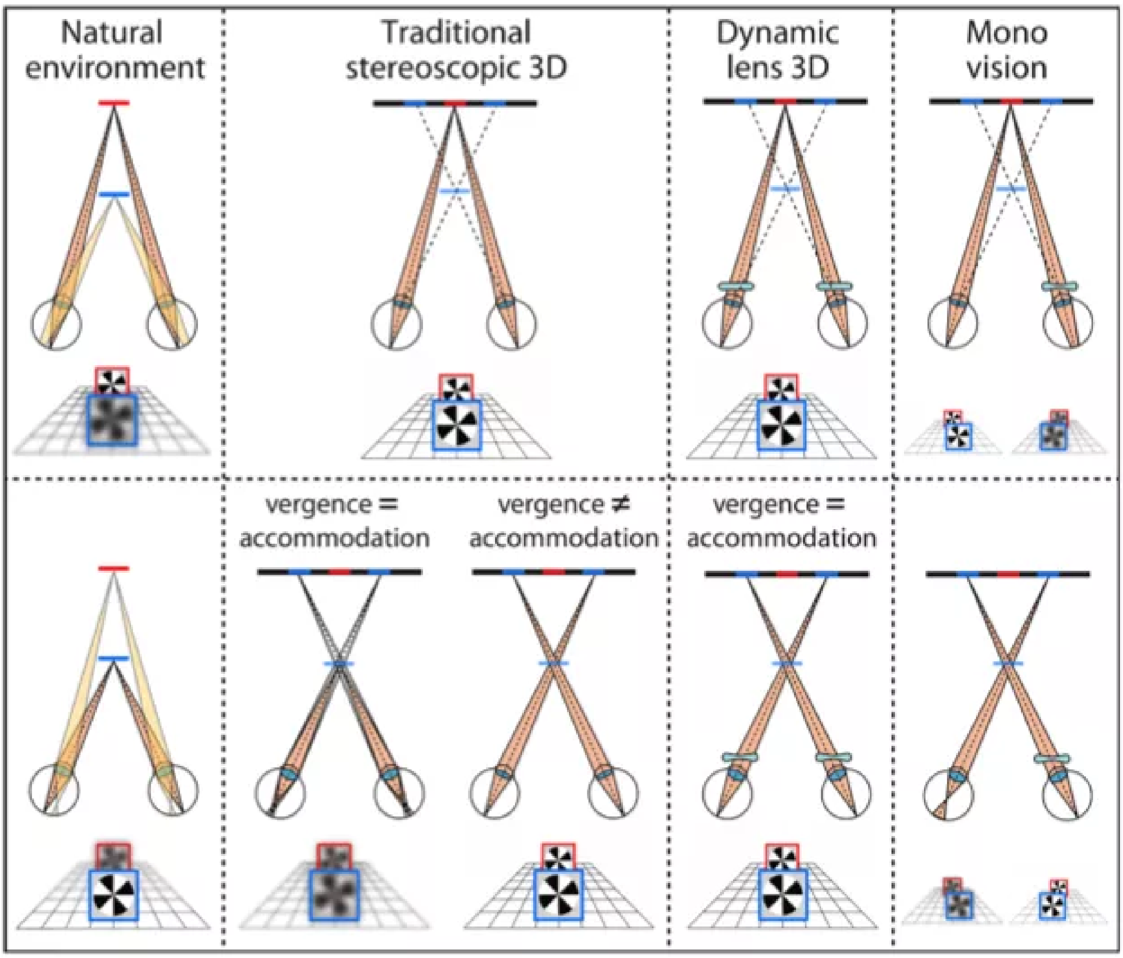


Figure 8. Focus cues in different viewing conditions for natural scenes, a conventional S3D display, and our proposed displays. In each panel, the upper part is an overhead view of the situation and the lower part is a schematic of what a viewer would see. In natural viewing (left column), vergence and accommodation distances are the same. In conventional stereoscopic 3D displays (second column), vergence distance varies with the disparity of the simulated object while accommodation distance is fixed at the display screen. In the proposed dynamic-lens display (third column), accommodation distance can be adjusted depending on the content being displayed. This is implemented by changing the power of a lens in front of each eye. In this case, accommodation and vergence distances are matched. In the proposed monovision display (right column), fixed lenses of different powers are placed in front of the two eyes. There are two accommodative distances that match the vergence distance, one for the left eye and one for the right.

Over the past few years, virtual reality (VR) has transitioned from the realm of expensive research prototypes and military installations into widely available consumer devices. But the high pixel counts and frame rates of current commodity devices more than double the rendering costs of 1920x1080 gaming, and next-generation HMDs could easily double or triple costs again. As a result, VR experiences are limited in visual quality, performance, and other capabilities. Human visual perception has repeatedly been shown to be important to creating immersion while keeping up with increasing performance requirements. Thus, an understanding of visual perception and its applications in real-time VR graphics is vital for HMD designers, application developers, and content creators. In this course we began with an overview of the importance of human perception in modern virtual reality. We accompanied this overview with a dive into the key characteristics of the human visual system and the psychophysical methods used to study its properties. After laying the perceptual groundwork, we presented three case studies outlining the applications of human perception to improving the performance, quality, and applicability of VR graphics. Finally, we concluded with a forward looking discussion, highlighting important future work and open challenges in perceptual VR, and a questions session for more in-depth audience interaction.

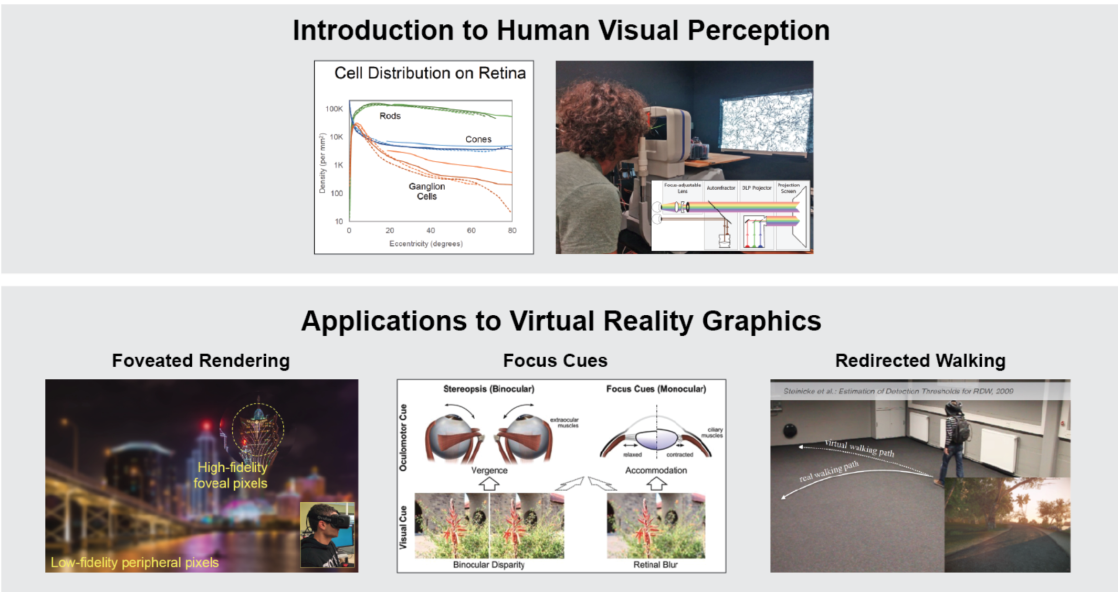


Figure 9. An overview of the topics covered in the course.

This work is a collaboration with Anjul Patney and Joohwan Kim, Nvidia, Marina Zanolli, Oculus VR, Gordon Wetzstein, Stanford University and Frank Steinicke, University of Hamburg. The course was presented at ACM SIGGRAPH 2017, Los Angeles, USA.

6.2.9. Real-time Binocular Tone Mapping

Participants: George-Alex Koulieris, George Drettakis

In real-world scenes, luminance values can simultaneously span several orders of magnitude. The human visual system has evolved such it can comfortably perceive this vast luminance gamut via adaptation mechanisms both in the eyes and the brain. Conventional displays can not reproduce such enormous dynamic ranges since their contrast ratio is severely limited. As a result, simulations of natural scenes significantly deviate from real-world percepts. Tone-mapping techniques approximate the appearance of high dynamic range scenes in limited dynamic range media. However, there exists an inherent trade-off between simultaneously inducing both a high dynamic range perception and preserving contrast in fine-scale details. We will alleviate this trade-off by capitalizing on the properties of the visual system's binocular fusion processes during dichoptic stimulation, i.e., when a different image is shown to each eye.

To be submitted: This work is an ongoing collaboration with Martin S. Banks, University of California, Berkeley, Rafal Mantiuk, University of Cambridge, and Fredo Durand, MIT.

6.2.10. A novel objective method for the assessment of binocular accommodative facility: A pilot study in a young adult population

Participants: George-Alex Koulieris

Accommodative facility (AF) is a clinical test used to evaluate the ability of the visual system to alter accommodation rapidly and accurately when the dioptric stimulus to accommodation is situated between two different distances. AF can be evaluated in monocular and binocular testing, providing a direct evaluation of the dynamics of the accommodative response. We investigated the validity of measuring the binocular accommodative facility using Hart charts in conjunction with the Grand Seiko Auto Ref/Keratometer in young participants. The main objective of the study was to propose a novel objective method to assess binocular accommodative facility in quantitative terms.

To be submitted: This work is an ongoing collaboration with Jesus Vera-Vilchez and Raimundo Jimenez Rodriguez, University of Granada, Spain.

6.2.11. Efficient Thin Shell Sounds

Participants: Gabriel Cirio, George Drettakis.

Thin shells, i.e. solids that are thin in one dimension compared to the other two, often produce rich and recognizable sounds when struck: from containers like a trash can or a plastic bottle, to musical instruments like a cymbal or a gong. Thin shells are notoriously difficult and expensive to simulate due to their nonlinear behavior under large excitations. To synthesize the sound generated by thin shells, we first reduce the problem to a small modal subspace, and compute all the required quantities directly in the subspace. We then further speed up the simulation by computing nonlinear dynamics using only a subset of low frequency vibrations, since these are responsible for most nonlinear phenomena, and use a frequency coupling to drive the remaining high frequency vibrations. Finally, we approximate the chaotic regime that can emerge in some thin shells (such as gongs and cymbals) by diffusing the power spectrum of the sound directly in the frequency domain, following a phenomenological approach to wave turbulence. We can produce rich and complex sounds for a wide range of behaviors with a computational cost orders of magnitude smaller than previous approaches.

This work is an ongoing collaboration with Changxi Zheng and Etian Grinspun from Columbia University in New York, and is supported by the EU H2020 Marie Sklodowska-Curie project PhySound.

6.2.12. Aether: An Embedded Domain Specific Sampling Language for Monte Carlo Rendering

Participant: Frederic Durand

Implementing Monte Carlo integration requires signifcant domain expertise. While simple samplers, such as unidirectional path tracing, are relatively forgiving, more complex algorithms, such as bidirectional path tracing or Metropolis methods, are notoriously diffcult to implement correctly.We propose Aether, an embedded domain specifc language for Monte Carlo integration, which offers primitives for writing concise and correct-by-construction sampling and probability code. The user is tasked with writing sampling code, while our compiler automatically generates the code necessary for evaluating PDFs as well as the book keeping and combination of multiple sampling strategies. Our language focuses on ease of implementation for rapid exploration, at the cost of run time performance. We demonstrate the effectiveness of the language by implementing several challenging rendering algorithms as well as a new algorithm, which would otherwise be prohibitively difficult.

The work [6] was published in a regular issue of the journal Transactions on Graphics and presented at the ACM SIGGRAPH conference in Los Angeles, USA, 2017.

6.2.13. Deep bilateral learning for real-time image enhancement

Participant: Frederic Durand

Performance is a critical challenge in mobile image processing. Given a reference imaging pipeline, or even human-adjusted pairs of images, we seek to reproduce the enhancements and enable real-time evaluation. For this, we introduce a new neural network architecture inspired by bilateral grid processing and local affine color transforms. Using pairs of input/output images, we train a convolutional neural network to predict the coefficients of a locally-affine model in bilateral space. Our architecture learns to make local, global, and content-dependent decisions to approximate the desired image transformation. At runtime, the neural network consumes a low-resolution version of the input image, produces a set of affine transformations in bilateral space, upsamples those transformations in an edge-preserving fashion using a new slicing node, and then applies those upsampled transformations to the full-resolution image. Our algorithm processes high-resolution images on a smartphone in milliseconds, provides a real-time viewfinder at 1080p resolution, and matches the quality of state-of-the-art approximation techniques on a large class of image operators. Unlike previous work, our model is trained off-line from data and therefore does not require access to the original operator at runtime. This allows our model to learn complex, scene-dependent transformations for which no reference implementation is available, such as the photographic edits of a human retoucher.

The work [10] was published in a regular issue of the journal Transactions on Graphics and presented at the ACM SIGGRAPH conference in Los Angeles, USA, 2017.

GRAPHIK Project-Team

7. New Results

7.1. Logics and Graph-Based Languages for Ontology-Mediated Query Answering

Participants: Jean-François Baget, Meghyn Bienvenu, Efstathios Delivorias, Michel Leclère, Marie-Laure Mugnier, Federico Ulliana, Arthur Boixel, Marin Julien, Benjamin Boisson, Thibault Bondetti.

Ontolology-mediated query answering (OMQA) is the issue of querying data while taking into account inferences enabled by an ontology. 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 (DLs) and existential rules (aka Datalog+). Both frameworks correspond to fragments of first-order logics, which are incomparable in general, but closely related in the context of OMQA: indeed, the DLs considered for OMQA (so-called Horn-DLs) are naturally translated into specific classes of existential rules. Compared to existential rules, Horn-DLs feature lower complexity classes and allow for specific algorithmic techniques. A well-known Horn-DL is the lightweight description logic family DL-Lite. Importantly, the foundational work carried by the KR community led to the definition of several W3C standards for Semantic Web languages, namely the family of OWL languages. For example, DL-Lite corresponds to OWL 2 QL, a dialect of OWL 2 with polynomial conjunctive query answering (in terms of data complexity; conjunctive queries are the basic and most frequent relational database queries). Furthermore, the ontology-based paradigm for data access is also supported by commercial systems, such as Oracle 11g, which offers a module dedicated to Semantic Web technologies (https://docs.oracle.com/cd/B28359_01/appdev.111/b28397/toc.htm).

This year, we further investigated OMQA with both description logics and existential rules. We also broadened this research line, by investigating ontological languages for non-relational data, hereby continuing the work initiated last year on OMQA for key-value stores.

7.1.1. Ontology-Mediated Query Answering in the Description Logics Framework

The OWL 2 QL profile, based upon the DL-Lite family, is a popular ontology language for applications involving large amounts of data. OWL 2 QL possesses the first-order rewritability property, meaning that conjunctive query answering can be reduced to database query evaluation by means of query rewriting. However, query rewriting can be costly and/or produce rewritten queries that are hard to evaluate, so it is important to understand when and how one can construct small and efficient rewritings, and more generally, under which conditions can OWL 2 QL be queried effectively. Building upon our earlier work, we explored these questions together with colleagues from Birkbeck College and the Free University of Bozen-Bolzano.

First, we studied the overhead of answering ontology-mediated queries (OMQs) in ontology-based data access compared to evaluating their underlying tree-shaped and bounded treewidth conjunctive queries (CQs). We showed that OMQs with bounded-depth ontologies have nonrecursive datalog (NDL) rewritings that can be constructed and evaluated in LOGCFL (a strict subclass of PTIME) for combined complexity, even in NL if their CQs are tree-shaped with a bounded number of leaves, and so incur no overhead in complexity-theoretic terms. For OMQs with arbitrary ontologies and bounded-leaf CQs, NDL-rewritings are constructed and evaluated in LOGCFL. We conducted experiments that demonstrate feasibility and scalability of our rewritings compared to standard NDL-rewritings.

- *These results were published at* ***PODS 2017*** *[22]*

We investigated the parameterised complexity of answering tree-shaped ontology-mediated queries in OWL 2 QL under various restrictions on their ontologies and CQs. We proved that answering OMQs with tree-shaped CQs is not fixed-parameter tractable if the ontology depth is regarded as the parameter, and that answering OMQs with a fixed ontology (of infinite depth) is NP-complete for tree-shaped and LOGCFL for bounded-leaf CQs. Moreover, we constructed an ontology T such that answering OMQs (T, q) with tree-shaped CQs q is W[1]-hard if the number of leaves in q is regarded as the parameter. The number of leaves had previously been identified as an important characteristic of CQs as bounding it leads to tractable OMQ answering. Our result shows that treating it as a parameter does not make the problem fixed-parameter tractable, even for a fixed ontology.

- *These results were published at* ***DL 2017*** *[23]*

7.1.2. Ontology-Mediated Query Answering in the Existential Rule Framework

The class of existential rules that naturally generalizes OWL 2 QL is called linear existential rules. Such rules have a body restricted to a single atom. Linear existential rules are in turn generalized by guarded existential rules, one of the main classes of existential rules.

Building upon our work on OWL 2 QL (reported Section 7.1.1), we developed optimal rewriting-based methods for answering ontology-mediated queries (O,q) where O is a set of linear existential rules and q is a CQ of bounded hypertree width. Assuming that the arity of predicates is bounded, we show that polynomial-size nonrecursive Datalog rewritings can be constructed and executed in (i) LOGCFL for OMQs with ontologies of bounded existential depth; (ii) NL for OMQs with ontologies of bounded depth and CQs whose hypertree decompositions have a bounded number of leaves; (iii) LOGCFL for OMQs with acyclic CQs whose join trees have a bounded number of leaves.

- *These results were published at* ***DL 2017*** *[24]*

While most work on ontology-mediated query answering considers conjunctive queries, navigational queries are gaining increasing attention. Last year, we conducted a first study of such queries in the setting of existential rules, focusing on linear rules and regular path queries. This year, in a continued collaboration with Michael Thomazo (Inria CEDAR), we have significantly extended these results by considering the problem of answering two-way conjunctive regular path queries (CRPQs) over knowledge bases whose ontology is given by a set of guarded existential rules. We first showed that for the subclass of linear existential rules, CRPQ answering is EXPTIME-complete in combined complexity and NL-complete in data complexity, matching the recently established bounds for answering non-conjunctive RPQs. For guarded rules, we gave a non-trivial reduction to the linear case, which allowed us to show that the complexity of CRPQ answering is the same as for CQs, namely 2EXPTIME-complete in combined complexity and PTIME-complete in data complexity.

- *These results were published at* ***IJCAI 2017*** *[20]*

Besides, three internships (L3, Master 1 and Master 2) explored different aspects related to existential rules.

7.1.3. Ontology-Mediated Query Answering on top of Key-Value Stores

Ontology-mediated query answering has been mainly investigated so far based 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 OMQA can be developed for non-relational structures, like those shared by increasingly popular NOSQL languages sustaining Big-Data analytics, has just begun to be investigated. Last year, we carried out the first study of OMQA for key-values stores, which are systems providing fast and scalable access to JSON records [46]. We proposed a rule language to express domain knowledge, with rules being directly applicable to key-value stores, without any translation of JSON into another data model. However, some limitations of our proposal were (1) the absence of correspondence with logic, the semantics remaining operational, and (2) the need to drastically restrict the rules to ensure decidability.

Building on this previous work, we pursued the investigation of a rule language for JSON records, together with colleagues from Inria Lille. This yielded a novel rule language, with a natural translation into first-order logics, and more precisely into guarded existential rules. From known results on existential rules, we got the decidability of query answering in our framework but only rough complexity bounds. By establishing an interesting and non-trivial connection to word rewriting, we were able to pinpoint the exact combined complexity of query answering in our framework and obtain promising tractability results for data complexity. The upper bounds were proven using a query reformulation technique, which can be implemented on top of key-value stores, thereby exploiting their querying facilities.

- *These results were published at* ***IJCAI 2017*** *[21]*

A master student project led to an implementation of OMQA for MongoDB tree-pattern queries and a subset of the proposed rule language featuring key inclusions and mandatory keys. The system contains query rewriting procedures for data access as well as an optimization module for parallelizing the query reformulation process.

- *Demo paper at* ***BDA 2017*** *[31]*

7.1.4. Applications to Computer Aided Design

Participant: Federico Ulliana.

Complementing the theoretical work on the OMQA issue, the team also participated in the building of OMQA-based systems applied to the field of CAD (Computer Aided Design). We developed a system for querying and exploring complex 3D CAD models corresponding to the assembly of manufactory products (for example, an airplane wing). Our system features a pipeline of two modules : a geometric analysis module which reasons on numeric features of the CAD model and a knowledge-based module which reasons on symbolic information which is extracted by the former module. The knowledge-based module exploits a geometry-ontology for manufactory assemblies, that we developed in collaboration with an expert. This allows for an automatic classification of the solids that appear in a 3D scene (for example, for labelling screws and bolts), but also for associating them their functional role (for example, planar supports, seals, rotating guides). By automatically annotating objects, we minimize the errors usually introduced by the manual processes of annotation. Complex CAD models can therefore be queried by selecting objects and components based on the types (e.g., select all bolts of an airplane wing) or functions (e.g., planar supports) and the results of queries visualized in a 3D browser. This work is performed in the context of our collaboration with the Inria Imagine Team. A website http://3dassblyanlysis.gforge.inria.fr/3d/ gives a public access to a knowledge-based assembly example.

- *These results were published in* ***EGC 2017*** *and received a prize for* Best Application Paper

7.2. Dealing with Imperfect Information

Participants: Pierre Bisquert, Patrice Buche, Abdelraouf Hecham, Madalina Croitoru, Jérôme Fortin, Rallou Thomopoulos, Bruno Yun.

Reasoning in presence of inconsistencies is a challenging task both from a theoretical and an application point of view. From a theoretical point of view, it means finding methods that can tolerate the inconsistency. From an application point of view, it means providing meaningful results to the user. In the works carried out this year inconsistency arose while developing a decision support system assisting human experts with a given task. The main challenges we faced where first to provide the user with a comprehensive vision over the different possibilities and then to assist her while she makes a decision.

7.2.1. Argumentation in the Existential Rule Setting

Our first line of work focussed on the use of argumentation-based methods for reasoning in presence of inconsistencies within knowledge bases expressed in the formalism of existential rules. Such inconsistency can occur either in the facts or in the rules of the knowledge base.

Logical based argumentation instantiates abstract argumentation frameworks by $i)$ constructing arguments from inconsistent knowledge bases, $ii)$ computing attacks between them, and $iii)$ using so-called argumentation semantics in order to select acceptable arguments and their conclusions. The advantage of using argumentation for reasoning in an inconsistent setting lies in the explanatory power of argumentation frameworks. We considered the first case of inconsistency arising from the factual level and investigated the formal properties of the argumentation frameworks. We showed then that the argumentation is of practical use as it allows for a principled explanatory dialogue. Finally, we carried out an experiment that compared the explanatory power of argumentation in this setting and found out that positive results are only achieved if particular attention is given to the phrasing of such interaction.

- *These results were published at **ESA 2017** [12], **IJAR 2017** [13], and **DL 2017** [28]*

In logical based argumentation, arguments are sometimes based upon equivalent data. Cores are notions introduced in that delete such arguments. We investigated two different notions of core in such a logically instantiated argumentation framework (more details about the instantiation can be found in [12]) that will remove redundant arguments and attacks in a different manner. We do not follow the argumentation semantics "a la Dung" but study ranking semantics that return a total order over the set of arguments in the logical argumentation framework. We show that the manner of defining the core of a logically instantiated argumentation framework affects the ranking output of ranking semantics.

- *These results were published at **AAMAS 2017** [38] and IDA [37]*

Another setting we explored was when the inconsistency arises from the rules (also sometimes referred to as incoherence). In this setting we investigated defeasible logics and proposed a refined formalism for defeasible existential rules. We showed that in the case of defeasible reasoning one may be interested in generating all provenance paths of an atom, an issue which raises an interesting technical challenge. In order not to lose paths due to the skolemisation process we introduced a new combinatorial structure called the graph of atom dependency and showed how using this structure prevents provenance paths loss. We implemented our approach and showed that it has a very good performance with respect to the other argumentation based tools that could be used for defeasible reasoning in existential rules.

- *These results were published at **RuleML+RR 2017** [29] and **AAMAS 2017** [30]*

7.2.2. Human Interaction and Decision Making

Our second line of contributions focussed on how to bridge the gap between the human and the machine in a decision support setting. We thus investigated how human reason and how cognitive biases can influence decision making. Then, we approached the decision making process by developing methods based on voting theory and classical decision theories allowing us to achieve desirable properties.

We proposed a dual system for artificial agents combining deductive logical reasoning with intuitive reasoning for the sake of argumentation. Our contribution is the definition of a new formal model of flexible argument evaluation. We consider that, when it is not possible for an agent to make a logical inference (since it requires too much cognitive effort or she has insufficient knowledge), she might replace certain parts of the logical reasoning with mere associations. We applied our work on the Durum Wheat variety selection in the context of the French National Agency (ANR) Dur-Dur project.

- *These results were published at **MM 2017** [15]*

Collective decision making is classically done via social choice theory with each member of the group expressing preferences as a (total) order over a given set of alternatives, and the group's aggregated preference is computed using a voting rule. However, such methods do not take into account the rationale behind agents' preferences. Our research hypothesis is that a decision made by a group of participants understanding the qualitative rationale (i.e., arguments) behind each other's preferences has better chances to be accepted and used in practice. To this end we proposed a novel qualitative decision process which combines argumentation with computational social choice for modelling the decision-making problem. We show that a qualitative approach based on argumentation can overcome some of the social choice deficiencies. A first version of this approach was implemented and practically demonstrated in [25].

- *These results were published at **ADT 2017** [41]*

A recent work in cooperation with Laval University (Canada) and AGIR joint research unit (Toulouse) deals with the combination of argumentation and system dynamics simulation for decision support in the agri-food sector. We propose a systematic method to assess possible options, based on the complementarity of argumentation modeling and system dynamics (SD) simulation, in conjunction with field experimentation. As a practical application, we assess various options available to agri-food chain stakeholders when considering the adoption of cereal-legume intercrops as an alternative to sole crops. Moreover, we carried out complementary studies to explore the possible added-value of argumentation for decision support in practical cases related to agri-food chains. We proposed the introduction of numerical indicators in argumentation systems in order to evaluate to what extent the system studied (a short food supply chain) is polemical, i.e. subject to divergent viewpoints, and which criteria are mainly involved in these divergences. As a study case, we considered a food policy about bread-making which illustrated that a given argument may be interpreted through different scenarios, among which unexpected worst-cases can occur.

- *These results were published at* ***IEA/AIE 2017*** *[33], [35] and* ***WCCA 2017*** *[34], [32]*

7.3. Miscellaneous

We describe here some complementary work carried out this year in knowledge representation and knowledge engineering. First, we started a new collaboration with the Center for Structural Biochemistry in Montpellier, on the translation of boolean functions in a biological language, so as to help the design of biological devices satisfying formal properties. Second, in collaboration with MAREL team at LIRMM, which designs algorithms for Formal Concept Analysis, we developed a new algorithm for generating text under constraints, implemented in a tool that relies on our tool Cogui. Third, we report some complementary work carried out in the IATE team on the construction of ontologies in the agronomy domain and their use to integrate heterogeneous data, the obtained knowledge base acting as an input to a decision support system.

7.3.1. Encoding Boolean Functions in Biological Systems

Participants: Michel Leclère, Federico Ulliana, Guillaume Perution Kihli.

This work has been done as part of a new collaboration started in 2017 with the ”Centre de Biochimie Structurale (CBS) de Montpellier” with Sarah Guiziou and Jérôme Bonnet. CBS is interested in developing a framework dedicated to the automatic design of “recombinase” biological systems implementing a boolean function. Recombinases are genetic enzymes which allow to manipulate the structure of genomes, and to control gene expression, which is seen as the output of a boolean function. Different ways of designing such systems are possible. In this collaboration, we study the design of biological sequences of DNA that are intended to implement a specific boolean function defined by the expert biologist. From our side, we study the logical expressivity of such systems. Concretely, our goal is to characterize the set of boolean functions that do admit a biological implementation under certain constraints. Then, whenever this is possible, devise a method for automatically constructing such sequence.

This first year, we have studied and highlighted some characteristic properties of biological sequences, namely equivalence, irreducibility, and simplifiability. We also develop an algorithm to exhaustively explore the set of irreducible and not simplifiable sequences with n inputs (which allows us to implement a boolean function with n variables). This algorithm has been implemented in a distributed way and run on a high performance cluster. From its outputs, we built a database allowing to associate the different possible sequences to each boolean function up to 4 variables (http://genetix.lirmm.fr).

- *Our first findings are contained in a preliminary report [42]*

7.3.2. Text Generation Under Constraints on top of Cogui

Participants: Michel Chein, Alain Gutierrez.

We built a tool that can be used for building, editing, and reusing, large corpuses for text generation under constraints. Text generation is made by dynamically instantiating templates with terms that are drawn from a collection of available textual corpuses. We developed a database indexing technique based on a sub-order of a Galois lattice (so-called AOC-poset) that we use to describe the structure of the input texts as well as the terms that they contain. Thanks to the index we can efficiently find terms for the text generations process. The final tool is developed on top of Cogui. Finally, we conducted an experimental evaluation that outlines the size and construction time of indexes (which are built off-line), as well as the performance of text-generation.

- *Our results have been published in* ***ISMIS 2017*** *[27]*

7.3.3. Complementary Work on Ontologies for Data Integration in Agronomy

Participant: Patrice Buche.

We use here ontologies to integrate experimental data across complementary sub-domains in agronomy. Scientific literature in the agronomy field is growing fast and could be a valuable source of data for researchers willing to address extended research questions, for example, comparing the efficiency of the same biomass treatment applied in different contexts. However, scientific data is abundant, mostly in textual format, and heterogeneously structured, all factors that can hinder its systematic reuse. We put an effort on the implementation of decision support systems using ontologies and structured knowledge to integrate scientific data coming from different sources. This led to the definition of a new ontology network called Agri-Food Experiment Ontology (AFEO), which was developed based on two ontological resources AEO (Ontology for Agricultural Experiments) and OFPE (Ontology for Food Processing Experiments) and of a termino-ontological resource to compare ligno-cellulosic biomass and agro-waste valorisation routes. We studied methods for linking existing ontologies in life sciences and environment. To extract knowledge from data, we also devised an automatically discovery and extraction method for relevant data modeled as n-ary relations in plain text.

- *Results were published in* ***CEAR*** *[17],* ***WCCA 2017*** *[26],* ***ESA*** *[14], and* ***AKDM*** *[39]*

Heterogeneous data integrated thanks to ontology networks are reused in Decision support systems (DSS). Two prototypes have been implemented in the domain of food packaging selection for respiring and non respiring fresh foods. Additionnaly, our team contibutes to international initiatives to suggest ontological standards in sub-domains of Agriculture.

- *Results were published in* ***F1000Research*** *[18],* ***Innovations Agronomiques*** *[19], and* ***Packaging Research*** *[16]*

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. This analysis is heavily dependent on the behavior of the cable. Three main models can be used: *ideal* (no deformation of the cable due to the tension, the cable shape is a straight line between the attachements points), *elastic* (cable length changes according to the tension to which it is submitted, straight line cable shape) and *sagging* (cable shape is not a line as the cable is submitted to its own mass). The different models leads to very different analysis with a complexity increasing from ideal to sagging. All cables exhibit sagging but the sagging effect may often be neglected if the CDPR is relatively small while the sagging cannot be neglected for large CDPRs. Still even when using the ideal cable model we are contronted to complex issues. For example CDPR simulation assumes continuous time control while in reality discrete-time control is used. We have proposed a discrete-time simulation tools of CDPR [10] with surprising results (much larger tension variation in the cable, oscillation) and a complex implementation (the numerical accuracy that is required to get exact results very often exceed floating-point accuracy) that has required a very strict mathematical analysis.

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). IK for ideal cable is straightforward while more complicated for elastic cables and very complex for sagging cables. As for FK it is already complex for ideal and elastic cables while very difficult for sagging cable. We have proposed last year IK and FK solving scheme for sagging cables but they are relatively computer intensive. A major problem for the FK is that it usually provides several solutions while the control requires to determine only the solution corresponding to the current pose of the platform. A natural approach to both speed-up the FK algorithm and to get only the current pose is to add sensors on the robot. Measuring the cable tensions will be useful but has been shown to be very difficult and noisy while measuring the cable and platform orientation may be possible. But it is necessary to investigate how many sensors and their location are necessary to get a single solution for the FK: we have provided an extensive analysis of this problem for all 3 cable models [16],[17].

Last year we have investigated the calculation of cross-section of the workspace of CDPR with ideal and elastic cables, using approaches that are too computer intensive for sagging cable. We have proposed this year a preliminary algorithm for CDPRs with sagging cable that is much efficient [15] as it is based on an approximate continuation method for finding the border but it is still computer intensive. Figure 4 presents a horizontal cross-section of the workspace: the blue area are in fact the concatenation of the border of several zones that are part or are outside the workspace. In view of the complexity of the workspace border it appears that progress have to be made on that topic.

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.

We have co-founded 2 years ago the XtreeE (xtreee.eu) start-up company that is currently one of the leading international actors in large-scale 3D concrete printing.

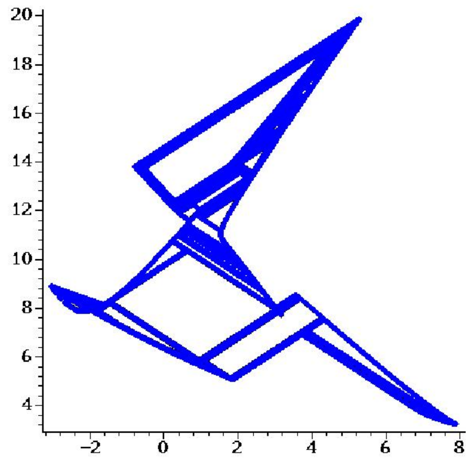


Figure 4. Cross-section of the workspace of a CDPR

We have been scientific advisors of this company for the design of an innovative new large scale CDPR - but its development, scheduled this year, has been postponed for strategical reasons.

7.2. Assistance

We are still going on in building a framework for customizable and modular assistive robotics including hardware, software and communication and medical monitoring [12]. The development of our platforms shows that we are now able to identify problematic issues for end-users, helpers and the medical community and to propose appropriate hardware/software solutions. But the most time consuming part of our work is related to evaluation and therefore experimentation: this involves legal/ethical issues (for which we contribute [11]), participation of the medical community (for evaluation and recruitment) and heavy administrative management.

7.2.1. Rehabilitation in an immersive environment

Participants: Artem Melnyk, Jean-Pierre Merlet.

Rehabilitation is a tedious and painful process and it is difficult to assess its trend. Using an immersive environment has shown to increase the patient motivation but is not sufficient regarding rehabilitation efficiency. First the visual feedback (event 3D) is not sufficient to provide a full immersive feeling as body motion is not involved. Controling body motion is also very important for therapists that currently must continuously correct the patient pose so that the rehabilitation exercise is the most efficient. We propose to add motion generators in the environment to reinforce realism (thereby increasing patient motivation) but also to allow therapists to use these generators to control the body pose so that they will be able to repeat rehabilitation exercises in a controlled context. Furthermore these generators are instrumented to provide information on the body pose and additional external sensors complete these measurements for rehabilitation assessment. We have developed 3 types of motions generators: one 6 d.o.f. motion base, a CDPR that is able to lift a patient and 2 multipurpose lifting columns. We are in the process of mixing visual feedback with these generators but unfortunately Inria-Sophia immersive room that we were planning to use is no more available. Hence we have been obliged to develop a renderer and this has slowed down the integration process. Still we have currently a preliminary experiment going on: our columns are able to modify the slope and inclination of a treadmill so that we can simulate a walk in the mountain while controlling the inclination to enforce the use of one specific leg. External and wearable sensors allow us to monitor the walking pattern and provide synthetic indicators on this pattern for the therapist.

7.2.2. Smart Environment for Human Behaviour Recognition

Participants: Mohamed Hedi Amri, Alain Coulbois, Aurélien Massein, Artem Melnyk, Jean-Pierre Merlet, Yves Papegay, Odile Pourtallier, Valérie Roy, Eric Wajnberg.

The general aim of this research activity focuses on long term indoor monitoring of frail persons. In particular we are interested in early detection of daily routine and activity modifications. These modifications may indicate health condition alteration of the person and may require further medical or family care. Note that our work does not aim at detecting brutal modifications such as faintness or fall.

In our research we envisage both individual and collective housing such as rehabilitation center or retirement home.

Our work relies on the following leading ideas :

- We do not base our monitoring system on wearable devices since it appears that they may not be well accepted and worn regularly,
- Privacy advocates adequacy between the monitoring level needed by a person and the detail level of the data collected. We therefore strive to design a system fitted to the need of monitoring of the person.
- In addition to privacy concern, intrusive feature of video led us not to use it.

The main aspect that grounds this work is the ability to locate a person or a group in their indoor environment. We focus our attention to the case where several persons are present in the environment. As a matter of fact the single person case is less difficult.

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 another. Henceforth each zone are polygonal.

We are following several directions :

- monitoring system design,
- material development,
- data gathering and analysis,
- experimentation.

7.2.2.1. Monitoring system design

Monitoring systems provide information 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.

There is an ongoing PhD work about to be defended : metrics have been defined to evaluate quality of sensors solutions and placement to infer people behaviors inside a smart environments, and a methodology for optimal design of smart environments has been developed.

7.2.2.2. Material development, signal processing and data fusion

Based on the experimentation we initiated in 2016 in Ehpad Valrose and this year at the Institut Claude Pompidou in Nice, we designed, developed and tested a new class of multi-sensors barriers to overcome difficulties arising from wider environment, reflection properties of walls and light exposures.

These multi-sensor barriers contains a selection of infra red distance sensors and motion sensors of passive infrared type. Dedicated signal processing, and fusion of the different sets of signals provide information on crossing time, direction of crossing, speed and size of crossing person, object, or group. This last information is helpful to differentiate for example a person using a wheelchair, a valid person (e.g medical staff), or an elderly.

7.2.2.3. Data analysis for activity recognition

Data are issued from long-term recording during on-going experimentation and from simulation tools developed on purpose from probabilistic models.

At Ehpad Valrose, a monitoring system is installed since last year in the first floor. Area of monitoring is 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. Hence few people are entering the experimentation area, with significant characteristics : elderly with rolling chairs or rollators, autonomous elderly, technical staff with trolleys, visitors, caregivers. On this experiment, we focus our analysis on inferring from data, quantitative indicators on the activity of each resident. Data analysis generates several possible scenarii of activities. They are discriminated, based on distinction of people when crossing barriers and on additional knowledge on their habits.

7.2.2.4. Experimentation

A new monitoring system has been installed in Institut Claude Pompidou in Nice. Area of monitoring is an half floor dedicated to a consultations and day care unit of the Centre Mémoire de Ressources et de Recherche, together with a clinical research unit of the Cobtek team. It consists in 15 rooms articulated on a simple network of hallways, including offices, training rooms, consultation rooms, waiting area, toilets, resting room for staff, delimited by an entrance and a communication to the research center. Patients, service staff, clinical staff, researcher are using the monitored area. The aim of this experiment is to determine identify the different flows of people between different zones to qualify uses of the facilities and interaction between the different groups of users.

Twenty barriers have been installed for a total of 77 sensors and kilometers of cable deployed. Installation and set-up of the system led to several electrical, electronical and technical problems, efficiently solved by the engineers of our group that played a crucial role.

7.3. Miscellaneous results

7.3.1. Symbolic tools for modeling and simulation

Participant: Yves Papegay.

This activity is the main part of a long-term ongoing collaboration with Airbus whose goal is to directly translate the conceptual work of aeronautics engineers into digital simulators to accelerate aircraft design.

An extensive modeling and simulation platform - MOSELA - has been designed which includes a dedicated modeling language for the description of aircraft dynamics models in term of formulae and algorithms, and a symbolic compiler producing as target an efficient numerical simulation code ready to be plugged into a flight simulator, as well as a formatted documentation compliant with industrial requirements of corporate memory.

Technology demonstrated by our prototype has been transferred : final version of our modeling and simulation environment has been delivered to Airbus in November 2012 and developer level know-how has been transferred in 2013 to a software company in charge of its industrialization and maintenance.

Since 2014, we are working on several enhancements and extension of functionalities, namely to enhance the performances and the numerical quality of the generated C simulation code, and ease the integration of our environment into the airbus toolbox.

In 2016, we continued our integration effort of connect the MOSELA environment with other Airbus modeling tools.

A study has been launched to guarantee that the result of simulation performed by the generated C code is not dependent on the description order of the equations in the model.

INDES Project-Team

5. New Results

5.1. Type Abstraction for Relaxed Noninterference

Information-flow security typing statically prevents confidential information to leak to public channels. The fundamental information flow property, known as *noninterference*, states that a public observer cannot learn anything from private data. As attractive as it is from a theoretical viewpoint, noninterference is impractical: real systems need to intentionally declassify some information, selectively. Among the different information flow approaches to declassification, a particularly expressive approach was proposed by Li and Zdancewic, enforcing a notion of *relaxed noninterference* by allowing programmers to specify *declassification policies* that capture the intended manner in which public information can be computed from private data. The paper [15] shows how we can exploit the familiar notion of type abstraction to support expressive declassification policies in a simpler, yet more expressive manner. In particular, the type-based approach to declassification—which we develop in an object-oriented setting—addresses several issues and challenges with respect to prior work, including a simple notion of label ordering based on subtyping, support for recursive declassification policies, and a local, modular reasoning principle for relaxed noninterference. This work paves the way for integrating declassification policies in practical security-typed languages.

5.2. Multiparty Reactive Sessions

Synchronous reactive programming (SRP) is a well-established programming paradigm whose essential features are logical instants, broadcast events and event-based preemption. This makes it an ideal vehicle for the specification and analysis of reactive systems, and indeed several programming languages and frameworks based on SRP have been put forward. On the other hand, *session-based concurrency* is the model of concurrent computation induced by *session types*, a rich typing discipline designed to specify the structure of interactions. In a nutshell, session types describe communication protocols between two or more participants by specifying the sequencing of messages along communication channels, as well as their functionality (sender, receiver and type of carried data). Originally conceived as a static analysis technique for an enhanced version of the π-calculus, session types have been subsequently transferred to functional, concurrent, and object-oriented programming languages, and adapted to support run-time verification.

A combination of session-based concurrency and SRP features appears to be appropriate to specify and analyse communication-centric systems in which some components may have a reactive and/or timed behaviour. In joint work with colleagues from I3S and the University of Groningen, currently submitted, we study the integration of SRP and session-based concurrency. To this end, we propose a calculus for multiparty sessions enriched with features from SRP. In this calculus, protocol participants communicate by broadcast messages, have the ability to suspend themselves while waiting for an absent message, and may react to the presence of particular events by triggering alternative behaviours. We equip the calculus with a session type system which enforces expected session properties such as communication safety, protocol fidelity, and input lock freedom. This session type system departs significantly from existing ones: the interplay of classical, well-established assumptions of SRP with session-based constructs requires revisiting central notions of multiparty session types, such as those of global type, local type and projection.

5.3. Multiparty Reversible Sessions

Reversibility has been an active trend of research for the last fifteen years. A reversible computation is a computation that has the ability to roll back to a past state. Allowing computations to reverse is a means to improve system flexibility and reliability. In the setting of concurrent process calculi, reversible computations have been first studied for CCS, then for the π-calculus, and only recently for session calculi. In [14] we present a multiparty session calculus with reversible computations. Our proposal improves on existing reversible session calculi in several respects: it allows for concurrent and sequential composition within processes and types, it gives a compact representation of the *past* of processes and types, which facilitates the definition of rollback, and it implements a fine-tuned strategy for backward computation. We propose a refined session type system for this calculus and show that it enforces the expected properties of session fidelity, forward and backward progress, as well as causal consistency. In conclusion, our calculus is a conservative extension of previous proposals, offering enhanced expressive power and refined analysis techniques.

5.4. JavaScript ahead-of-time compilation

Nowadays, JavaScript is no longer confined to the programming of web pages. It is also used for programming server-side parts of web applications, compilers, and there is a growing trend for using it for programming internet-of-things (IoT) applications. All major industrial actors of the field are looking for, or are already providing, JavaScript based development kits (IoT.js, Espruino, JerryScript, Kinoma.js, ...). In this application domain, JavaScript programs execute on tiny devices that have limited hardware capacities, for instance only a few kilobytes of memory. Just-in-time (JIT) compilation, which has proved to be so effective for improving JavaScript performances, is unthinkable in these constrained environments. There would be just not enough memory nor CPU capacity to execute them at runtime. Pure JavaScript interpreters are then used but this comes with a strong performance penalty, especially when compared to assembly or C programs, that limits the possible uses.

When JIT compilation is not an option and when interpretation is too slow, the alternative is static compilation, also known as ahead-of-time (AOT) compilation. It has the promise of combining small memory footprints and good performances. However, this implementation technique seems not to fit the JavaScript design whose unique combination of antagonistic features such as functional programming support, high mutation rates of applications, introspection, and dynamicity, makes most known classical AOT compilation techniques ineffective.

Indeed, JavaScript is hard to compile, much harder than languages such as C, Java, and even harder than other functional languages like Scheme and ML. This is because a JavaScript source code accepts many more possible interpretations than other languages do. It forces JavaScript compilers to adopt a defensive position by generating target codes that can cope with all the possible, even unlikely, interpretations. This difficulty probably explains why JavaScript AOT compilation has received so little attention from the scientific community. All these difficulties cannot be solved with traditional compilation techniques. They demand new strategies. This is what we explore. We are developing a prototype of a new compiler that distinguishes from classical compilers by relying on static program analyses that are not governed by approximating all possible program executions but by inferring properties that suit the compiler back-end. For instance, instead of inferring types that describe a super set of all possible executions, this compiler infers types for which the compiler is able to deliver good code.

The whole year has been devoted to implementing an operational prototype of the compiler. The preliminary results we have obtained are very promising but we still have to improve the code generation quality before writing and publishing complete reports describing it. This will be one of our main objectives for 2018.

5.5. Orchestration of Web applications

Modern Web applications are composed of numerous heterogeneous actors (users, distant servers and services, IoT devices, etc.) interacting together by means of asynchronous events. The harmonious interaction between these actors is called *orchestration*. JavaScript, the mainstream language for writing Web applications, enables programmers to orchestrate events with an asynchronous event-loop. However, event-loop based orchestration is known to be a difficult problem leading to programs which are difficult to write, read and maintain. To address this problem, Hiphop.js, a domain-specific language (DSL), has been developed during the last two years. It extends JavaScript by means of *temporal constructors* allowing explicit synchronization, parallelism and preemption. These constructors are inspired from the Esterel synchronous language.

During this year Hiphop.js has gained in maturity. First, a development environment has been developed. It is now possible to debug Hiphop.js programs by visualizing the code source during the execution, inspecting instructions state and signals value. Moreover, it is possible to queue reactions in order to analyze step-by-step the global state of the program between each reaction. The debugger can also be used and controlled remotely, using a simple Web browser. It is an important feature since Hiphop.js applications can run on different types of devices, especially smartphones or headless devices, on which debugging is impossible. Besides, in order to have a deeper integration with JavaScript and to make the adoption of Hiphop.js easier for new users, a new syntax has been designed and implemented.

A short paper describing HipHop has been accepted for publication at the SAC'18 symposium.

Finally, Hiphop.js is used in the context of a music show during the *MANCA* (http://www.cirm-manca.org/manca2017/) festival in Nice. It is used to orchestrate the composition of lights and songs during the show. Moreover, the public can interact with musicians by the means of smartphones, playing specific songs during delimited periods of the performance. Those interactions are implemented using Hiphop.js.

5.6. On the Content Security Policy Violations due to the Same-Origin Policy

Modern browsers implement different security policies such as the Content Security Policy (CSP), a mechanism designed to mitigate popular web vulnerabilities, and the Same Origin Policy (SOP), a mechanism that governs interactions between resources of web pages.

In the work [17], we describe how CSP may be violated due to the SOP when a page contains an embedded iframe from the same origin. We analyse 1 million pages from 10,000 top Alexa sites and report that at least 31.1% of current CSP-enabled pages are potentially vulnerable to CSP violations. Further considering real-world situations where those pages are involved in same-origin nested browsing contexts, we found that in at least 23.5% of the cases, CSP violations are possible.

During our study, we also identified a divergence among browsers implementations in the enforcement of CSP in srcdoc sandboxed iframes, which actually reveals a problem in Gecko-based browsers CSP implementation. To ameliorate the problematic conflicts of the security mechanisms, we discuss measures to avoid CSP violations.

5.7. Control What You Include! Server-Side Protection Against Third Party Web Tracking

Third party tracking is the practice by which third parties recognize users accross different websites as they browse the web. Recent studies show that 90% of websites contain third party content that is tracking its users across the web. Website developers often need to include third party content in order to provide basic functionality. However, when a developer includes a third party content, she cannot know whether the third party contains tracking mechanisms. If a website developer wants to protect her users from being tracked, the only solution is to exclude any third-party content, thus trading functionality for privacy.

We describe and implement a privacy-preserving web architecture [16] that gives website developers a control over third party tracking: developers are able to include functionally useful third party content, and at the same time ensuring that the end users are not tracked by the third parties.

5.8. A Better Facet of Dynamic Information Flow Control

Multiple Facets (MF) is a dynamic enforcement mechanism which has proved to be a good fit for implementing information flow security for JavaScript. It relies on multi executing the program, once per each security level or view, to achieve soundness. By looking inside programs, MF encodes the views to reduce the number of needed multi-executions.

We extend Multiple Facets in three directions. First, we propose a new version of MF for arbitrary lattices, called Generalised Multiple Facets, or GMF. GMF strictly generalizes MF, which was originally proposed for a specific lattice of principals. Second, we propose a new optimization on top of GMF that further reduces the number of executions. Third, we strengthen the security guarantees provided by Multiple Facets by proposing a termination sensitive version that eliminates covert channels due to termination.

5.9. Impossibility of Precise and Sound Termination Sensitive Security Enforcements

An information flow policy is termination sensitive if it imposes that the termination behaviour of programs is not influenced by confidential input. Termination sensitivity can be statically or dynamically enforced. On one hand, existing static enforcement mechanisms for termination sensitive policies are typically quite conservative and impose strong constraints on programs like absence of while loops whose guard depends on confidential information. On the other hand, dynamic mechanisms can enforce termination sensitive policies in a less conservative way. SME, one of such mechanisms, was even claimed to be sound and precise in the sense that the enforcement mechanism will not modify the observable behaviour of programs that comply with the termination sensitive policy. However, termination sensitivity is a subtle policy, that has been formalized in different ways. A key aspect is whether the policy talks about actual termination, or observable termination.

We prove that termination sensitive policies that talk about actual termination are not enforceable in a sound and precise way. For static enforcements, the result follows directly from a reduction of the decidability of the problem to the halting problem. However, for dynamic mechanisms the insight is more involved and requires a diagonalization argument.

In particular, our result contradicts the claim made about SME. We correct this claim by showing that SME enforces a subtly different policy that we call indirect termination sensitive noninterference and that talks about observable termination instead of actual termination. We construct a variant of SME that is sound and precise for indirect termination sensitive noninterference. Finally, we also show that static methods can be adapted to enforce indirect termination sensitive information flow policies (but obviously not precisely) by constructing a sound type system for an indirect termination sensitive policy.

5.10. BELL: Browser fingerprinting via Extensions and Login-Leaks

Recent work showed that websites can detect browser extensions that users install and websites they are logged into. This poses significant privacy risks, since extensions and Web logins can leak sensitive information and be used to track users via fingerprinting.

In joint work with Gabor Gulyas and Claude Castelluccia (Privatics team, Inria Grenoble), we report on the first large-scale study of this new form of fingerprinting, based on more than 16,000 users who visited our website [0]. Our website identifies installed Google Chrome extensions via Web Accessible Resources, and detects logged in websites by methods that rely on URL redirection and CSP violation report. Our website is able to test and detect the presence of 16,743 Chrome extensions, covering 28% of all free Chrome extensions. We also test whether the user is connected to 60 different websites.

We compute uniqueness of collected fingerprints, and find out that 54.86% of users that have installed at least one detectable extension are unique; 19.53% are unique because they logged in one or more detectable websites; and 89.23% of users are unique because they have at least one extension and one login detected.

We optimize the fingerprinting algorithm and show that it is possible to fingerprint a user in less than 625 milliseconds by selecting the most identifying combinations of extensions. Moreover, we discover that 22.98% of users can be uniquely identified and tracked by Web logins, even if they disable JavaScript. We conclude with possible countermeasures.

[0] https://extensions.inrialpes.fr/

5.11. Large-scale measurement of invisible images for Web tracking

In joint work with Arnaud Legout (DIANA team, Inria Sophia Antipolis), we perform large scale Web measurements to evaluate Web tracking and privacy leaks in every-day Web browsing. Unlike the related work, our study focuses on the third-party HTTP requests for invisible images. We have identified two types of images that are invisible to the end user and most likely used for Web tracking: one-pixel images and empty images.

We have visited 4,351,318 pages from 38,000 web sites and identified that almost half of the third-party images are invisible to the end user. This finding raises a lot of concerns regarding Web tracking and user privacy on the Web. We made the first evaluations on how much of this invisible tracking is prevented by the popular browser extensions used for the privacy protection. We also find the top invisible trackers and the invisible trackers not blocked by the browser extensions.

We continue this work by analysing all the HTTP requests and responses that lead to invisible images in order to (1) provide a fine-grained classification of third-party cookie tracking; (2) analyse new techniques of cookie-synching used by the companies; (3) evaluate redirection chains that lead to user's information exchange between various companies; (4) identify companies that use invisible images for none of the known tracking techniques, and analyse such requests and responses further to reveal new Web tracking technologies.

KAIROS Team

6. New Results

6.1. Formal Model-Based, Platform-Based System Engineering for CPS heterogeneous systems

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

The proper inclusion of our models and techniques into a realistic or proto-industrial design flow is a topic of discussion with partners, which brings back a number of fundamental issues about the nature of modeling itself, specially to allow and promote further analysis. The modeling of execution platforms, which may seem primarily architectural, is itself in fact subject to combined physical model interplay with functionality (as in power consumption and heat dissipation in processors); Internet of Things and industrial embedded systems are new specific focuses for us here. In this context we have been concentrating in the course of the PIA Clarity project (see 7.1) on the CAPELLA system engineering language, and its multi-view aspects; in the new IRT Saint-Exupery ATIPPIC collaboration we intend to focus on a realistic-scale use-case modeled with CAPELLA and proper formal annotations for the design of micro-satellite systems with COTS processor architectures.

6.2. Cyber extensions for the FMI physical API

Participants: Julien Deantoni, Giovanni Liboni, Robert de Simone.

The challenge here is to specify how an appropriate behavioral interface can be specified at the language level so that individual simulators can provide sufficient interface information to allow their correct coordination in terms of correctness and performance. Using our modeling approaches to describe formally the specificities of simulators and scheduling patterns, maybe even targeting synthesis of efficient interactions, is a new research topic [9], conducted in art in the context of the GLOSE project (see 7.1.2) in collaboration with SAFRAN tech.

6.3. Logical Time and Uncertain Physical environments

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

We developed a specific formalism to express logical time constraints on models. Currently it remains mainly aimed at purely “cyber” models. Combination with continuous physical models, and stochastic uncertainty, will be further studied at the level of constraint expressiveness. The issue of expressing meaningful discrete clocks from stochastic clock schemes, and combining the resulting clocks borne from physics to other clocks borne from sampling oberver environment, is a topic of collaboration with ECNU Shanghai through the PhD long-term visit of AN Dongdong to Sophia, and other discusions as well [3].

6.4. Automatic analysis and verification for specific classes of models

Participants: Robert de Simone, Frédéric Mallet, Emilien Kofman, Julien Deantoni.

This part aims at continuing and extending our work on “mostly-automatic”verification, with SMT solvers and model-checking in place to compute optimal scheduling and allocation, for instance. The new expressiveness of CPS adds new challenges [10]. While the global problem of schedulability for a generic CCSL specification is an open problem. We have identified a particular subclass of scheduling called "periodic scheduling" and establish a sufficient conditions for detecting if there is a valid periodic scheduling for a given CCSL specification. This condition is checked using the MAUDE rewriting system that directly encodes the operational semantics of CCSL [8]. However, the performances highly depend on the "period" of the periodic scheduling.

A more efficient solution based on SMT solver is under investigation and has given first encouraging results. A specific direction is reported in Emilien Kofman PhD thesis [1].

6.5. Behavioral semantics and equivalence notions for Open Systems

Participants: Eric Madelaine, Xudong Qin.

Model-Based Design naturally implies model transformations. To be proven correct, they require equivalence of “Open” terms, in which some individual component models may be omitted. Proper behavioral equivalence in the domain of CPS (which may include variants) is the challenge here. Such models take into account various kind of data parameters, including, but not limited to, time. The middle term goal is to build a formal framework, but also an effective tool set, for the compositional analysis of such programs. Our joint work (between Eric Madelaine and Ludovic Henrio from France, professors Zhang Min, Deng Yuxin and students from ECNU) on symbolic approaches to the composition of concurrent processes has progressed mainly on the pratical side, with an implementation of a prototype algorithm computing the symbolic semantics (called Open Automata) of open systems, and validating the approach for encoding constructs of various formalisms. A paper has been submitted for publication. As a particular set of use-cases, we have started using pNets to encode the behavior of “Architecture Templates” of the BIP language, with the aim of proving generic properties of these constructs, and building full systems by combining such architectures, with proven guarantees.

We have published preliminary work proposing a framework for open systems defining their symbolic semantics and some verification mechanisms (equivalences, model-checking), and we have started developping prototype tools supporting this approach.

This is joint work with ZHANG Min, from ECNU Shanghai, partially conducted in the framework of the FM4CPS associated-team.

6.6. Formal model of computations, mobility and resource discovery adapted for CPS

Participants: Robert de Simone, Luigi Liquori.

We will adapt formal Models of Computations and formal system like Type Theory to capture properties for distributed, networked and mobile CPS. Discovering and synchronizing, possibly in presence of mobility, are important issues in CPS. We will extend our past distributed resource discovery model with a notion of logical time; the difficulty comes to both discover and synchronize CPSs having different logical times.

6.7. Logical Frameworks with logical time

Participants: Luigi Liquori, Robert de Simone.

Adapting the Logical Framework (LF) based on Type Theory to better understand the analysis and verification of CPS is the challenge here. Previous works on extending Logical Framework with Locked Types and Proof-functional logics could captures the notion synchronizing (via a suitable constraint resolution) two proof systems: the internal and the external one; this type can be viewed as a form of communication between the internal and the external logic. Applications could be feed by suitable outputs of the CPS co-modeling pillar phase like, e.g. CCSL expressions.

6.8. From code to model

Participant: Sid Touati.

This research result is about modeling code performances using gaussian mixtures. Thanks to this performance model, we propose additional precise performance metrics. Our additional statistical metrics for analysing and comparing program performances give the user more precise decision tools to select best code versions, not necessarily based on mean or median numbers. Also, we provide a new metric to estimate performance variability based on Gaussian mixture model. Our statistical methods are implemented with R and distributed as open source code.

This is a collaboration with Julien Worms (LMV, UVSQ), reported in [7].

6.9. From model to code

Participants: Amine Oueslati, Robert de Simone, Arsak Megkrampian.

Synthesizing programs and algorithms in an optimal fashion may call for model transformations, as above, but also on careful tuning at program level, which make take into consideration a number of concrete phenomena absent from abstract models (at the cost of losing exhaustivity). Specific code optimization techniques in a CPS design context is the challenge here. WE are collaborating with Dumitru Potop-Butucaru (formerly from the Aoste team) on the topic, where he develops the LoPhT (Logical to Physical Time) environment dealing with these issues.

LAGADIC Project-Team

7. New Results

7.1. Visual Perception

7.1.1. Visual Tracking for Motion Capture

Participant: Eric Marchand.

This work is achieved in collaboration with Anatole Lécuyer (Inria Hybrid group) through the co-supervision of Guillaume Cortes Ph.D.

In the context of the development of new optical tracking devices, we propose an approach to greatly increase the tracking workspace of VR applications without adding new sensors [69]. Our approach relies on controlled cameras able to follow the tracked markers all around the VR workspace providing 6 DoF tracking data. We designed the proof-of-concept of such approach based on two consumer-grade cameras and a pan-tilt head. This approach has also been extended for the tracking of a drone in GPS denied environment [42].

We also achieved a short study related to the analysis of the 3D motion of head and hand in CAVE-based applications with the goal to optimize optical tracking sensors placement [43].

7.1.2. Object 3D Tracking based on Depth Information and CAD Model

Participants: Agniva Sengupta, Eric Marchand, Alexandre Krupa.

In the context of the iProcess project (see Section 9.3.3.2), we started this year a new study related to pose estimation and tracking of a rigid object observed by a RGB-D camera. We developed a pose estimation approach based on depth information measurement and the use of a CAD model represented by a 3D tetrahedral mesh. The pose parameters are estimated through an iterative optimization process that minimizes the point-to-plane Euclidean distance between the point cloud observed by the RGB-D camera and the surface of the 3D mesh. Preliminary results obtained with simple objects constituted by a set of orthogonal planes showed good performance of this approach. However, the method failed for the case of complex objects that exhibit important curvature surfaces. In order to address this issue we are currently extending the approach to take into account also the RGB information in the optimization criterion.

7.1.3. General Model-based Tracker

Participants: Souriya Trinh, Fabien Spindler, François Chaumette.

We have generalized the model-based tracker [2] available in ViSP [5] to integrate the depth information provided by a RGB-D sensor using the method described in the previous paragraph. It is now possible to fuse in the same optimization scheme measurements such as points of interest, edges, and depth, which allows to improve the robustness and accuracy of the tracker.

7.1.4. 3D Localization for Airplane Landing

Participants: Noël Mériaux, Pierre-Marie Kerzerho, Patrick Rives, Eric Marchand, François Chaumette.

This study was 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 implemented a direct registration method based on dense vision-based tracking that allows localizing the on-board camera from a set of keyframe images corresponding to the landing trajectory. First experiments with simulated and real images have been carried on with promising results. This approach is particularly interesting at the beginning of the descent when the landing track is far away and not very observable in the image. In that sense, the direct registration method is strongly complementary with the model-based approach studied before.

7.1.5. Extrinsic Calibration of Multiple RGB-D Cameras

Participants: Eduardo Fernandez Moral, Patrick Rives.

In collaboration with Alejandro Perez-Yus from the University of Zaragoza, we developed a novel method to estimate the relative poses between RGB and depth cameras without the requirement of an overlapping field of view, thus providing flexibility to calibrate a variety of sensor configurations. This calibration problem is relevant to robotic applications which can benefit of using several cameras to increase the field of view. In our approach, we extract and match lines of the scene in the RGB and depth cameras, and impose geometric constraints to find the relative poses between the sensors. In [31], an analysis of the observability properties of the problem is presented. We have validated our method in both synthetic and real scenarios with different camera configurations, demonstrating that our approach achieves good accuracy and is very simple to apply, in contrast with previous methods based on trajectory matching using visual odometry or SLAM.

7.1.6. Scene Registration with Large Convergence Domain

Participants: Renato José Martins, 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 [12]. The main idea is to explore the properties given by planar surfaces with co-visibility and their normals from two distinct viewpoints. We estimate, in two decoupled stages, the rotation and then the translation, both based on the normal vectors orientation and on the depth. These two stages are efficiently computed by using low resolution depth images and without any feature extraction/matching. In [53], we also analyze the limitations and observabilty of this approach, and its relationship to ICP point-to-plane. Notably, if the rotation is observable, at least five DoF can be estimated in the worst case. To demonstrate the effectiveness of the method, we evaluate the initialization technique in a set of challenging scenarios, comprising simulated spherical images from the Sponza Atrium model benchmark and real spherical indoor sequences.

7.1.7. Scene Semantization based on Deep Learning Approach

Participants: Eduardo Fernandez Moral, Patrick Rives.

Semantic segmentation of images is an important problem for mobile robotics and autonomous driving because it offers basic information which can be used for complex reasoning and safe navigation. This problem constitutes a very active field of research, where the state-of-the-art evolves continuously with new strategies based on different kinds of deep neural networks for image segmentation and classification. RGB-D images are starting to be employed as well for the same purpose to exploit complimentary information from color and geometry. The team LAGADIC has explored several strategies to increase the performance and the accuracy of semantic segmentation from RGB-D images. We propose a multi-pipeline architecture to exploit effectively the complimentary information from RGB-D images and thus to improve the semantic segmentation results. The multi-pipeline architecture processes the color and depth layers in parallel, before concatenating their feature maps to produce the final semantic prediction. Our results are evaluated on public benchmark datasets to show the improved accuracy of the proposed architecture. [46] Though we address this problem in the context of urban images segmentation, our results can also be extended to other contexts, like indoor scenarios and domestic robotics.

Our research is partly motivated by the need of semantic segmentation solutions with better segmentation around contours. Besides, we note that one of the main issues when comparing different neural networks architectures is how to select an appropriate metric to evaluate their accuracy. We have studied several metrics for multi-class classification, and we propose a new metric which accounts for both global and contour accuracy in a simple formulation to overcome the weaknesses of previous metrics. This metric is based on the Jaccard index, and takes explicitly into account the distance to the border regions of the different classes, to encode jointly the rate of correctly labeled pixels and how homeomorphic is the segmentation to the real object boundaries. We also present a comparative analysis of our proposed metric and several commonly used metrics for semantic segmentation together with a statistical analysis of their correlation.

7.1.8. Online Localization and Mapping for UAVs

Participants: Muhammad Usman, Paolo Robuffo Giordano.

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.

7.1.9. Reflectance and Illumination Estimation for Realistic Augmented Reality

Participants: Salma Jiddi, Eric Marchand.

A key factor for realistic Augmented Reality is a correct illumination simulation. This consists in estimating the characteristics of real light sources and use them to model virtual lighting. This year, we studied a novel method for recovering both 3D position and intensity of multiple light sources using detected cast shadows. Our algorithm has been successfully tested on a set of real scenes where virtual objects have visually coherent shadows [70].

7.1.10. Optimal Active Sensing Control

Participants: Marco Cognetti, Paolo Salaris, Paolo Robuffo Giordano.

This study concerns the problem of active sensing control whose objective is to reduce the estimation uncertainty of an observer as much as possible by determining the inputs of the system that maximize the amount of information gathered by the few noisy outputs while at the same time reduce the negative effects of the process/actuation noise. The latter is far from being negligible for several robotic applications (a prominent example being aerial vehicles).

Last year, we extended a previous work [9] to the case where the observability property is not instantaneously guaranteed, and hence the optimal estimation strategy cannot be given in terms of the instantaneous velocity direction of the robot and consequently of the onboard sensors. These outcomes of this research have been presented in [61] for nonlinear differentially flat systems. This year, we have moved some steps forward in order to improve and generalize the work in [61]: first of all, we have replaced the Observability Gramian (OG) with the Constructibility Gramian (CG). Despite their similar form, they differ from the fact that the OG measures the information collected along the path about the initial state of the nonlinear system while the CG measures the one about the current/final state with which most robotics applications are more concerned. Second, we have overcome the limit of previous work [61] that only deals with the case where the OG and the CG are known in closed-form. We have also applied our method to the unicycle vehicle which is a more complex dynamic system than the one used in [61] and tested our machinery to the cases of self-calibration and environment reconstruction. Moreover, thanks to the arrival of Marco Cognetti in our group as Post-doc, we are currently working on the application of our method to a quadrotor UAV, which is a much more complex dynamic system, for which the CG is not known in closed-form. The ultimate goal is to test our new machinery in a real experiment with a quadrotor UAV. Finally, we have also worked on the problem of considering the process/actuation noise in the optimization algorithm. As the CG (or the OG) does not take into account the degrading effects on the information collected through the outputs of the process/actuation noise, we have proposed to directly maximize the smallest eigenvalue of the covariance matrix given by the Riccati differential equation of the EKF, used as estimation algorithm. The results of this approach have been submitted to ICRA 2018.

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 LS2N in Nantes, France. It concerned 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 well-known case of using three image points as visual feature, and then solved the general case of n image points [16]. The case of three image straight lines has also been solved for the first time [17].

We have also designed a control scheme in order to avoid these singularities during the execution of a visual servoing scheme [38].

7.2.2. Visual Servoing through Mirror Reflection

Participants: François Chaumette, Eric Marchand.

Apart the use of catadioptric cameras, only few visual servoing works exploit the use of mirror. Such a configuration is however interesting since it allows overpassing the limited camera field of view. Based on the known projection equations involved in such a system, we studied the theoretical background that allows the control of planar mirror for visual servoing in different configurations. Limitations intrinsic to such systems, such as the number of DoF actually controllable, have been studied. The case of point feature was considered in [51] and this has been extended to line in [52].

7.2.3. Visual Servoing of Humanoid Robots

Participants: Giovanni Claudio, 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).

We have designed the modeling of the visual features at the acceleration level to embed visual tasks and visual constraints in an existing Quadratic Programming controller [13]. Experimental results have been obtained on Romeo (see Section 6.8.4).

7.2.4. Model Predictive Visual Servoing

Participants: Paolo Robuffo Giordano, François Chaumette.

This study was realized in collaboration with Pierre-Brice Wieber, from Bipop group at Inria Rhône Alpes, through the co-supervision of Nicolas Cazy's Ph.D.

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 study, 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 [41].

7.2.5. Model Predictive Control for Visual Servoing of a UAV

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

Visual servoing is a well-known 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 underactuation 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 chose to rely on MPC for explicitly dealing with this kind of constraints during flight. We have recently considered the problem of controlling in minimum-time a quadrotor UAV equipped with a downlooking camera that needs to reach a desired pose w.r.t. a target on the ground from visual input. The control problem is solved by an online replanning strategy that is able to generate (at camera rate) minimum-time trajectories towards the final pose while coping with actuation constraints (limited propeller thrusts) and sensing constraints (target always in the camera fov). By exploiting the camera images during motion, the replanning strategy is able to adjust online the optimal trajectory and, thus, be robust against unmodeled effects and other disturbances (which can be typically expected on a quadrotor flying aggressively). The approach has been validated via numerical simulations in [59]. We are now working towards an experimental validation, as well as novel algorithmic extensions allowing for the possibility of temporarily losing sight of the target object for relaxing the visibility constraint (and, thus, gain in maneuverability).

7.2.6. UAVs in Physical Interaction with the Environment

Participants: Quentin Delamare, Paolo Robuffo Giordano.

Most research in UAVs deals with either contact-free cases (the UAVs must avoid any contact with the environment), or in "static" contact cases (the UAVs need to exert some forces on the environment in quasi-static conditions, reminiscent of what has been done with manipulator arms). Inspired by the vast literature on robot locomotion (from, e.g., the humanoid community), in this research topic we aim at exploiting the contact with the environment for *helping* a UAV maneuvering in the environment, in the same spirit in which we humans (and, supposedly, humanoid robots) use our legs and arms when navigating in cluttered environments for helping in keeping balance, or perform maneuvers that would be, otherwise, impossible.

As an initial case study, we have considered a planar UAV equipped with a 1 DoF actuated arm capable of hooking at some pivots in the environment. This UAV (named MonkeyRotor) needs to "jump" from one pivot to the next one by exploiting the forces exchanged with the environment (the pivot) and its own actuation system (the propellers). This study considers the full dynamics in both cases (hooked, free-flying), proposes an optimization problem for finding optimal trajectories from an initial hooked configuration to the next one, and validates the approach in simulation. We are now working towards a physical realization of a first prototype. This activity is done in cooperation with LAAS-CNRS (Dr. Antonio Franchi who is co-supervising Quentin Delamare).

7.2.7. Visual Servoing for Steering Simulation Agents

Participants: Axel Lopez Gandia, Eric Marchand, François Chaumette, Julien Pettré.

Steering is one of the basic functionality of any character animation system. It provides characters with the ability to locally move in the environment so as to achieve basic navigation tasks, such as reaching a goal, avoiding a collision with an obstacles, etc. This problem has been explored in various contexts (e.g., motion planning, autonomous characters or crowd simulation). It turned out that this component plays an important role on the quality of character animation and received a lot of attention. Many important steps have been taken to improve steering techniques: potential fields, sets of attractive and repulsive forces, linear programming in the velocity space, local optimization of navigation functions, etc. Each new category of approach leads to characters close to forming realistic trajectories when achieving navigation.

Nevertheless, all these techniques remain quite far from the way real humans form their locomotion trajectory, because they are all based on kinematics and geometry. Humans obviously do not solve geometrical problems of this nature while moving in their environment but control their motion from perceptual features, and more especially visual features they perceive from the environment. For simulating more accurately the perception-action loop used by humans to navigate in their environment, we developed a technique which provides characters with vision capabilities, by equipping them with a virtual retina on which we project information about their surroundings. In a first version, we projected information about the relative motion of objects around them, allowing characters to estimate the risk of collision they face, and to move so as to minimize this risk [21]. More recently, we projected a purely visual information, and we established the relations that exist between the visual features characters perceive and the motion they perform. This way, we are able to steer characters so as their visual flow satisfies some conditions, allowing them for example to reach a goal while avoiding surrounding obstacles, could they be static or moving.

7.2.8. Direct Visual Servoing

Participants: Quentin Bateux, Eric Marchand.

We have proposed a deep neural network-based method to perform high-precision, robust and real-time 6 DoF visual servoing [63]. We studied how to create a dataset simulating various perturbations (occlusions and lighting conditions) from a single real-world image of the scene. A convolutional neural network is fine-tuned using this dataset to estimate the relative pose between two images of the same scene. The output of the network is then employed in a visual servoing control scheme. The method converges robustly even in difficult real-world settings with strong lighting variations and occlusions.

7.3. Medical Robotics

7.3.1. Visual Servoing using Wavelet and Shearlet Transforms

Participants: Lesley-Ann Duflot, Alexandre Krupa.

In collaboration with Femto-ST lab in Besançon and the Research Group on Computational Data Analysis at Universitat Bremen, we developed a new generation of direct visual servoing methods in which the signal control inputs are the coefficients of a multiscale image representation. In particular, we considered the use of multiscale image representations that are based on discrete wavelet and shearlet transforms. We succeeded to derive an analytical formulation of the interaction matrix related to the wavelet and shearlet coefficients and experimentally demonstrated the performances of the proposed visual servoing approaches. We also considered this control framework in the design of a medical application which consists in automatically moving a biological sample carried by a parallel micro-robotic platform using Optical Coherence Tomography (OCT) as visual feedback. The objective is to automatically retrieve the region of the sample that corresponds to an initial optical biopsy for diagnosis purpose. First results obtained with a 3 DoF eye-to-hand visual servoing demonstrated the feasibility to use the wavelet coefficients of the OCT image as input of the control law.

7.3.2. 3D Steering of Flexible Needle by Ultrasound Visual Servoing

Participants: Jason Chevrie, Marie Babel, Alexandre Krupa.

We pursued our work on 3D steering of a flexible needle using ultrasound visual servoing [11]. This year, in collaboration with the Surgical Robotics Laboratory of the University of Twente, we developed a method to control a 2 DoF needle insertion device attached to the end-effector of a 6-DoF robotic arm in order to automatically insert a flexible needle toward a spherical target embedded in a moving biological tissue (bovine liver). We proposed a method that uses both base manipulation control and tip-based control while compensating the tissue motion to avoid lateral tearing. The visual feedback provided by the ultrasound probe was used to track the target and an electromagnetic tracker attached inside the needle was used to locate its tip. In this study, the motion compensation of the moving tissue was performed by minimizing the interaction force measured at the base of the needle insertion device. In our approach we used the generic task control framework to fuse the needle targeting and motion compensation tasks into a single control law. First experimental ex-vivo results demonstrated the efficiency of the proposed control to reach a target in moving biological tissue.

7.3.3. Robotic Assistance for Ultrasound Elastography by Visual Servoing, Force Control and Teleoperation

Participants: Pedro Alfonso Patlan Rosales, Alexandre Krupa.

This work concerns the development of a robotic assistant system for quantitative ultrasound elastography. This imaging modality provides the elastic parameters of a tissue which are commonly related with a certain pathology. It is performed by applying continuous stress variation on the tissue in order to estimate a strain map. Usually, this stress variation is performed manually by the user through the manipulation of the ultrasound probe and it results therefore in an user-dependent quality of the strain map. 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 [72]. This year we extended our previous robotic palpation system in order to perform 3D elastography and allow the user to teleoperate the probe orientation through a haptic device [56]. This extension is based on the use of a 3D ultrasound probe held by a 6 DoF robotic arm and the design of a new control law based on the task control framework that simultaneously performs three tasks: i) autonomous palpation by force control of the tissue required for the strain map estimation, ii) probe lateral alignment on a stiff target of interest for optimizing its visibility by visual servoing and iii) teleoperation of the probe orientation by the user for exploration purpose. Recently, we also proposed a solution that allows the estimation of the strain map of a moving tissue that is subject to physiological motion [57]. It is based on the combination of a non-rigid motion tracking of the tissue of interest in the ultrasound image and an automatic 6 DoF compensation of the perturbation motion by visual servoing using dense ultrasound information.

7.3.4. Haptic Guidance of a Biopsy Needle

Participants: Hadrien Gurnel, Alexandre Krupa.

We started a new study in collaboration with Maud Marchal (Inria Hybrid group) related to the assistance of manual needle steering for biopsies or therapy purposes (see Section 9.1.7). Instead of automatically inserting the needle by a robotic arm as we did in other works, our objective is to develop a solution that provides haptic cue feedback to the clinician that helps him during its manual gesture. The haptic cue feedback will be provided by a haptic device holding the needle. This year we developed a software tool that simulates and visualizes the interaction of a virtual needle with a deformable virtual organ. This organ is represented by a 3D mesh and a mass-spring-damper model was considered to simulate its deformation due to the needle insertion motion. The development of this software was based on our libraries UsTk and ViSP and the external library VTK (Visualization Toolkit). We also interfaced to this simulator our Haption Virtuose 6D haptic device to allow the user to teleoperate the virtual needle and to feel the force applied by the needle on the virtual tissue. This simulator will constitute an important tool for our future development of dynamic haptic guides before testing them in a real experimental setup.

7.4. Teleoperation

7.4.1. Shared Control for Remote Manipulation

Participants: Firas Abi Farraj, 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. Recently, we have extended this framework in several directions:

1. in a first extension, the existing instantaneous interface has been improved towards an "integral" approach in which the user can command parts of the future manipulator trajectory, while the autonomy makes sure that no constraint is violated (in this case we considered, again, joint limits and singularities, as well as a more realistic vision constraint for keeping the gripper and the object always in visibility and not overlapping). This shared control algorithm was validated in simulation in [58]. We are currently completing a full implementation on our dual-arm system (the two Viper robots);
2. second, we have 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 [37];
3. third, we have considered a grasping scenario in which a post-grasp task is specified (e.g., the grasped object needs to follow a predefined trajectory): in this scenario, the operator (supported by the robot autonomy) needs to decide where to best grasp in order to then execute the desired post-grasp action. However, different grasping poses will result in easier/harder execution by the robot because of any possible constraint (e.g., joint limits and singularities). Since awareness of these constraints is hard for any operator, in this case the autonomy component cues the operator with a force feedback indicating the best grasp pose w.r.t. the existing constraints and post-grasp task. The operator has still control over where to grasp, but she/he is guided by the force feedback into more feasible grasp poses than what she/he could have guessed without any feedback [48];
4. finally, we have considered the task of assisting an operator in control of a UAV which is mapping a remote environment with an onboard camera. In this scenario the operator can control the UAV motion during the mapping task. However, as in any estimation problem, different motions will result less/more optimal w.r.t. the scene estimation task: therefore, a force feedback is produced in order to assist the operator in selecting the UAV motion (in particular, its linear velocity) that also results optimal for the sake of facilitating the scene estimation process. The results have been validated with numerical simulations in a realistic environment [39].

7.4.2. Wearable haptics

Participants: Marco Aggravi, Claudio Pacchierotti.

Kinesthetic haptic feedback is used in robotic teleoperation to provide the human operator with force information about the status of the slave robots and their interaction with the remote environment. Although kineshetic feedback has been proven to enhance the performance of teleoperation systems, it still shows several limitations, including its negative effect on the safety and stability of such systems, or the limited workspace, available DoF, high cost, and complexity of kinesthetic interfaces. In this respect, wearable haptics is gaining great attention. Safe, compact, unobtrusive, inexpensive, easy-to-wear, and lightweight haptic devices enable researchers to provide compelling touch sensations to multiple parts of the body, significantly increasing the applicability of haptics in many fields, such as robotics, rehabilitation, gaming, and immersive systems.

In this respect, our objective has been to study, design, and evaluate novel wearable haptic interfaces for the control of remote robotic systems as well as interacting with virtual immersive environments.

We have started by working on a multi-point wearable feedback solution for robotic manipulators operating in a cluttered environment [40]. The slave system is composed of an anthropomorphic soft robotic hand attached to a 6-axis force-torque sensor, which is in turn fixed to a 6-DoF robotic arm. The master system is composed of a Leap Motion controller and two wearable vibrotactile armbands, worn on the forearm and upper arm. The Leap Motion tracks the user's hand pose to control the pose of the manipulator and the grasping configuration of the robotic hand. The armband on the forearm conveys information about collisions of the slave hand/wrist system (green patch to green armband, see Fig. 8), whereas the armband on the upper arm conveys information about collisions of the slave arm (orange patch to orange armband). The amplitude of the vibrotactile feedback relayed by the armbands is proportional to the interaction force of the collision. A camera mounted near the manipulator's end-effector enables the operator to see the environment in front of the robotic hand. To validate our system, we carried out a human subjects telemanipulation experiment in a cluttered scenario. Twelve participants were asked to control the motion of the robotic manipulator to grasp an object hidden between debris of various shapes and stiffnesses. Haptic feedback provided by our wearable devices significantly improved the performance of the considered telemanipulation tasks. Finally, all subjects but one preferred conditions with wearable haptic feedback.

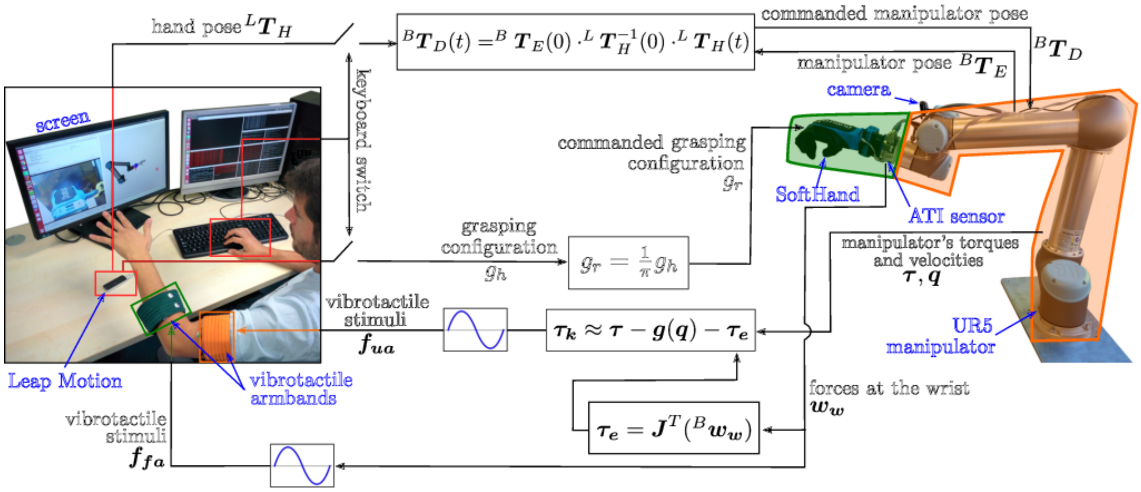


Figure 8. Haptic-enabled teleoperation system. We used two vibrotactile wearable devices to provide multi-point haptic feedback about collisions of the slave robot with the remote environment [40].

We have also used wearable haptics for guidance [20]. In this context, haptic feedback is not used to provide information about a force exerted by the salve robot in the remote environment, but it provides guidance cues about a predetermined trajectory to follow. Toward this, we developed a novel wearable device for the forearm. Four cylindrical rotating end effectors, located on the user's forearm, can generate skin stretch at the ulnar, radial, palmar, and dorsal sides of the arm. When all the end effectors rotate in the same direction, the cutaneous device is able to provide cues about a desired pronation/supination of the forearm. On the other hand, when two opposite end effectors rotate in opposite directions, the device is able to provide cutaneous cues about a desired translation of the forearm. Combining these two stimuli, we can provide both rotation and translation guidance. To evaluate the effectiveness of our device in providing navigation information, we carried out two experiments of haptic navigation. In the first one, subjects were asked to translate and rotate the forearm toward a target position and orientation, respectively. In the second experiment, subjects were asked to control a 6-DoF robotic manipulator to grasp and lift a target object. Haptic feedback provided by our wearable device improved the performance of both experiments with respect to providing no haptic feedback. Moreover, it showed similar performance with respect to sensory substitution via visual feedback, without overloading the visual channel.

Finally, we also used wearable haptics for immersive virtual and augmented reality experiences, mainly addressing tasks related to entertainment and industrial training. In these case, we used wearable devices for the fingertips able to provide pressure and skin stretch sensations [24]. This article has also been featured in the News section of Science Magazine.

We also presented a review paper on the topic of wearable haptic devices for the hand [29].

7.5. Navigation of Mobile Robots

7.5.1. Visual Navigation from an Image Memory

Participants: Paolo Robuffo Giordano, François Chaumette.

This study achieved during Suman Raj Bista's Ph.D. was 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 only, but on a combination of points of interest and straight lines since they are more common indoors [60]. Satisfactory experimental results have been obtained using the Pioneer mobile robot (see Section 6.8.2) and Pepper (See Section 6.8.4).

7.5.2. 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. Last year, we brought the empirical evidence that humans actually set a specific strategy to avoid robots: they showed a preference to give way to a robot [36]. However, the robot was passive, i.e., not reacting to the presence of participants. This year, we studied interactions between humans and reactive robot, performing avoidance maneuvers to avoid collisions. Our conclusions are that, in such situations of human-robot interactions, human behave again as during human-human avoidance interactions. Again, this study provides useful guidelines about the design of robot control techniques.

7.5.3. Semi-Autonomous Control of a Wheelchair for Navigation Assistance

Participants: Louise Devigne, Marie Babel.

In order to improve the access to mobility for people with disabilities, we have previously designed a semi-autonomous assistive wheelchair system which progressively corrects the trajectory as the user manually drives the wheelchair and smoothly avoids obstacles. Within the frame of ISI4NAVE associated team (see Section 9.4.1.2), we investigated probabilistic blending approaches which take into account uncertainty in the interaction [45]. We also designed a shared-control curb-following solution for outdoor assisted power wheelchair navigation. Once a curb is detected, user input is blended with constraints deduced from the distance from sensors to the detected curb. This provides an intuitive shared control scheme capable of assisting the user while needed i.e. while approaching a curb. Preliminary validation tests of the robotic system were conducted within the PAMELA facility.

Developing and testing such systems for wheelchair driving assistance requires a significant amount of material resources and clinician time. With Virtual Reality technology, prototypes can be developed and tested in a risk-free and highly flexible Virtual Environment before equipping and testing a physical prototype. Additionally, users can "virtually" test and train more easily during the development process. We then designed a power wheelchair driving simulator allowing the user to navigate with a standard wheelchair in an immersive 3D Virtual Environment. In order to validate the framework including the driving assistance solution, we performed tests on the Immersia platform (Inria Hybrid team) with able-bodied participants and we have shown that the simulator it generates a good sense of presence and requires rather low cognitive effort from users [44].

7.5.4. Wheelchair Kinematics and Dynamics Modeling for Shared Control

Participants: Aline Baudry, Marie Babel.

The driving experience of an electric powered wheelchair can be disturbed by unpleasant dynamic effects of the caster wheels, particularly during maneuvers in narrow rooms and direction changes. In order to prevent their nasty behaviour, we propose to model caster wheel kinematics and dynamics in order to implement a control law for a semi-autonomous assistance to maneuver in narrow environments. We conducted a preliminary study that has been achieved for our three types of wheelchair, each presenting different kinematic behaviors: front caster type, rear caster type and mid-wheel drive (see Figure 3 .c). Transfer functions for each of these configurations have been identified. We achieved to design a parametric transfer function of the caster's behavior regarding to the initial orientation, wheelchair's velocity and user mass, in order to develop a sensorless maneuver control law.

7.5.5. Wheelchair Autonomous Navigation for Fall Prevention

Participants: Solenne Fortun, Marie Babel.

The Prisme project (see Section 9.1.8) is devoted to fall prevention and detection of inpatients with disabilities. For wheelchair users, falls typically occur during transfer between the bed and the wheelchair and are mainly due to a bad positioning of the wheelchair. In this context, the Prisme project addresses both fall prevention and detection issues by means of a collaborative sensing framework. Ultrasonic sensors are embedded onto both a robotized wheelchair and a medical bed. The measured signals are used to detect fall and to automatically drive the wheelchair near the bed at an optimal position determined by occupational therapists. We first designed a detection solution based on a multiple echoes technique that enhances the system perception abilities. This augmented perception system is planned to be used for wheelchair navigation as well as fall detection.

7.5.6. Robotic Platform for Assistance to People with Reduce Mobility

Participants: Dayana Hassan, Paolo Salaris, Patrick Rives.

The main objective of this work is to develop, in collaboration with AXYN Robotics (see Section 8.2.4), an intelligent vehicle to help elderly or persons with reduced mobility to move safely within a retirement home, an hospital or other much more crowded and dynamic environments. First of all, the vehicle has to be able to move within the environment while at the same time update the current map as accurately as possible. Once the map of the environment is available, the robot has to be able to plan the trajectory and reach a given destination. The robot should also follow a person taking into account social behaviors or bring towards a given destination, e.g. the canteen, making sure that an elderly person, affected e.g. by Alzheimer's disease, follows the robot. The robot should also work as an intelligent walker and help people in case of falling. In all these cases, it is very important to include humans (i.e. his/her model, his/her behaviors, his/her intentions etc.) within the study in order to develop adaptable human-aware path planning and control strategies. During this first year, the problem of following a person has been studied, starting from the literature, in order to find a suitable control scheme that merges feedback control laws, aimed at reactively cope with neighborhood environment events and feedforward ones, mainly intended to take into account the intentions of the person to follow, also including social behaviors.

7.6. Multi-robot and Crowd Motion Control

7.6.1. Rigidity-based Methods for Formation Control

Participants: Fabrizio Schiano, 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 our previous works we have addressed the problem of coordinating a team of quadrotor UAVs equipped with onboard cameras from which one could extract "relative bearings" (unit vectors in 3D) w.r.t. the neighboring UAVs in visibility. This problem is known as bearing-based formation control and localization. The basic assumption, however, was to always have a bearing rigid graph which may easily conflict with any sensing/communication constraint (measurements/edges can be lost whenever, e.g., a UAV leaves the camera fov, or it is occluded by another UAV/obstacle). In [62] we have then tackled the problem of "bearing rigidity maintenance" by studying how to formalize the problem of maintaining bearing rigidity over time despite possible sensing/communication constraints (min/max range, limited camera fov and occlusions in the reported work). Thanks to a suitable weighing machinery, we could define a "bearing rigidity eigenvalue" as a suitable metric for quantifying the degree of rigidity in the interaction graph, and then we could propose a gradient-based controller able to maintain the rigidity eigenvalue always positive (and, thus, guarantee bearing rigidity maintenance). The approach has been validated by experiments run on 5 quadrotor UAVs.

7.6.2. 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. Results have been obtained for image-based localization of a single UAV, enabling to characterize the pose uncertainty domain from measurements uncertainties [50], and also fusion with onboard proprioceptive sensors [49]. Extension to cooperative localization in a multi-UAV fleet has been studied in the two-robot case and continues as an ongoing work.

LEMON Team

6. New Results

6.1. Boundary conditions and Schwarz waveform relaxation method for linear viscous Shallow Water equations in hydrodynamics

In [1] we propose in the present work an extension of the Schwarz waveform relaxation method to the case of viscous shallow water system with advection term. We first show the difficulties that arise when approximating the Dirichlet to Neumann operators if we consider an asymptotic analysis based on large Reynolds number regime and a small domain aspect ratio. Therefore we focus on the design of a Schwarz algorithm with Robin like boundary conditions. We prove the well-posedness and the convergence of the algorithm.

6.2. Modeling and control of in-situ decontamination of large water resources

In [3] we address the problem of the optimal control of in situ decontamination of water resources. We review several modeling, simulation and optimization techniques for this problem and their results. We show the benefit of combining tools from finite dimensional optimal control theory and numerical simulations of hydrodynamics equations, for providing simple and efficient feedback strategies.

6.3. On nontraditional quasi-geostrophic equations

In [7] 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 carefully consider terms in δ/ε, where δ (aspect ratio) and ε (Rossby number) are both small numbers. We provide here some rigorous crossed-asymptotics with regards to these parameters, prove some mathematical results and compare QHQG and QG models.

6.4. Source term closures in shallow water models with porosity

In [4] the validity of flux and source term formulae used in shallow water models with porosity for urban flood simulations is assessed by solving the two-dimensional shallow water equations over computational domains representing periodic building layouts. The models under assessment are the Single Porosity (SP), the Integral Porosity (IP) and the Dual Integral Porosity (DIP) models. 9 different geometries are considered. 18 two-dimensional initial value problems and 6 two-dimensional boundary value problems are defined. This results in a set of 96 fine grid simulations. Analysing the simulation results leads to the following conclusions: (i) the DIP flux and source term models outperform those of the SP and IP models when the Riemann problem is aligned with the main street directions, (ii) all models give erroneous flux closures when is the Riemann problem is not aligned with one of the main street directions or when the main street directions are not orthogonal, (iii) the solution of the Riemann problem is self-similar in space-time when the street directions are orthogonal and the Riemann problem is aligned with one of them, (iv) a momentum balance confirms the existence of the transient momentum dissipation model presented in the DIP model, (v) none of the source term models presented so far in the literature allows all flow configurations to be accounted for(vi) future laboratory experiments aiming at the validation of flux and source term closures should focus on the high-resolution, two-dimensional monitoring of both water depth and flow velocity fields.

6.5. Consistency and bicharacteristic analysis of integral porosity shallow water models

The Integral Porosity and Dual Integral Porosity two-dimensional shallow water models have been proposed recently as upscaled models for urban floods. Very little is known so far about their consistency and wave propagation properties. Simple numerical experiments show that both models are unusually sensitive to the computational grid. In the present paper, a two-dimensional consistency and characteristic analysis is carried out for these two models. In [5] the following results are obtained: (i) the models are almost insensitive to grid design when the porosity is isotropic, (ii) anisotropic porosity fields induce an artificial polarization of the mass/momentum fluxes along preferential directions when triangular meshes are used and (iii) extra first-order derivatives appear in the governing equations when regular, quadrangular cells are used. The hyperbolic system is thus mesh-dependent, and with it the wave propagation properties of the model solutions. Criteria are derived to make the solution less mesh-dependent, but it is not certain that these criteria can be satisfied at all computational points when real-world situations are dealt with.

6.6. Dual integral porosity shallow water model for urban flood modelling

With CPU times 2 to 3 orders of magnitude smaller than classical shallow water-based models , the shallow water equations with porosity are a promising tool for large-scale modelling of urban floods. In [6], a new model formulation called the Dual Integral Porosity (DIP) model is presented and examined analytically and computationally with a series of benchmark tests. The DIP model is established from an integral mass and momentum balance whereby both porosity and flow variables are defined separately for control volumes and boundaries, and a closure scheme is introduced to link control volume-and boundary-based flow variables. Previously developed Integral Porosity (IP) models were limited to a single set of flow variables. A new transient momentum dissipation model is also introduced to account for the effects of sub-grid scale wave action on porosity model solutions, effects which are validated by fine-grid solutions of the classical shallow-water equations and shown to be important for achieving self-similarity in dam-break solutions. One-dimensional numerical test cases show that the proposed DIP model outperforms the IP model, with signicantly improved wave propagation speeds, water depths and discharge calculations. A two-dimensional field scale test case shows that the DIP model performs better than the IP model in mapping the floods extent and is slightly better in reproducing the anisotropy of the flow field when momentum dissipation parameters are calibrated.

6.7. DG method for dispersive Green-Naghdi equations

Concerning the development of the WaveBox code, we have introduced in [2] the first available numerical code allowing to solve some fully nonlinear and weakly dispersive asymptotic shallow water models on unstructured meshes. More precisely, we introduce a discontinuous Finite Element formulation (discontinuous-Galerkin) on simplicial unstructured meshes for the study of free surface flows based on the fully nonlinear and weakly dispersive Green-Naghdi equations. Working with a new class of asymptotically equivalent equations, which have a simplified analytical structure, we consider a decoupling strategy: we approximate the solutions of the classical shallow water equations sup- plemented with a source term globally accounting for the non-hydrostatic effects and we show that this source term can be computed through the resolution of scalar elliptic second-order sub-problems, with a use of a L-DG method. The assets of the proposed discrete formulation are: (i) the handling of arbitrary unstructured simplicial meshes, (ii) an arbitrary order of approximation in space, (iii) the exact preservation of the motionless steady states, (iv) the preservation of the water height positivity, (v) a simple way to enhance any numerical code based on the nonlinear shallow water equations. To improve the efficiency of the resolution of the elliptic part of the formulation, we also investigate the use of very recent skeleton Hybrid-High-Order (HHO) methods. These methods allow to dramatically reduce the number of degrees of freedom (DOF), using only the DOF located on the mesh skeleton. To initiate the development of such methods for nonlinear and un-stationnary problems, a new discrete formulation was developed for the advective Cahn-Hilliard equations in [17]. Such an approach will be extended to more complex asymptotic shallow water models in a near future.

MARELLE Project-Team

6. New Results

6.1. Implementing Theorem Proving in Higher Order Logic Programming

Participants: Enrico Tassi, Luc Chabassier, Cyril Cohen, Cvetan Dunchev [University of Bologna], Ferruccio Guidi [University of Bologna], Claudio Sacerdoti Coen [University of Bologna].

We are designing a Coq plugin named elpi providing an extension language based on λ-prolog to write new commands and tactics. This year, we re-designed the constraint handling engine of the elpi interpreter. Luc Chabassier illustrated the use of this extension on the problem of generating automatically equality test functions for arbitrary recursive types, together with their proof of correctness.

Another experiment was conducted by Cyril Cohen on using elpi to compute genericity theorems. For now the unary and binary cases have been covered in a concise fashion.

An article on this topic has been submitted to MSCS [19], a presentation will also be given at the CoqPL workshop [21].

6.2. Coqoon: An IDE for interactive proof development in Coq

Participants: Enrico Tassi, Alexander Faithfull [ITU Copenhagen], Jesper Bengtson [ITU Copenhagen], Carst Tankink.

The work of previous years on Coqoon has been published in an international journal [6].

6.3. Proofs of transcendence

Participants: Sophie Bernard, Yves Bertot, Laurence Rideau.

Sophie Bernard completed a proof of the Lindemann-Weierstrass theorem concerning the algebraic independence of spans of exponentials of rationally dependent numbers. This result required that we extend the theory of symmetric multivariate polynomials in order to formalize the notion of conjugates of a polynomial. This was described in an article presented at an international conference [13] and at a workshop associated to ANR project FastRelax.

6.4. 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], Simon Huber [Chalmers University, Sweden], Ralph Matthes [CNRS, University of Toulouse].

This work mainly concerns Univalent Foundations and Homotopy Type Theory, especially in the form of cubical type theory. The code is visible at https://github.com/mortberg/cubicaltt. This year, Anders Mörtberg has been working on formalizing cubical set models in univalent type theory and on extending cubical type theory with a general class of higher inductive types, in collaboration with Cyril Cohen, Thierry Coquand and Simon Huber.

Anders Mörtberg extended work with Ralph Matthes, Benedikt Ahrens and Vladimir Voevodsky on the representation of syntax of programming languages using category theory in univalent type theory. This paper was accepted for publication in JAR.

Anders Mörtberg also prepared a series of lectures introducing to cubical type theory. this lead to invited talks at the workshops "Type Theory based Tools (TTT)", and "Syntax and Semantics of Type Theory".

6.5. Formal study of double-word arithmetic algorithms

Participants: Laurence Rideau, Erik Martin-Dorel [IRIT Toulouse], 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" [24]. The formalization is progressing. A notable event is that we detected a small error in the article proof, which required a correction by the authors.

6.6. Formal study of comparisons between numbers in different formats

Participants: Laurent Théry, Arthur Blot, Jean-Michel Muller [CNRS and ENS Lyon].

We show how a library of formalized mathematics about continuous functions can be used to derive an algorithm that compares two floating point number one in base 2 and one in base 10 [14].

6.7. A formal study of the towers of Hanoi

Participant: Laurent Théry.

The towers of Hanoi is a classical example that illustrates the power of recursive programming. Proving that the recursive program solves the problem is elementary but proving that it is a minimal solver is harder. This is even more difficult if we consider the general problem that considers arbitrary starting and final positions. We present the formalisation of this problem in the Mathematical Component Library [22].

6.8. Formaly study of algorithms to compute π

Participants: Yves Bertot, Laurence Rideau, Laurent Théry.

We studied formal proofs for several algorithms used to computed π to very high precisions, the famous BBP formula and an algorithm derived from it and another algorithm based on arithmetic-geometric means that is used in the MPFR library. These results show that Coq can be used directly to compute a million decimals or the billionth hexa-decimal in isolation [5].

6.9. Formal foundations of 3D geometry for robot manipulators

Participants: Cyril Cohen, Reynald Affeldt [AIST, Japan].

We resumed our collaboration with the team at AIST for the formal description of robotics aspects [7]. Reynald Affeldt visited Sophia Antipolis for 10 days during which we improved the connection between our library for algebra and the Coquelicot library for analysis.

6.10. Formalization of Analysis concepts

Participants: Cyril Cohen, Damien Rouhling.

To study problems in control, we worked on the notion of compacts and showed how to express it using filters, as in Coquelicot.

We experimented with sets of notations to make computing with limits simpler. We also generalized the notion of "big enough" that can usually be found when reasoning about functions at infinity (or sequences) so that it now works with arbitrary filters. Finally, we started experimenting with a new point of view on "small o" notations.

We also started work on formalizing in Coq the Cauchy-Lipschitz theorem (also known as Picard-Lindelöf), which proves the existence and uniqueness of solutions to differential equations.

We expect all these small advances to prepare the ground for work on various aspects of robotics and control. Part of this work was published in an international conference [20].

6.11. Formalization of proofs in control theory

Participants: Damien Rouhling, Cyril Cohen.

We worked on dynamical systems and differential equations. Damien Rouhling fully formalized in Coq LaSalle's invariance principle with the help of Cyril Cohen. This principle uses Lyapunov functions to prove the stability of a dynamical system defined by a differential equation. We wrote a paper about this formalization, which has been published in the proceedings of the ITP 2017 conference [15].

We improved this formalization to apply this principle to an example of robotics and control theory. We formalized in Coq the correctness of a control function for an inverted pendulum. Damien Rouhling wrote a paper about this, accepted for publication at an international conference in early 2018 [20].

6.12. Formalization of graph algorithms

Participants: Yves Bertot, Cyril Cohen, Ran Chen [Chinese Academy of Science], Jean-Jacques Lévy [Pi.r2 and Chinese Academy of Science], Clément Sartori, Laurent Théry.

We studied algorithms to compute strongly connected components in graphs, as a way to prepare a comparative study with the work of Levy and Chen: "A Semi-Automatic Proof of Strong Connectivity" [23].

In a similar vein, Yves Bertot and Clément Sartori have been studying the combinatorial aspects of triangulations, and in particular Delaunay triangulations, seen as graphs. In the long run, we expect this effort to contribute to formal descriptions of Voronoi diagrams and uses in robot motion planning.

6.13. Extension of the CoqEAL library

Participants: Cyril Cohen, Enrico Tassi.

The CoqEAL library provides a framework to connect efficient executable functional programs to the algorithms that are described formally using the mathematical components library. Key aspects rely on the capacity to refine abstract views of the algorithms and data into concrete views, where the efficiency can be fine-tuned. For this refinement, we also need to rely on properties of programming languages such as parametricity. We experimented on relying on the ELPI plugin to implement this parametricity feature. In the long run, this means that the ELPI plugin should play an instrumental role in making CoqEAL easy to use and to extend.

6.14. Formalizing Exterior Algebras

Participants: Maxime Bombar, Cyril Cohen.

We formalized exterior algebras as vector spaces with dimension 2^n. This provides an alternative representation to that constructed earlier by Laurent Théry and Laurent Fuchs. The new representation is closer to the objects found in the mathematical components library.

6.15. Formalizing Cylindrical Algebraic Decomposition

Participants: Boris Djalal, Yves Bertot, Cyril Cohen.

Our study of cylindrical algebraic decomposition requires that we find a good representation of semi-algebraic sets, which are usually determined by a collections of comparisons between polynomial formulas. We wrote an article on this topic, which has been accepted for publication at an international conference to be held in early 2018 [18].

6.16. Formal study of probabilistic programs

Participants: Benjamin Grégoire, Gilles Barthe [IMDEA], François Dupressoir [University of Surrey], Thomas Espitau [UPMC Paris 6], Sebastian Faust [Ruhr Universitat Bochum], Justin Hsu [University of Pennsylvania], Vitor Pereira [INESC TEC], François-Xavier Standaert [Université Catholique de Louvain].

This year, we proposed new logics to make a link between "probabilistic Relationnal Hoare Logic" and the traditionnal notion of couplings from probability theory [12]. We have also showed that coupling can be use to prove non-relationnal properties like uniformity and probabilistic independence [11].

We used Easycrypt to prove the security of Secure Function Evaluation (SFE) based on garble circuits [9].

6.17. Generating Efficient Resistant Code

Participants: Benjamin Grégoire, José Bacelar Almeida [INESC TEC], Manuel Barbosa [INESC TEC], Gilles Barthe [IMDEA], Arthur Blot [ENS Lyon], Vincent Laporte [IMDEA], Tiago Oliveira [INESC TEC], Hugo Pacheco [INESC TEC], Benedikt Schmidt [Google Inc.], Pierre-Yves Strub [Ecole Polytechnique].

We develop a certified compiler named Jasmin to generate high-speed and high-assurance cryptographic code.

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/models allowing to check the correctness of counter measures (masking schemes) [10].

6.18. Formal Security Proof in EasyCrypt: case studies and extensions

Participants: Cécile Baritel-Ruet, Benjamin Grégoire.

We completed a formal proof of security for CMAC, a scheme for cipher-based message authentication code. A publication is being submitted on this topic. We also experimented on a formal study of the forking lemma, which is present in many security proofs for signing schemes that rely on lattice problems.

The lessons derived from these experiments lead us to proposing new tools for matching instructions and unifying formulas with meta-variables in EasyCrypt.

6.19. Formalizing Bourbaki-style mathematics

Participant: José Grimm.

Most of the work described here is inspired by the experiment of giving formal proofs in Coq of the exercises found in Bourbaki's exposition of set theory. However, some of the results go beyond what can be found in Bourbaki.

We studied order relations by proving several properties about the *length* and *width* of order relations, for instance showing that when a set has $nm + 1$ elements, the lengh or the with of any order on this set is larger than either n or m. We then considered similar theorems on the set of all parts of a given set, ordered by inclusion. In particular, this gives formal proofs of results by Dilworth and Erdös and Zserkeres.

We also studied ordinal addition, which is non-commutative. Given a finite sequence of ordinals, one can compute the number of different results of the sum of these elements, depending on the order in which this sequence is taken. There is an explicit formula for this number, with a proof that we formalized.

Last, we studied a footnote from Bourbaki, that indicates that 1 is a notation for a term whose normal form has several tens of thousands of signs. We compute this size (about 10^{13} or 10^{60} depending on whether some constructs are given by axioms or by definitions) and provide statistics on the distributions of signs in the normal form.

MATHNEURO Team

4. New Results

4.1. Neural Networks as dynamical systems

4.1.1. Latching dynamics in neural networks with synaptic depression

Participants: Elif Köksal Ersöz, Carlos Aguilar [Université de Nice - BCL], Pascal Chossat [Université de Nice - LJAD, Inria MathNeuro], Martin Krupa [UCA, Inria MathNeuro], Frédéric Lavigne [Université de Nice - BCL].

Prediction is the ability of the brain to quickly activate a target concept in response to a related stimulus (prime). Experiments point to the existence of an overlap between the populations of the neurons coding for different stimuli, and other experiments show that prime-target relations arise in the process of long term memory formation. The classical modelling paradigm is that long term memories correspond to stable steady states of a Hopfield network with Hebbian connectivity. Experiments show that short term synaptic depression plays an important role in the processing of memories. This leads naturally to a computational model of priming, called latching dynamics; a stable state (prime) can become unstable and the system may converge to another transiently stable steady state (target). Hopfield network models of latching dynamics have been studied by means of numerical simulation, however the conditions for the existence of this dynamics have not been elucidated. In this work we use a combination of analytic and numerical approaches to confirm that latching dynamics can exist in the context of a symmetric Hebbian learning rule, however lacks robustness and imposes a number of biologically unrealistic restrictions on the model. In particular our work shows that the symmetry of the Hebbian rule is not an obstruction to the existence of latching dynamics, however fine tuning of the parameters of the model is needed.

This work has been published in PLoS one and is available as [13].

A natural follow-up of the work which has lead to the article [13] has been initiated through the postdoc project of Elif Köksal Ersöz. The objective is to extend the previous results in several ways. First, to gain more robustness in the heteroclinic chains sustained by the network model. Second, to be able to simulate much larger networks and exhibit heteroclinic dynamics in them. Third, to link with experimental data. The postdoc of Elif Köksal Ersöz is funded by the "tail" of the ERC Advanced Grant NerVi held by Olivier Faugeras.

4.1.2. Special issue for Martin Golubitsky

Participants: Pietro-Luciano Buono University Of Ontario Institute Of Technology, Canada ,, Martin Krupa [UCA, Inria MathNeuro], Ian Stewart [University of Warwick, UK].

The work is the introducion of this special issue, co-edited by Martin Krupa. It has been published in Dynamical Systems: An International Journal and is available as [17].

4.1.3. Consecutive and non-consecutive heteroclinic cycles in Hopfield networks

Participants: Pascal Chossat [Université de Nice - LJAD, Inria MathNeuro], Martin Krupa [UCA, Inria MathNeuro].

We review and extend the previous work [38] where a model was introduced for Hopfield-type neural networks, which allows for the existence of heteroclinic dynamics between steady patterns. This dynamics is a mathematical model of periodic or aperiodic switching between stored information items in the brain, in particular, in the context of sequential memory or cognitive tasks as observed in experiments. The basic question addressed in this work is whether, given a sequence of steady patterns, it is possible by applying classical learning rules to build a matrix of connections between neurons in the network, such that a heteroclinic dynamics links these patterns. It has been shown previously that the answer is positive in the case where the sequence is a so-called simple consecutive cycle. We show that on the contrary the answer is negative for a non-simple cycle: heteroclinic dynamics does still exist; however, it cannot follow the sequence of patterns from which the connectivity matrix was derived.

This work has been published in Dynamical Systems: An International Journal and is available as [21].

4.1.4. Asymptotic stability of pseudo-simple heteroclinic cycles in $\mathbb{R}^4$

Participants: Pascal Chossat [Université de Nice - LJAD, Inria MathNeuro], Olga Podvigina [Institute of Earthquake Prediction Theory and Mathematical Geophysics, Russia].

Robust heteroclinic cycles in equivariant dynamical systems in $\mathbb{R}^4$ have been a subject of intense scientific investigation because, unlike heteroclinic cycles in $\mathbb{R}^3$, they can have an intricate geometric structure and complex asymptotic stability properties that are not yet completely understood. In a recent work [51], we have compiled an exhaustive list of finite subgroups of $O(4)$ admitting the so-called simple heteroclinic cycles, and have identified a new class which we have called pseudo-simple heteroclinic cycles. By contrast with simple heteroclinic cycles, a pseudo-simple one has at least one equilibrium with an unstable manifold which has dimension 2 due to a symmetry. Here, we analyze the dynamics of nearby trajectories and asymptotic stability of pseudo-simple heteroclinic cycles in $\mathbb{R}^4$.

This work has been published in Journal of Nonlinear Science and is available as [26].

4.1.5. The period adding and incrementing bifurcations: from rotation theory to applications

Participants: Albert Granados [Polytechnic University of Catalonia, Barcelona, Spain], Lluís Alsedà [Autonomous University of Barcelona, Spain], Martin Krupa [UCA, 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 published in SIAM Review and is available as [24].

4.1.6. Inverse correlation processing by neurons with active dendrites

Participants: Tomasz Górski [UNIC, CNRS, France], Romain Veltz, Mathieu Galtier [UNIC, CNRS, France], Helissande Fragnaud [UNIC, CNRS, France], Bartosz Teleńczuk [UNIC, CNRS, France], Alain Destexhe [UNIC, CNRS, France].

In many neuron types, the dendrites contain a significant density of sodium channels and are capable of generating action potentials, but the significance and role of dendritic sodium spikes are unclear. Here, we use simplified computational models to investigate the functional effect of dendritic spikes. We found that one of the main features of neurons equipped with excitable dendrites is that the firing rate of the neuron measured at soma decreases with increasing input correlations, which is an inverse relation compared to passive dendrite and single-compartment models. We first show that in biophysical models the collision and annihilation of dendritic spikes causes an inverse dependence of firing rate on correlations. We then explore this in more detail using excitable dendrites modeled with integrate-and-fire type mechanisms. Finally, we show that the inverse correlation dependence can also be found in very simple models, where the dendrite is modeled as a discrete-state cellular automaton. We conclude that the cancellation of dendritic spikes is a generic mechanism that allows neurons to process correlations inversely compared to single-compartment models. This qualitative effect due to the presence of dendrites should have strong consequences at the network level, where networks of neurons with excitable dendrites may have fundamentally different properties than networks of point neuron models.

This work has been submitted for publication and is available as [33].

4.2. Mean field theory and stochastic processes

4.2.1. Emergence of collective phenomena in a population of neurons

Participants: Benjamin Aymard, Fabien Campillo, Romain Veltz.

In this work, we propose a new model of biological neural network, combining a two-dimensional integrate-and-fire neuron model with a deterministic model of electrical synapse, and a stochastic model of chemical synapse. We describe the dynamics of a population of neurons in interaction as a piecewise deterministic Markov process. We prove the weak convergence of the associated empirical process, as the population size tends to infinity, towards a McKean-Vlasov type process and we describe the associated PDE. We are also interested in the simulation of these dynamics, in particular by comparing "detailed" simulations of a finite population of neurons with a simulation of the system with infinite population. Benjamin Aymard has the adapted toolkit to attack these questions numerically. The mean field equations studied by Benjamin are of transport type for which numerical methods are technical. However, they are the domain of expertise of Benjamin. His postdoc is funded by the Flagship Human Brain Project.

4.2.2. Off-line numerical Bayes identification of dynamical systems for life sciences

Participants: Fabien Campillo, Vivien Rossi [CIRAD].

In this project, we develop Monte Carlo algorithms for the identification of parameters and hidden components for dynamic systems used in the life sciences. The peculiarity of these systems and they do not require online processing and they call for data of various natures and sometimes low quality. We use particle filtering techniques so that we try to improve the prediction phases using MCMC techniques.

4.2.3. On the variations of the principal eigenvalue with respect to a parameter in growth-fragmentation models

Participants: Fabien Campillo, Nicolas Champagnat [Inria, project-team TOSCA, Nancy], Coralie Fritsch [Inria, project-team TOSCA, Nancy].

We study the variations of the principal eigenvalue associated to a growth-fragmentation-death equation with respect to a parameter acting on growth and fragmentation. To this aim, 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.

This work has been published in Communications in Mathematical Sciences and is available as [18].

4.2.4. Hopf bifurcation in a nonlocal nonlinear transport equation stemming from stochastic neural dynamics

Participants: Audric Drogoul [Thales, France], Romain Veltz.

In this work, we provide three different numerical evidences for the occurrence of a Hopf bifurcation in a recently derived mean field limit of a stochastic network of excitatory spiking neurons [40], [46]. The mean field limit is a challenging nonlocal nonlinear transport equation with boundary conditions. The first evidence relies on the computation of the spectrum of the linearized equation. The second stems from the simulation of the full mean field. Finally, the last evidence comes from the simulation of the network for a large number of neurons. We provide a "recipe" to find such bifurcation which nicely complements the works in [40], [46]. This suggests in return to revisit theoretically these mean field equations from a dynamical point of view. Finally, this work shows how the noise level impacts the transition from asynchronous activity to partial synchronization in excitatory globally pulse-coupled networks.

This work has been published in Chaos and is available as [22].

4.2.5. Mathematical statistical physics applied to neural populations

Participants: Émilie Soret, Olivier Faugeras, Étienne Tanré [Inria, project-team TOSCA, Sophia-Antipolis].

This project focuses on Mean-Field descriptions or thermodynamics limits of large populations of neurons. They study a system of Stochastic Differential Equations (SDEs) which describes the evolution of membrane potential of each neuron over the time when the synaptic weights are random variables (not assumed to be independent). This setup is well suited to Émilie, who has worked during her PhD and first postdoc on mathematical statistical physics and stochastic processes. Her postdoc is funded by the Flagship Human Brain Project.

4.2.6. A numerical approach to determine mutant invasion fitness and evolutionary singular strategies

Participants: Coralie Fritsch [Inria, project-team TOSCA, Nancy], Fabien Campillo, Otso Ovaskainen [University of Helsinki, Finland].

We propose a numerical approach to study the invasion fitness of a mutant and to determine evolutionary singular strategies in evolutionary structured models in which the competitive exclusion principle holds. Our approach is based on a dual representation, which consists of the modelling of the small size mutant population by a stochastic model and the computation of its corresponding deterministic model. The use of the deterministic model greatly facilitates the numerical determination of the feasibility of invasion as well as the convergence-stability of the evolutionary singular strategy. Our approach combines standard adaptive dynamics with the link between the mutant survival criterion in the stochastic model and the sign of the eigenvalue in the corresponding deterministic model. We present our method in the context of a mass-structured individual-based chemostat model. We exploit a previously derived mathematical relationship between stochastic and deterministic representations of the mutant population in the chemostat model to derive a general numerical method for analyzing the invasion fitness in the stochastic models. Our method can be applied to the broad class of evolutionary models for which a link between the stochastic and deterministic invasion fitnesses can be established.

This work has been published in Theoretical Population Biology and is available as [23].

4.3. Neural fields theory

4.3.1. Spatiotemporal canards in neural field equations

Participants: Daniele Avitabile [University of Nottingham, UK], Mathieu Desroches, Edgar Knobloch [University of California Berkeley, USA].

Canards are special solutions to ordinary differential equations that follow invariant repelling slow manifolds for long time intervals. In realistic biophysical single-cell models, canards are responsible for several complex neural rhythms observed experimentally, but their existence and role in spatially extended systems is largely unexplored. We identify and describe a type of coherent structure in which a spatial pattern displays temporal canard behavior. Using interfacial dynamics and geometric singular perturbation theory, we classify spatiotemporal canards and give conditions for the existence of folded-saddle and folded-node canards. We find that spatiotemporal canards are robust to changes in the synaptic connectivity and firing rate. The theory correctly predicts the existence of spatiotemporal canards with octahedral symmetry in a neural field model posed on the unit sphere.

This work has been published in Physical Review E and is available as [14].

4.3.2. 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, 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, centre 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 published in Physica D and is available as [27].

4.4. Slow-fast dynamics in Neuroscience

4.4.1. Ducks in space: from nonlinear absolute instability to noise-sustained structures in a pattern-forming system

Participants: Daniele Avitabile [University of Nottingham, UK], Mathieu Desroches, Edgar Knobloch [University of California Berkeley, USA], Martin Krupa [UCA, Inria MathNeuro].

A subcritical pattern-forming system with nonlinear advection in a bounded domain is recast as a slow-fast system in space and studied using a combination of geometric singular perturbation theory and numerical continuation. Two types of solutions describing the possible location of stationary fronts are identified, whose origin is traced to the onset of convective and absolute instability when the system is unbounded. The former are present only for non-zero upstream boundary conditions and provide a quantitative understanding of noise-sustained structures in systems of this type. The latter correspond to the onset of a global mode and are present even with zero upstream boundary conditions. The role of canard trajectories in the nonlinear transition between these states is clarified and the stability properties of the resulting spatial structures are determined. Front location in the convective regime is highly sensitive to the upstream boundary condition, and its dependence on this boundary condition is studied using a combination of numerical continuation and Monte Carlo simulations of the partial differential equation. Statistical properties of the system subjected to random or stochastic boundary conditions at the inlet are interpreted using the deterministic slow-fast spatial dynamical system.

This work has been published in Proceedings of the Royal Society A and is available as [15].

4.4.2. Canard dynamics and anticipated synchronisation in spiking models

Participants: Elif Köksal Ersöz, Mathieu Desroches, Claudio Mirasso [University of the Balearic Islands, Palma, Spain], Serafim Rodrigues [Ikerbasque, BCAM, Bilbao, Spain].

This project is on the phenomenon of anticipated synchronisation, studied theoretically in a number of models of excitable systems over the past fifteen years or so, and observed experimentally in laser systems. The idea is that when coupling two identical excitable system unidirectionally from a "master" system to a "slave" system with a delayed term of the slave's signal in its own differential equation, one may observe that the slave reacts to an external stimulus before the master, and this is referred to as *anticipation* or *anticipated synchronisation*. Even though a number of studies have reported and analysed this effect in various systems, its main underpinning mechanisms remain elusive. In the current project, we show that in the case where the systems have an explicit slow-fast nature, then the canard regime can induce anticipation and explain its feature. Our objective is to go beyond the theoretical explanation, on which we are currently preparing an article, and to propose an electrophysiological protocol so as observe this phenomenon in real neurons. This is very much related to the PhD work of Elif Köksal Ersöz on the synchronisation properties of canard oscillators, in particular to the paper [25] (see Section 4.4.5 below). This postdoc is funded by the "tail" of the ERC Advanced Grant NerVi held by Olivier Faugeras.

4.4.3. *Spike-adding in a canonical three time scale model: superslow explosion & folded-saddle canards*

Participants: Mathieu Desroches, Vivien Kirk [University of Auckland, New-Zealand].

We examine the origin of complex bursting oscillations in a phenomenological ordinary differential equation model with three time scales. We show that bursting solutions in this model arise from a Hopf bifurcation followed by a sequence of spike-adding transitions, in a manner reminiscent of spike-adding transitions previously observed in systems with two time scales. However, the details of the process can be much more complex in this three-time-scale context than in two-time-scale systems. In particular, we find that spike-adding can involve canard explosions occurring on two different time scales and is associated with passage near a folded-saddle singularity. We show that the form of spike-adding transition that occurs depends on the geometry of certain singular limit systems, specifically the relative positions of the critical and superslow manifolds. We also show that, unlike the case of spike-adding in two-time-scale systems, the onset of a new spike in our model is not typically associated with a local maximum in the period of the bursting oscillation.

This work has been submitted for publication and is available as [31].

4.4.4. *Piecewise-linear (PWL) canard dynamics: Simplifying singular perturbation theory in the canard regime using piecewise-linear systems*

Participants: Mathieu Desroches, Soledad Fernández-García [University of Sevilla, Spain], Martin Krupa [UCA, Inria MathNeuro], Rafel Prohens [University of the Balearic Islands, Spain], Antonio Teruel [University of the Balearic Islands, Spain].

In this chapter we gathered recent results on piecewise-linear (PWL) slow-fast dynamical systems in the canard regime. By focusing on minimal systems in $\mathbb{R}^2$ (one slow and one fast variables) and $\mathbb{R}^3$ (two slow and one fast variables), we proved the existence of (maximal) canard solutions and show that the main salient features from smooth systems is preserved. We also highlighted how the PWL setup carries a level of simplification of singular perturbation theory in the canard regime, which makes it more amenable to present it to various audiences at an introductory level. Finally, we presented a PWL version of Fenichel theorems about slow manifolds, which are valid in the normally hyperbolic regime and in any dimension, which also offers a simplified framework for such persistence results.

This work has been accepted for publication as a chapter in a book titled *Nonlinear Systems; Vol. 1: Mathematical Theory and Computational Methods* (Springer, in press) and is available as [28].

4.4.5. *Synchronization of weakly coupled canard oscillators*

Participants: Elif Köksal Ersöz, Mathieu Desroches, Martin Krupa [UCA, Inria MathNeuro].

Synchronization has been studied extensively in the context of weakly coupled oscillators using the so-called phase response curve (PRC) which measures how a change of the phase of an oscillator is affected by a small perturbation. This approach was based upon the work of Malkin, and it has been extended to relaxation oscillators. Namely, synchronization conditions were established under the weak coupling assumption, leading to a criterion for the existence of synchronous solutions of weakly coupled relaxation oscillators. Previous analysis relies on the fact that the slow nullcline does not intersect the fast nullcline near one of its fold points, where canard solutions can arise. In the present study we use numerical continuation techniques to solve the adjoint equations and we show that synchronization properties of canard cycles are different than those of classical relaxation cycles. In particular, we highlight a new special role of the maximal canard in separating two distinct synchronization regimes: the Hopf regime and the relaxation regime. Phase plane analysis of slow-fast oscillators undergoing a canard explosion provides an explanation for this change of synchronization properties across the maximal canard.

This work has been published in Physica D and is available as [25].

4.5. Models of neural excitability

4.5.1. Modeling cortical spreading depression induced by the hyperactivity of interneurons

Participants: Mathieu Desroches, Olivier Faugeras, Martin Krupa [UCA, Inria MathNeuro], Massimo Mantegazza [IMPC, Sophia Antipolis].

Cortical spreading depression (CSD) is a wave of transient intense neuronal firing leading to a long lasting depolarization block of neuronal activity. It is a proposed pathological mechanism of migraine with aura. Some molecular/cellular mechanisms of migraine with aura and of CSD have been identified studying a rare mendelian form: familial hemiplegic migraine (FHM). FHM type 1 & 2 are caused by mutations of the CaV2.1 Ca^{2+} channel and the glial Na^{+} / K^{+} pump, respectively, leading to facilitation of CSD in mouse models mainly because of increased glutamatergic transmission/extracellular glutamate build-up. FHM type 3 mutations of the SCN1A gene, coding for the voltage gated sodium channel NaV1.1, cause gain of function of the channel and hyperexcitability of GABAergic interneurons. This leads to the counterintuitive hypothesis that intense firing of interneurons can cause CSD ignition. To test this hypothesis in silico, we developed a computational model of an E-I pair (a pyramidal cell and an interneuron), in which the coupling between the cells in not just synaptic, but takes into account also the effects of the accumulation of extracellular potassium caused by the activity of the neurons and of the synapses. In the context of this model, we show that the intense firing of the interneuron can lead to CSD. We have investigated the effect of various biophysical parameters on the transition to CSD, including the levels of glutamate or GABA, frequency of the interneuron firing and the efficacy of the KCC2 co-transporter. The key element for CSD ignition in our model was the frequency of interneuron firing and the related accumulation of extracellular potassium, which induced a depolarization block of the pyramidal cell. Our model can be used to study other types of activities in microcircuits and of couplings between excitatory and inhibitory neurons.

This work has been submitted for publication and is available as [30].

MCTAO Project-Team

6. New Results

6.1. Stability properties of geodesic flows on Riemannian manifolds

Participants: Ludovic Rifford, Rafael Ruggiero [PUC, Rio de Janeiro, Brazil].

In a paper by Rifford and Ruggiero [25], the C^2-structural stability conjecture from Mañé's viewpoint for geodesics flows of compact manifolds without conjugate points is investigated. The structural stability conjecture is an open problem in the category of geodesic flows because the C^1 closing lemma is not known in this context. Without the C^1 closing lemma, we combine the geometry of manifolds without conjugate points and a recent version of Franks' Lemma from Mañé's viewpoint to prove the conjecture for compact surfaces, for compact three dimensional manifolds with quasi-convex universal coverings where geodesic rays diverge, and for n-dimensional, generalized rank one manifolds.

6.2. Optimal transport and sub-Riemannian geometry

6.2.1. Uniquely minimizing costs for the Kantorovitch problem

Participants: Ludovic Rifford, Robert Mccann [Univ of Toronto, Canada], Abbas Moameni [Carleton Univ, Ottawa, Canada].

In continuation of the work by McCann and Rifford [65], a paper by Moameni and Rifford [24] study some conditions on the cost which are sufficient for the uniqueness of optimal plans (provided that the measures are absolutely continuous with respect to the Lebesgue measure). As a by-product of their results, the authors show that the costs which are uniquely minimizing for the Kantorovitch problem are dense in the C^0-topology. Many others applications and examples are investigated.

6.2.2. The Sard conjecture in sub-Riemannian geometry, optimal transport and measure contraction properties

Participants: Zeinab Badreddine, Ludovic Rifford.

Zeinab Badreddine [13] obtained the first result of well-posedness for the Monge problem in the sub-Riemannian setting in the presence singular minimizing curves. This study is related to the so-called measure contraction property. In collaboration with Rifford [14], Badreddine obtained new classes of sub-Riemannian structures satisfying measure contraction properties.

6.3. Optimal control of fully actuated micro-swimmers

6.3.1. A general geometric approach of optimal strokes for driftless micro-swimmers

Participants: Thomas Chambrion [Univ. Lorraine], Laetitia Giraldi, Alexandre Munnier [Univ. Lorraine].

In [3], we study the control problem associated to the locomotion of a deformable swimmer. we present a unified geometric approach for optimization of the body deformation of the swimmers in a 3D Stokes flow (case of micro-swimmers) and 2D or 3D potential flow. The latter cases correspond to the analysis of the sphere in a sub-Riemannian space. A general framework is introduced, allowing the complete analysis of five usual nonlinear optimization problems to be carried out. The results are illustrated with examples and with a in-depth study of a swimmer in a 2D potential flow. Numerical tests are also provided.

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 [43], this model describes 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 contribution is 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, see [16]. 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) and K. Sérier's PhD (started September, 2017), see [10], [42] and other publications under review.

6.4. Modelling and controllability of Magneto-elastic Micro-swimmers

6.4.1. Purcell magneto-elastic swimmer controlled by an external magnetic field

Participants: François Alouges [École Polytechnique], Antonio Desimone [SISSA Trieste, Italy], Laetitia Giraldi, Marta Zoppello [Univ. di Padova, Italy].

We have studied the mechanism of propulsion of a Purcell swimmer whose segments are magnetized and react to an external magnetic field applied into the fluid. By an asymptotic analysis, we prove that it is possible to steer the swimmer along a chosen direction when the control functions are prescribed as an oscillating field. Moreover, there are obstructions that have to be overcome in order to get classical controllability result for this system. This is exposed in [7] (IFAC World Congress, Toulouse, July 2017).

6.4.2. Local Controllability of the Two-link Magneto-elastic Micro-swimmer

Participants: Laetitia Giraldi, Pierre Lissy [Univ. Paris Dauphine], Clément Moreau, Jean-Baptiste Pomet.

For the smallest magneto-elastic micro-swimmer (2 links), we have been able to prove a strong local controllability result around its straight position of the swimmer. This is exposed in[6]. However, the latter result is weaker than the classical local controllability concept called STLC which means that a system could reach any position around its equilibrium with a small control (as small as the desired displacement of the system). Moreover, we prove in [5] that the 2-link magneto-elastic swimmer is indeed *not* STLC.

6.5. Numerical aspect of the N-link micro-swimmer model

Participants: Hermes Gadhêla [Univ. of York, UK], Laetitia Giraldi, Clément Moreau, Jean-Baptiste Pomet.

This topic was initiated with a 1 year research invitation of Clément Moreau at University of York and further collaboration. The goal is to compare the ODE given by the "N-link swimmer" model with the PDE for an elastic rod.

In [22], we study inertialess fluid-structure interaction of active and passive inextensible filaments. In this work, we compare two different approaches that lead to model the behavior of a microscopic elastic filament immersed into a fluid. The first which derives from a continuous formalism corresponds to solve a PDE, the second method exploits the momentum balance in the asymptotic limit of small rod-like elements which are integrated semi-analytically. The equivalence between the continuous and asymptotic model allows a direct comparison between the two formalisms. The asymptotic model is simple and intuitive to implement, and generalisations for complex interaction of multiple rods. We demonstrate these via four benchmarks: transient dynamics, force-displacement buckling instability, magnetic artificial swimmer and cross-linked filament-bundle dynamics.

6.6. Optimal Control and Averaging in Aerospace Engineering

6.6.1. Chance-constrained optimal control problems in aerospace

Participants: Jean-Baptiste Caillau, Max Cerf [Airbus Safran Launchers], Achille Sassi [ENSTA Paristech], Emmanuel Trélat [Univ. Paris VI], Hasnaa Zidani [ENSTA Paristech].

The aim is to minimize the fuel mass of the last stage of a three-stage launcher. Since the design parameters of the spacecraft are not exactly known prior to the launch, uncertainties have to be taken into account. Although these parameters are supposed to be uniformly distributed on fixed ranges, it is not desirable to use "worst-case" robust optimization as the problem may not even be feasible for some values of the parameters due to very strong sensitivities. The idea is to frame instead a stochastic optimization problem where these parameters are independent stochastic variables. The original constraint becomes a stochastic variable, and one only asks that the desired target is reached with some given probability. A key issue in solving this chance constrained problem is to approximate the probability density function of the constraint. Contrary to Monte-Carlo methods that require a large number of runs, kernel density estimation [68] has the strong advantage to permit to build an estimator with just a few constraint evaluations. This approach allows to treat efficiently uncertainties on several design parameters of the launcher, including the specific impulse and index of the third stage and using a simple affine discretization of the control (pitch angle). In [19], 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, and we show how this technique can be applied and implemented for a class of problems including the Goddard problem (with bang-bang or bang-singular-bang controls) and the trajectory optimization of an Ariane 5-like launcher. This work has been done in collaboration with Airbus Safran Launchers at Les Mureaux.

An involved question in chance constrained optimization is the existence and computation of the derivative of the stochastic constraint with respect to deterministic parameter. This shall be investigated in the light of new results in the Gaussian case [78]. Using a single deterministic control to reach a given target (or a given level of performance) with some fixed probability when the parameters of the system are randomly distributed is very similar to issues of ensemble controllability addressed in the recent work [26]. One expects some insight from the comparison of the two viewpoints.

6.6.2. Metric approximation of minimum time control systems

Participants: Jean-Baptiste Caillau, Lamberto Dell'Elce, Jean-Baptiste Pomet, Jérémy Rouot.

Slow-fast affine control systems with one fast angle are considered in this work [20]. An approximation based on standard averaging of the extremal is defined. When the drift of the original system is small enough, this approximation is metric, and minimum time trajectories of the original system converge towards geodesics of a Finsler metric. The asymmetry of the metric accounts for the presence of the drift on the slow part of the original dynamics. The example of the J_2 effect in the two-body case in space mechanics is examined. A critical ratio between the J_2 drift and the thrust level of the engine is defined in terms of the averaged metric. The qualitative behaviour of the minimum time for the real system is analyzed thanks to this ratio. Work in progress aims at dealing with multiphase averaging for systems driven by several fast angles.

6.6.3. Approximation by filtering in optimal control and applications

Participants: Jean-Baptiste Caillau, Thierry Dargent [Thales Alenia Space], Florentina Nicolau [Univ. Cergy-Pontoise].

Minimum time control of slow-fast systems is considered in this analysis [8]. In the case of only one fast angle, averaging techniques are available for such systems. The approach introduced in [57] and [34] 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 motivation is that averaging over an entire period may not provide a good enough approximation to initialize a convergent numerical resolution of the original system; considering a continuous set of intermediate approximations (filtering over windows of size varying from the period to zero) may ensure convergence. The method is illustrated on problems coming from space mechanics and has been implemented as an addition to the industrial code `T3D` of Thales Alenia Space.

6.6.4. Higher order averaging

Participants: Jean-Baptiste Pomet, Thierry Dargent [Thales Alenia Space], Florentina Nicolau [Univ. Cergy-Pontoise].

A further step in defining a suitable approximation of slow-fast oscillating controlled systems is to go beyond the $O(\varepsilon)$ uniform error provided by simple averaging. An original approach has been proposed in [58] and demonstrated numerically; it consists in correcting the boundary values of the slow averaged variables to ensure an $O(\varepsilon^2)$*average* error, without the difficulties of classical second order averaging [73] (that leads to an $O(\varepsilon^2)$*uniform* error, that we do not need), and allows an $O(\varepsilon)$ approximation of the angle. It is proved in [9] that it is indeed possible, at least for initial value problems, to compute order one corrections of the initial slow variables to guarantee such an error. From the numerical side, this process is a key to be able to initialize shooting methods on the non-averaged system by averaged solutions when using a model with full perturbations in orbit transfer.

6.7. Stability of nonlinear high frequency amplifiers

Participants: Sébastien Fueyo, Jean-Baptiste Pomet, Laurent Baratchart [APICS project-team APICS (FACTAS as of 2018)].

Sébastien Fueyo's PhD is co-advised between McTAO and APICS on this topic. The problem is presented in section 4.4 .

Starting from infinite dimensional time-domain models for these devices, we obtained full justification (with some possible obstructions) to the prediction of stability through transfer function identification on academic examples of simple circuits, and are working on generalisations. A preliminary presentation will be given at a local conference, Université Côte d'Azur Complex Days, in January, 2018.

MORPHEME Project-Team

5. New Results

5.1. DIC (differential-interference-contrast) microscopy

Participants: Lola-Xiomara Bautista Rozo, Laure Blanc-Féraud.

This work is made in collaboration with Simone Rebegoldi, Marco Prato and Luca Zanni are in the Dipartimento di Scienze Fisiche, Informatiche e Matematiche, Universita di Modena e Reggio Emilia, Modena, Italy.

he DIC (differential-interference-contrast) microscopy states the problem of image phase reconstruction which is ill-posed (under-determinated) and non-convex optimization problem. We have worked on the phase reconstruction from color images by optimization of a non linear least-squares-like discrepancy term regularized with a total variation functional. We have considered two different penalties, the first one being the total variation (TV) functional which is suitable for piecewise constant images, while the second is the hypersurface (HS) potential, which is a smooth generalization of the TV able to reconstruct both sharp and smooth variations of the unknown phase. Since the latter choice leads to the minimization of a smooth functional, we developed a limited memory gradient method, in which suitable adaptive steplength parameters are chosen to improve the convergence rate of the algorithm. As concerns the TV–based model, we addressed the minimization problem by means of a recently proposed linesearch–based forward–backward method able to handle the nonsmoothness of the TV functional. Numerical tests show that in the case of smooth TV minimization funcitonal, the performance of the limited memory gradient method is much better than those of the conjugate gradient approaches proposed in the literature, in terms of number of function/gradient evaluations and, therefore, computational time. In the case of TV functional, despite the difficulties due to the presence of a nondifferentiable term, also the linesearch–based forward–backward method proposed in this case is able to provide reconstructed images with a computational cost comparable to that of the gradient methods, thus leaving to a potential user freedom to choose the desired regularizer without losing in efficiency.

This work has been done during the PhD thesis of Lola Bautista defended in June 2017 [1]. It has been published in the journal Inverse Problems in 2017 [4].

5.2. Towards a continuous relaxation of the $\ell_2 - \ell_0$ constrained problem

Participants: Gilles Aubert, Arne Henrik Bechensteen, Laure Blanc-Féraud.

We focus on the problem of minimizing the least-squares loss function under the constraint that the reconstructed signal is at maximum k-sparse. This is called the ℓ_2-ℓ_0 constrained problem. The minimization problem is of interest in signal processing, with application to compressed sensing, source separation and super-resolution imaging.

This problem has previously been relaxed, among other methods, by using the convex ℓ_1 norm instead of the ℓ_0 norm, but depending on the specific problem the global minimizer may not be the same.

The goal of our work is to propose a continuous exact relaxation of the ℓ_2-ℓ_0 constrained problem. The initial problem is non-continuous and is therefore from an algorithmic point of view difficult to minimize. A continuous exact relaxation has the same global minimizers as the initial problem, and a local minimizer of the relaxation is a local minimizer of the initial problem, with possible less local minimizers than the initial problem. Solving the initial ℓ_2-ℓ_0 constrained problem is equivalent, in the sense of the global minimizers, to solving the continuous relaxed form. Furthermore, a continuous exact relaxation provides better properties for the objective function in terms of minimization, because of the continuity and the number of local minimizers.

Based on the recent works of Marcus Carlson [17] we propose a continuous exact relaxation of the ℓ_2-ℓ_0 constrained problem S_γ, with an algorithm to minimize the function.

In order to increase the quality of the optimization, we have to chose “the best” exact relaxation. Inspired by the work by Emmanuel Soubies [23] we have computed the convex hull of the initial problem for a special case. The penalty term obtain, f_{cr} may be a continuous relaxation with respect to the initial problem, with fewer local minimizers than the initial problem and the relaxation S_γ (see figure 1). This has to be proven.

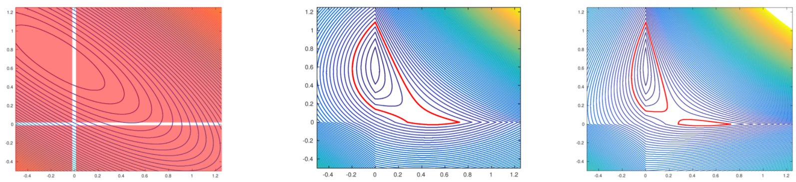


Figure 1. From the left to the right. The initial problem, the relaxation using f_{cr} and the relaxation using S_γ. The level lines of the relaxations are illustrated with a common level line marked in red.

The work will be presented at Mathematical Image Analysis 2018 conference in Berlin on the form of a poster.

5.3. Reconstruction of mosaic of microscopic images

Participants: Kévin Giulietti, Eric Debreuve, Grégoire Malandain.

This work takes place within the ANR PhaseQuant.

In microscopy imaging, a trade-off has to be made between a high resolution, that enables to see details, and the width of the field of view, that enables to see many objects. Such a trade-off is avoided by mosaicing, which consists in the acquisition of several images, say $N \times N$, with a small overlap between images. This way, an image with a N larger field of view can be reconstructed with the same resolution than a single microscopic image.

Such an imaging protocol is available on many microscopy software. Basically, displacements of the table on which lies the material to be imaged are programmed, and used to reconstruct the mosaic. However, it appears (at the overlapping areas), that a residual offset is still present. The cause of this has not be identified so far: this may be due to small geometric mis-alignement in the imaging device, or to the command of the micrometer table.

We thus investigate the stability of this residual offset with respect to time and to the image position within the mosaic.

5.4. Detection of cytoneme

Participants: Christelle Requena, Xavier Descombes.

This work is made in collaboration with Pascal Thérond, Tamas Matusek and Caterina Novelli (iBV). It is supported by the ANR project HMOVE.

Cellular communication is one of the most important processes for understanding and controlling morphogenesis (the set of laws that determine the structure of tissues and organs during embryonic development) necessary for the development of an organism. This is an important issue in the field of developmental biology and it has recently been shown that the exchange of information between cells is controlled by long cellular extensions called "cytonemes".

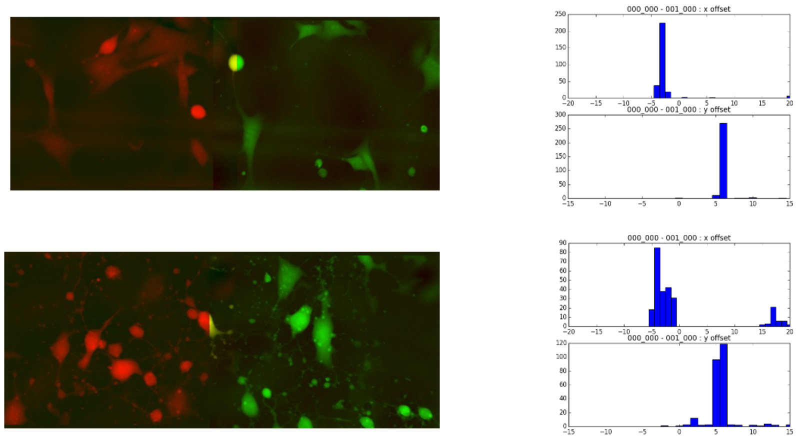


Figure 2. Example of mosaics reconstructed with two different datasets whose pairs of images were acquired at the same positions (0,0) in red and (1,0) in green. Histograms represent the offsets for all offsets overtime.

Due to the amount of information to be processed and the time required to study this information, it is essential to be able to provide image processing tools through which reliable, automatic and effective methods are proposed for these studies. In this work we have developped a pipeline for membrane extension and vesicles detection from in vivo data obtained by confocal microscopy. The vesicles are detected using a marked point process modeling. The cell extension detection embed the membrane detection using active contours and the filament detection using a tophat operator, the Frangi filter and Dijkstra algorithm. With this detection tool (exemplified in Figure 3), we have characterized a mutant population compared to a wild population of drosophila wings with respect to Hedgehog signalization. Interestingly we have shown that a significative difference appears in the cytonemes length but not in their number.

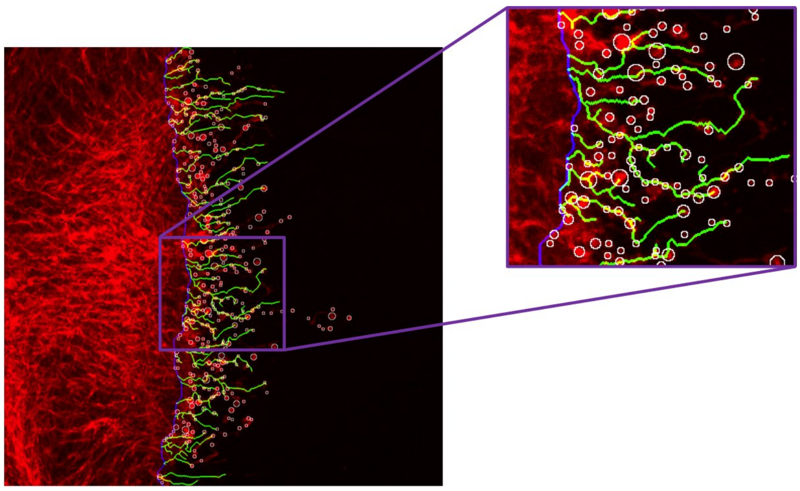


Figure 3. Cytoneme (green filaments) and Hedgehog vesicles detection (white circles).

5.5. 3D+t segmentation of single growing axons

Participants: Nadège Guiglielmoni, Caroline Medioni, Florence Besse, Xavier Descombes, Grégoire Malandain.

Our work is motivated by the study of developmental axonal remodeling, a genetically-controlled process characterized by a degeneration step followed by a rapid regrowth of axons. Here, we focus our interest on the axonal regrowth phase, which can be studied during brain development, using the fruit fly, *Drosophila melanogaster*, as a model system.

During the regrowth, small dynamical branches can be observed: they emanate from long stable branches and have generally a short lifetime. Such small branches may contribute to rebuild the axon connectivity during the adult stage. A better knowledge of the mechanisms controlling the dynamic of these branches may contribute to a better understanding of neuronal morphogenesis. In this work, we are particularly interested in the quantification of this process, for which the extraction of both the main and second branches is required.

Neuron tracing is still a challenge in neuroinformatics. Despite the huge progresses made during the last decades, this problem is still an open question. This is exacerbated with the development of new imaging techniques, that produce more and more images with improved quality and/or resolution. Among these, live-imaging techniques are more and more prominent. Indeed, acquisitions of 3D image sequences over long periods of time, in particular, have enabled neurobiologists to follow complex processes such as the development of neuronal populations. However, they produce time series of 3D volumes, for which there does not exist dedicated tracing approach.

Apart slight movements, the dynamic changes of axons are due to growing or retracting branches. Thus, we designed a topologically constrained tracking method that first ensures that the tree structure of the axon and its branches is preserved through the time sequence, and second enables a slight displacement of the axon (within an user-specified extend), while mimicing both the retraction and the growth of branches. Results are presented in figure 4 .

5.6. Detection and characterization of mitochondrials networks

Participants: Kévin Giulietti, Xavier Descombes.

This work is made in collaboration with Frédéric Bost, Stephan Clavel, Aurélie Charazac, Celia Decondé le Butor (C3M).

We consider in this project a high content microscopy based screening focused on the effects of endocrine disruptors on prostatic cancer cells metabolism. Specifically, we developed our automatic computational tool to detect and classify mitochondrial network morphology from microscopy acquired images. The first step consists in binarizing the image and the binary pattern representing the mitochondrial network is classified in a second step. To binarize the mitochondrial network we consider the different level sets in the original image. A score is computed on each connected component of the level set pyramid depending on the contrast between the component and the neighboring background and on a shape criteria. We thus select the best scored component considering a compromise between the component contrast and a shape prior. We then run a k-mean clustering on the set defined by all the mitochondrial component extracted from the whole database. The different estimated classes are typical mitochondrial network element such as filaments or blobs. An image is then classified based on its signature defined by the number of mitochondrial element detected for each of the pre-defined classes (see Figure5). This classification scheme provides a discrimination framework based on geometrical and topological mitochondrial network properties than can differentiate for example filamentous and aggregate networks. This tool will be used for automatically specifying the effect of endocrine disruptors.

5.7. Detection and classification of neuronal extensions on fluorescence microscopy images: application to the study of metabolic diseases such as obesity or anorexia

Participants: Sarah Laroui, Eric Debreuve, Xavier Descombes.

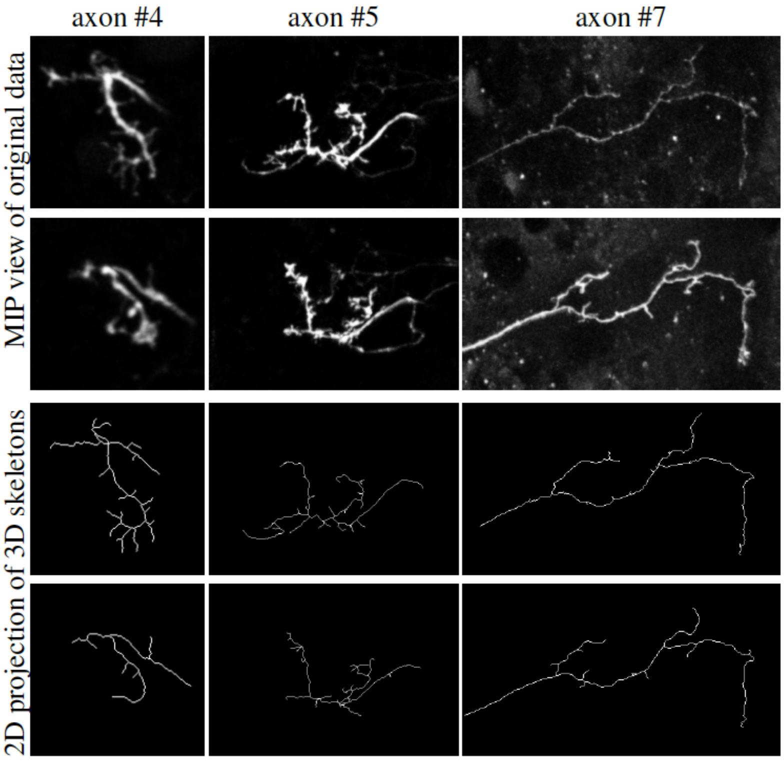


Figure 4. From top to bottom: MIP view of the first time point, MIP view of the last time point, 2D projection of the skeleton of the first time point, 2D projection of the skeleton of the last time point (series are made of 170 time points, with a 5 min time interval). Loops in skeleton projection views are projection artifacts.

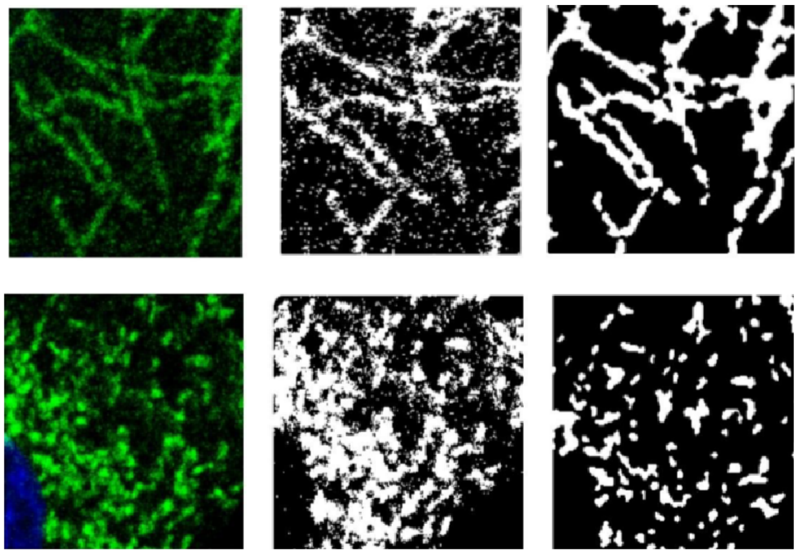


Figure 5. Detection of mitochondria filamentous/tubular (zoomed) network (top row), hyperfilamentous network (middle row) and aggregates network (bottom row). From left to right panels we have first input images (in green mitochondrial networks and in blue nuclei of the cells). Then binaries masks of mitochondrial networks using an automatic threshold. Then binaries masks resulting from our own developed method. Finally, classification of mitochondrial networks : in blue the filamentous/tubular forms, in green the hyperfilamentous form and in red the blobs forms.

This work is made in collaboration with Céline Cansell and Carole Rovere (IPMC, Sophia Antipolis).

The goal of this project is to classify 3D images of neuronal cells (astrocytes and microglia) into mice fed normally and mice fed with a high-fat diet (see Fig. 6). The distinction can be made in two different areas of interest of the hypothalamus: Median Eminence (EM) and Arcuate Nucleus (ARC).

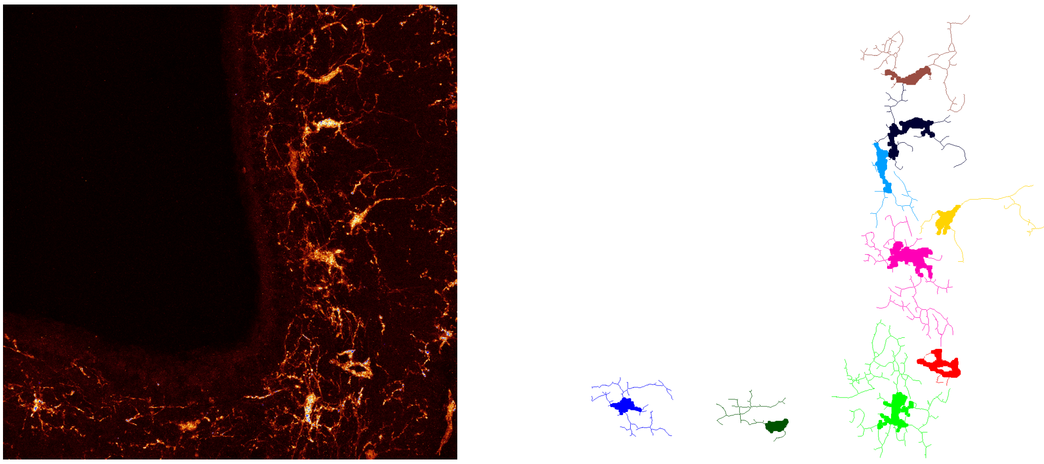


Figure 6. Maximum intensity projection (MIP) of the original image of microglias (left) and MIP of the network detection result (right).

Astrocytes are perceived as networks. Our goal is to find out if there is a difference in the organization of these networks between the two areas of interest and between the two mouse models. Regarding inflammatory cells (microglias), we first segment each cell body and their extensions using a Frangi filter bank to enhance filamentous structures. This produces network pieces that must be joined to build one network per microglia. Thus, we connect filaments to soma and filaments to filaments using minimal paths (using an image-based, anisotropic metric) computed by dynamic programming. Finally, we extract geometrical and topological parameters such as the length and width of the extensions, the number of branches ... These parameters will be used for clustering microglia networks in order to identity the different populations.

5.8. Automatic recognition of fungi phenotype by extraction and classification of morphometric parameters

Participants: Sarah Laroui, Eric Debreuve, Xavier Descombes.

This work is made in collaboration with Aurelia Vernay (Bayer) as part of a contract with Bayer.

Botrytis cinerea is a reference model of filamentous phytopathogen fungi. Some chemical treatments can lead to characteristic morphological changes, or phenotypic signatures, observable with transmitted light microscopy (see Fig. 7), which could be associated with the molecule Mode of Action.

In this context, we developed a robust image analysis and classification method relying on morphometric characteristics to automatically detect fungi observed using transmitted light microscopy, and classify them into predefined phenotypes. The detection task has been implemented in a classical way using a combination of mathematical morphology operations and active contours. The classification task has been solved in a supervised learning context.

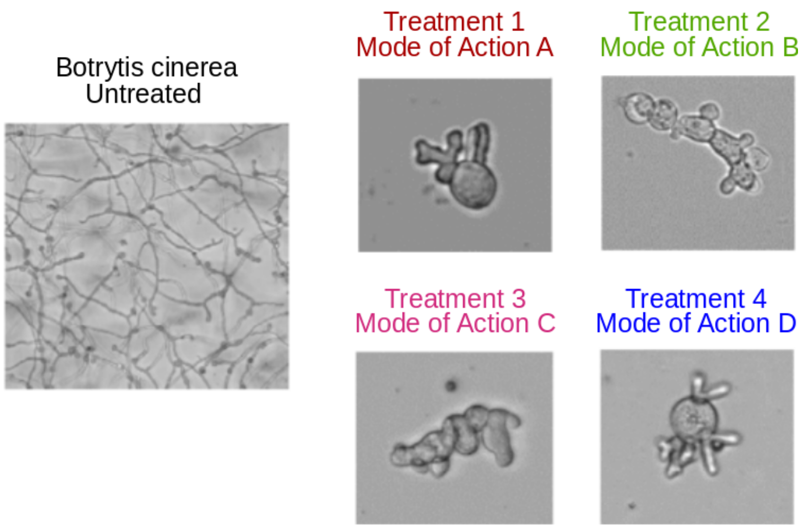


Figure 7. Characteristic phenotypic signatures for different chemical treatments (transmitted light microscopy, ImageXpress microscope, 10x lens).

Since a fungus can be described as tubular extensions connected to a spore (a roundish "root" cell), we proposed to describe such an object by its skeleton together with the distances from the skeleton to the fungus boundary. The skeleton was then converted into a valued graph. We selected a dozen topological and morphological features such as the number of nodes, the length of the longest branch, or the average and variance of the per-branch average skeleton-to-boundary distances.

These features were used in a supervised machine learning framework. Specifically, a cascade of two classifiers was proposed, the first one based on a decision tree to reject non relevant phenotypes (spores and mycelium), the second one to actually determine the phenotypes of the fungi. This second classifier was a Random Forest learned on the provided learning set composed of sample fungi from two phenotypes. Note that the classification accuracy can be computed either in a per-fungus way, or in a per-image way. Indeed, a given image corresponds to a unique chemical treatment so that all the fungi it contains exhibit the same phenotype (up to the natural biological variations), which can therefore be associated to the image itself. This per-image phenotype can be obtained by a majority vote among the individual fungus phenotypes. It represents the answer the biologists need. For the 2-phenotype problem we worked on, we obtained an image classification accuracy of around 90%, which is more than encouraging. In order to allow for a future, deeper analysis of the features characterizing each phenotype, we also computed the influence of each feature on the classification accuracy.

5.9. Density and repartition of cytoplasmic RNP (RiboNucleoprotein Particles) granules containing the Imp protein

Participants: Eric Debreuve, Xavier Descombes.

As part of the ANR project RNAGRIMP [0] (section 7.2.1), two series of images have been acquired using fluorescence microscopy: one where the cell cytoplasm has been stained with GFP (Green Fluorescent Protein), the second where the nuclei have been stained with DAPI (4',6-diamidino-2-phenylindole). The first steps are detecting the nuclei on the DAPI images and learning a classification procedure into living cell

[0] Imp = IGF-II mRNA-binding protein; IGF = Insulin-like Growth Factor; mRNA = Messenger Ribonucleic Acid.

or dead cell based on morphological and radiometric nuclei properties (average intensity, area, granularity, circularity...) (see Fig. 8).

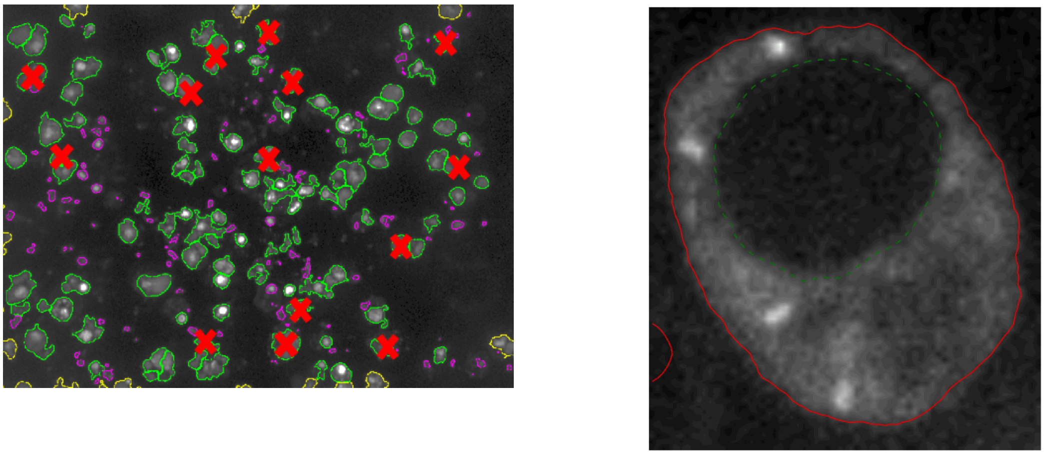


Figure 8. (left) Automatic classification of the detected nuclei into living (encircled in green) or dead (with a red cross). Objects encircled in yellow are cropped by the field of view, and objects encircled in purple are too small ; they are all discarded. (right) Active contour segmentation of the cytoplasm of a cell (previously classified as a living cell). Red contour: cytoplasm external boundary. Green, dashed contour: nucleus boundary (also cytoplasm internal boundary).

A specific CellProfiler [0] pipeline has been developed for this, and CellProfiler Analyst [0] has been used to learn a decision tree for automatic nuclei (hence, cell) classification. The next step is to segment (i.e., extract automatically the region of) the cell cytoplasms on the GFP images. Indeed, the target RNP-IMP granules appear in that compartment of the cell and are visible through their GFP response. We developed an active contour-based segmentation method relying on local image contrast with an initialization provided by a marked point process detection of ellipses [18] (see Fig. 8). Then, the detection of the particles can be performed inside the segmented cytoplasms (using a method called SPADE previously developed by the team).

5.10. Renal cell carcinoma classification from histopathological images

Participants: Mohammed Lamine Benomar, Nilgoon Zarei, Eric Debreuve, Xavier Descombes.

This work is made in collaboration with Damien Ambrosetti (MD, Pasteur Hospital, Nice).

The renal cell carcinoma is the most frequent type of kidney cancer (between 90% and 95% of all cases). Twelve classes of carcinoma can be distinguished, among which the clear cell carcinoma (CCRCC) and the papillary carcinoma (PRCC) are the two most common ones (75% and 10% of the cases, respectively). After the carcinoma has been diagnosed, the tumor is ablated and prepared for histological examination (fixation, staining, slicing, observation with a microscope) (see Fig. 9).

Along with genetic tests and protein reactions, the histological study allows to classify and grade the tumor in order to make a prognosis and monitor the patient treatment. Clinically speaking, digital histology is a recent domain (routinely, histological slices are studied by MDs directly on the microscope). The classical works on digital histology deal with the automatic analysis of cells (size, density ...). However, one crucial factor

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

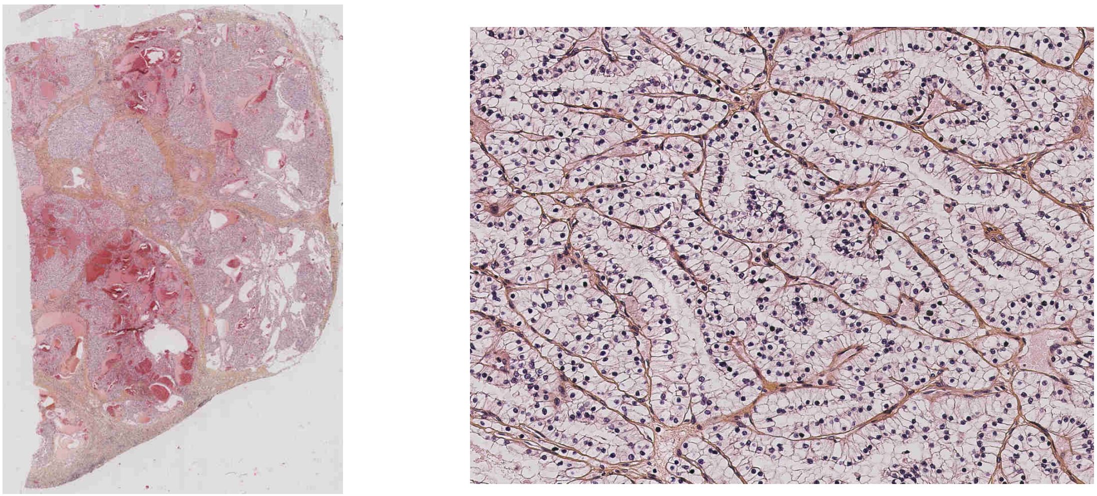


Figure 9. A histological slice through a kidney tumor: the whole slice (left) and a close-up (right) (the vascular network has a brownish color; the cell nuclei have a dark violet color).

for carcinoma classification is the structure of the vascular network. Coarsely, CCRCC is characterized by a "fishnet” structure while the PRCC has a tree-like structure.

In this context, we proposed to extract the vascular network from a given histological slice, compute features of the underlying graph structure, and classify the tumor into CCRCC or PRCC based on these features [24]. Then, we started to focus on performing a higher-level analysis of the vascular graphs. It can be noted that cells that are close to the vascular network naturally tend to align with it. Thus there might be specific “cell-vascular network” arrangements for each type of carcinoma. Our plan is to look for repeated subgraph patterns using pattern matching methods on labeled graphs, where a pattern would be a combination of (i) topological features from the graph, (ii) nearby cell features, and (iii) measures characterizing the coherence between nearby cells and the network (cell-to-network distances, cell density along the network, degree of alignment with the network...). There are chances that each carcinoma type exhibits a set of patterns that appear with a high frequency, therefore being characteristic of the given type. Such patterns would then represent discriminant features for carcinoma classification.

5.11. Comprehensive comparison of multi-labeled images

Participants: Gaël Michelin, Grégoire Malandain.

The data used for this work are courtesy of Yassin Refahi (Sainsbury Laboratory, Cambridge university) and Ulla-Maj Fiuza (CRBM, CNRS, Montpellier 1 & 2 university).

In the context of developmental biology, 3D+t microscopy imaging allows to quantitatively study the morphogenesis at the cellular level, but requires automated segmentation methods to handle the huge quantities of data. To minimize the necessary and tedious user interaction to correct unavoidable errors (3D images may have up to thousands of cells), it is desirable to improve such segmentation methods. This, in turn, motivates the need for a comprehensive evaluation methodology that will allow to automatically compare the outputs of two segmentation methods, not only in terms of cell border accuracy, but also in terms of cell detection.

The aim of the present work is to propose such an original comprehensive segmentation comparison method that provides an objective way for multi-object segmentation comparison. This method enables to determine automatically a region-to-region correspondence map and provides asymmetric shape similarity indexes between two segmented images, with a robustness to potential region border variations. We illustrate the applicability of the proposed method with two examples in figure 10 .

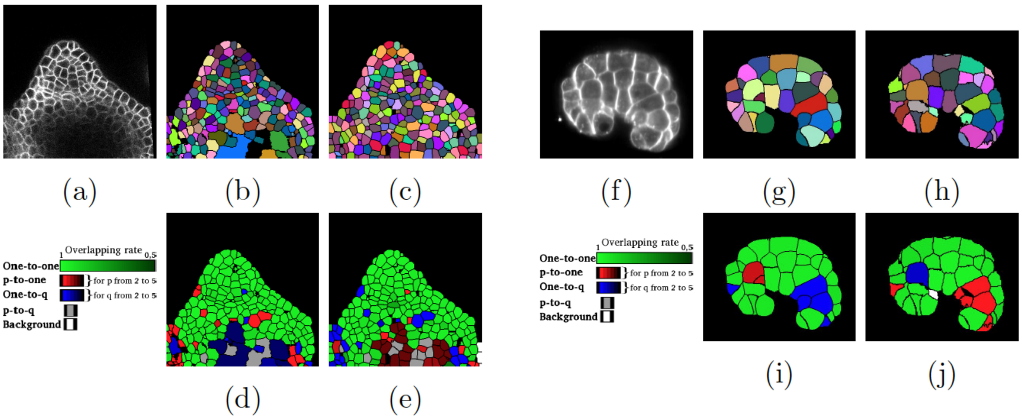


Figure 10. Cut-views of original 3D intensity images (a,f), the associated pairs of corresponding segmentations (b-c,g-h) and the results of regions association for each segmentation determined by the proposed method with the proposed method. (a-e) Floral meristem image. (f-j) Ascidian image.

5.12. Grouped Local Automated Cell Extractor (GLACE)

Participants: Gaël Michelin, Grégoire Malandain.

This work is made in collaboration with Julien Laussu, Patrick Lemaire (CRBM, CNRS, Montpellier 1 & 2 university), Emmanuel Faure (IRIT, CNRS, Toulouse) and Christophe Godin (Inria Virtual Plants team, Montpellier).

In developmental biology, the embryogenesis study relies in particular on image-based studies. Today, fluorescent confocal microscopy is a means for *in vivo* imaging of developing organisms at cell level with a high spatio-temporal resolution. To handle such 3D+t image sequences, adapted computer-assisted methods are highly desirable in order to extract essential information from these data.

More specifically, for developing ascidian embryos, an existing framework called `ASTEC` [19] is used by biologists in order to extract the cell segmentation and lineage from some 3D+t sequences. However, remaining issues about segmentation accuracy motivated us to propose a new framework as an alternative to `ASTEC` for cell segmentation and tracking. The originality of the proposed Grouped Local Automated Cell Extractor (`GLACE`) framework is to segment the i–th image of a sequence by applying *locally* the original 3D cell segmentation framework of [21] for all the regions of interest defined by the segmented cells of the $i-1$–th image of the sequence. The union of all the local reconstructions provides the segmentation of the i–th image of the sequence (figure 11). The `GLACE` framework does not replace the `ASTEC` framework, however they provide complementary results for embryo image sequence reconstructions.

5.13. Ascidian embryo cell lineage registration in 3D+t image sequences

Participants: Gaël Michelin, Grégoire Malandain.

This work is made in collaboration with Julien Laussu, Patrick Lemaire (CRBM, CNRS, Montpellier 1 & 2 university) and Christophe Godin (Inria Virtual Plants team, Montpellier).

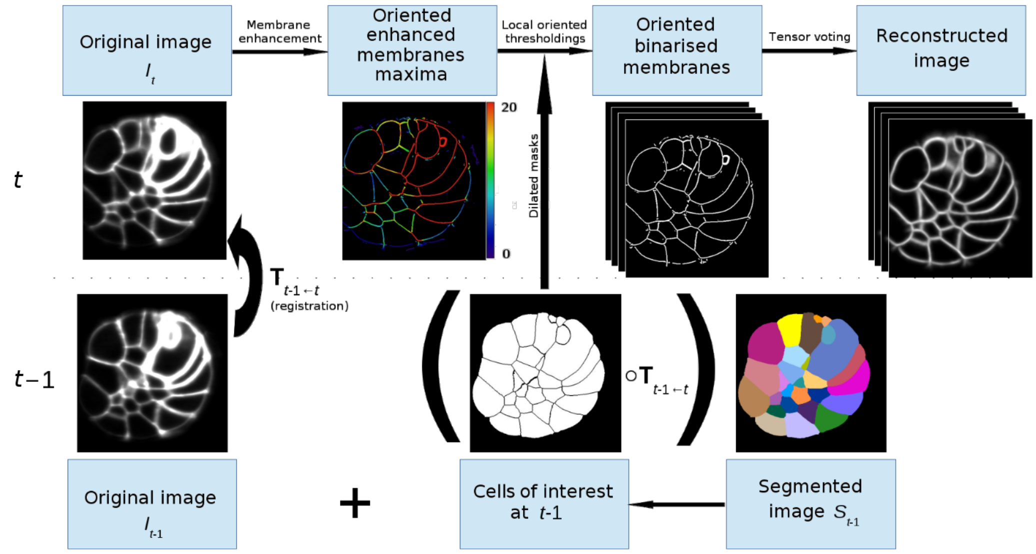


Figure 11. Pipeline for GLACE.

Until gastrulation, ascidian embryos have a very stereotyped and invariant development, so that it is possible to establish a cell-to-cell mapping between two developing embryos at a same developing stage. We proposed in a previous work a method for geometric registration that determines a linear (affine) transformation superimposing a test embryo into a reference one and that draws a cell-to-cell mapping up [20].

In the current work, we extend this framework for the determination of cell lineage mapping between two developing ascidian embryos by propagating an initial cell-to-cell mapping to the cell descendants since the cell correspondences are inherited for the ascidian embryo (figure 12 (top)). To do so, we use the information provided by the 3D+*t* sequences segmentation and lineage such as cell volume, life-span and relative position in the embryos. We experimented on real data the proposed cell lineage registration framework (figure 12 (bottom)).

5.14. Towards construction of digital atlases of plant tissues

Participants: Gaël Michelin, Grégoire Malandain.

This work is made in collaboration with Yassin Refahi (Sainsbury Laboratory, Cambridge university), Jonathan Legrand, Jan Traas (RDP, ENS Lyon, INRA, CNRS, Lyon) and Christophe Godin (Inria Virtual Plants team, Montpellier).

In developmental biology, the study of model organisms aims for the understanding of genetic mechanisms responsible of morphogenesis. Today, fluorescent confocal microscopy is a means for in vivo imaging of developing plants at cell level with a high spatio-temporal resolution.

We propose in this work some dedicated computational tools for the study of such 3D+t sequences. These methods offer the means to compare temporal sequences of flower development and to build 4D digital atlases of developing arabidposis floral meristems on which every individual can be projected (figure 13), opening the avenue to the statical analysis of populations.

5.15. 3D Coronary vessel tracking in x-ray projections

Participants: Emmanuelle Poulain, Grégoire Malandain.

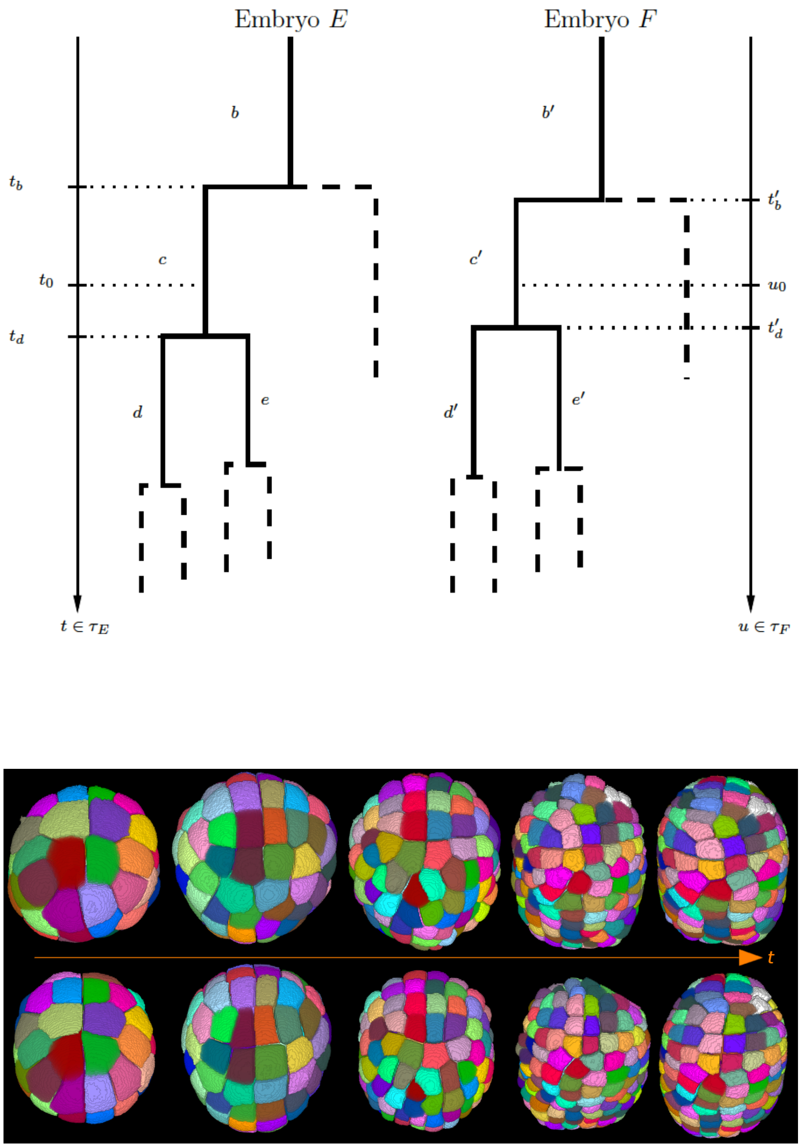


Figure 12. Ascidian embryo cell lineage registration. Top: sub-lineages from embryos E and F showing labels c and c' in correspondence with their birth (t_b) and death (t_d) (respectively t'_b and t'_d) time-points, mother cells (b and b') and daughters ((d,e) and (d',e')) along embryo lifespans τ_E and τ_F. Bottom: result of lineages registration between two developing embryos. Mapped cells appear with the same color. Cells in white are those for whom no corresponding cell was found in the other embryo. First column: cell-to-cell initial mapping.

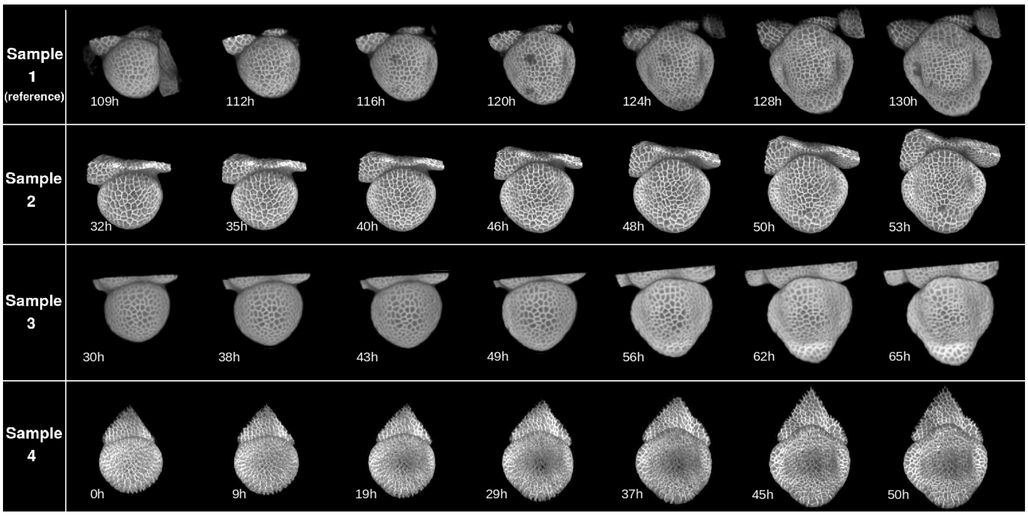


Figure 13. Visualization of the valid spatio-temporal sample alignments following the proposed registration method at different floral meristem developmental phases. One can observe the reliability of the registration method to identify developmental phases equivalences between the different samples.

This work is made in collaboration with Régis Vaillant (GE-Healthcare, Buc, France) and Nicholas Ayache (Inria Asclepios team).

Percutaneous Coronary Intervention (PCI) is a minimally procedure which is used to treat coronary artery narrowing. During the guidewire navigation, the lesion is crossed and in some cases, the physician could benefit from a visual assessment of the coronary wall. The x-ray imaging interventional system used for per-operative guidance is not able to display this information mostly by lack of density resolution. On the contrary, Computed Tomography Angiography (CTA) is a modality which has the capability of capturing the characteristics of the vessel wall.

Fusing pre-operative CT angiography with per-operative angiographic and fluoroscopic images is thus considered by physicians as a potentially useful tool for improved guidance. To be adopted, this tool has required the development of tracking methods adapted to the deformations of the arteries caused by the cardiac motion. We have proposed a 3D/2D temporal tracking of one coronary vessel, based on a spline deformation, using pairings with a controlled 2D stretching or contraction along the paired curves and a preservation of the length of the 3D curve which corresponds to the anatomic propriety [8], [9]. Experiments were conducted on a database of 10 vessels from 5 distinct patients, with dedicated metrics assessing both the global registration and the local coherency of the position along the vessel. The proposed results demonstrate the efficiency of the proposed method, with an average standard deviation of 2 mm for the localization of landmarks (see Fig. 14).

5.16. Modelling axon growth from in vivo data

Participants: Agustina Razetti, Xavier Descombes, Caroline Medioni, Florence Besse.

Axons develop embedded in mechanically constrained environments. Thus, to fully understand this dynamical process, one must take into account collective mechanisms and mechanical interactions within the axonal populations. However, techniques to directly measure this from living brains are today lacking or heavy to implement. This interdisciplinary work intends to close the gap between classic in vitro experimental assumptions and real in vivo situations, where the final neuronal morphology is acquired through a dynamical and environmental-dependent process. We use as biological model Drosophila γ axon remodeling and analyze,

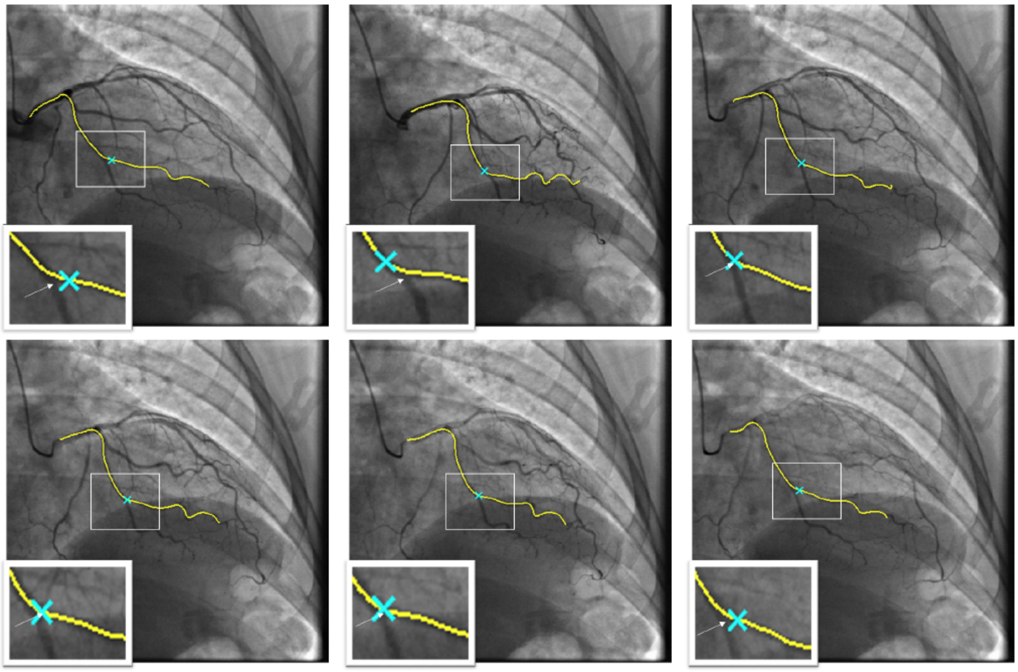


Figure 14. Visualization of the valid spatio-temporal sample alignments following the proposed registration method at different floral meristem developmental phases. One can observe the reliability of the registration method to identify developmental phases equivalences between the different samples.

for the first time to our knowledge, the mechanical situation of a whole population of γ neurons (650 individuals) growing together in a constraint space (i.e. medial lobe of the Mushroom Body).

We have designed a mathematical model of single axon growth based on Gaussian Markov Chains with two parameters, accounting for axon rigidity and attraction to the target field. We used this model to simulate the growing axons embedded in space constraint populations to test our hypothesis. We explored new branch formation mechanisms to mimic the growth of wild type γ axons population , as well as predict different mutant phenotypes. This approach allowed also to analyze dynamical aspects of the γ neuron collective growth process such as speed and density in function of space and time, which help to explain several characteristics of the γ neuron morphology and behavior during development. Among the obtained results, the proposed model is able to reproduce the intra-population morphological variability. Interestingly, applying the ESA distance between trees previously developed in the team [22] showed that real axons present shapes that showcase a compromise between collective elongation and morphological variability, essential for axonal connectivity (Figure 15). Finally, we explored other branch occurrence strategies –from uniformly random to occurrence upon mechanical interactions- to contrast and validate with previously developed hypothesis on the importance of branching for axonal elongation in vivo.

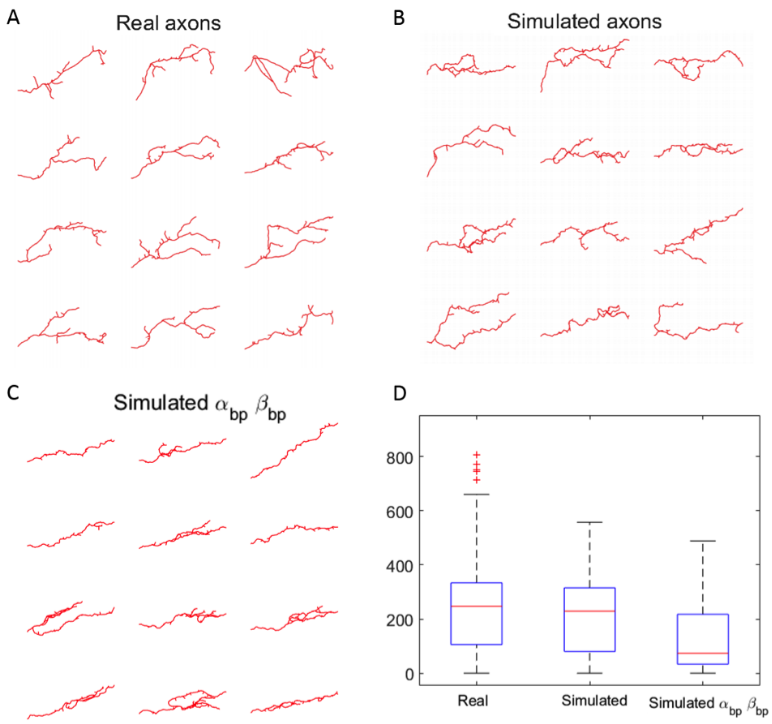


Figure 15. Impact of the parameter value on axonal morphologies. (A) Real wild type γ axons. (B) Axons simulated with parameters estimated from data. (C) Axons simulated with optimal parameters regarding collective elongation. (D) Intra-group variability measured with the ESA distance between all the axons in each group (A-C).

5.17. Jump point detection and parameter estimation from piecewise homogeneous Markov chains

Participants: Agustina Razetti, Xavier Descombes.

Piecewise homogeneous Markov chain processes can be applied to diverse phenomena of various nature, such as genetics, physics. Recent bibliography has focused on these systems, proposing different alternatives to detect the jump points and be able to separate between different phases of the signals. The Markov chain is usually defined by its transition matrix and the change points are modeled by a hidden Markov process. In this work, we focus on the Gaussian case with a Bernoulli distribution governing the change points. We have developped two different theoretical frameworks: one Bayesian with a Bernoulli prior, and the other one statistic-oriented, proposing a test of hypothesis based on ratio of likelihoods. For both cases we provide with robust algorithms to detect the jump points and reduce the error in the estimations of the parameters of the main model. We compare both methods and investigate their limits and advantages. We finally provided practical examples to showcase the power of the proposed approach (see Figure 16).

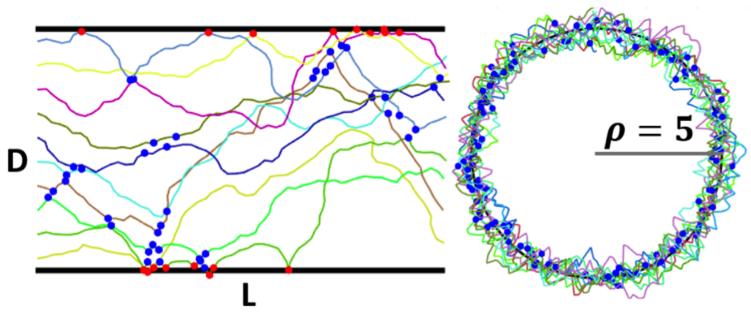


Figure 16. Two application examples. 10 particles of equal mass moving are shown at each case. When they collide another particle or the external limits, they follow elastic punctual collisions (shown by stars and circles). Left: particles inside a tube of diameter D and length L; right: particles moving around a circle of radius ρ.

NACHOS Project-Team

6. New Results

6.1. Electromagnetic wave propagation

6.1.1. 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 coupled 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. This is the object of the submitted paper [41]. At the same time, we pursue a study in collaboration with Serge Nicaise (Université de Valenciennes et du Hainaut-Cambresis) on the stability properties of this model both at the continuous and the discrete level.

6.1.2. Numerical modeling of metasurfaces

Participants: Loula Fezoui, Stéphane Lanteri, Liang Li [UESTC, Chengdu, China], Ronan Perrussel [Laplace laboratory, Toulouse].

Metamaterials are composed of periodic subwavelength metal/dielectric structures that resonantly couple to the electric and/or magnetic components of the incident electromagnetic fields, exhibiting properties that are not found in nature. Planar metamaterials with subwavelength thickness, or metasurfaces, consisting of a layer of dielectric or plasmonic nanostructures, can be readily fabricated using lithography and nanoprinting methods, and the ultrathin thickness in the wave propagation direction can greatly suppress the undesirable losses. Metasurfaces enable a spatially varying optical response, mold optical wavefronts into shapes that can be designed at will, and facilitate the integration of functional materials to accomplish active control and greatly enhanced nonlinear response. Designing metasurfaces is generally a challenging inverse problem. A recently introduced synthesis techniques is based on so-called General Sheet Transition Conditions (GSTC) that can be leveraged to define the components of general bianisotropic surface susceptibility tensors characterizing the metasurface. A GSTC-based design technique has several advantages: 1) it is exact; 2) it is general, transforming arbitrary incident waves into arbitrary reflected and transmitted waves, 3) it often admits closed-form solutions, 4) it provides deep insight into the physics of the transformations, 5) it allows multiple (at least up to 4) simultaneous and independent transformations. We study the numerical treatment of GSTC in the time-domain and frequency-domain regimes in the DG and HDG settings respectively.

6.1.3. Corner effects in nanoplasmonics

Participants: Camille Carvalho [Applied Mathematics Department, University of California Merced, USA], Patrick Ciarlet [ENSTA, POEMS project-team], Claire Scheid.

In this work, we study nanoplasmonic structures with corners (typically a diedral/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.

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 that form a parametrized family of solutions. 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. This is the object of the submitted paper [37] (currently under a minor revision process).

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. This work has been presented in 2017 in one conference (see [32] and at the occasion of an invitation for a seminar (see section Invited talks).

6.1.6. Multiscale DG methods for the time-domain Maxwell equations

Participants: Alexis Gobé, 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. The corresponding paper submitted at the end of 2016 is currently under revision (preprint available on HAL [14]). This work has also been presented in a conference in 2017, see [33]

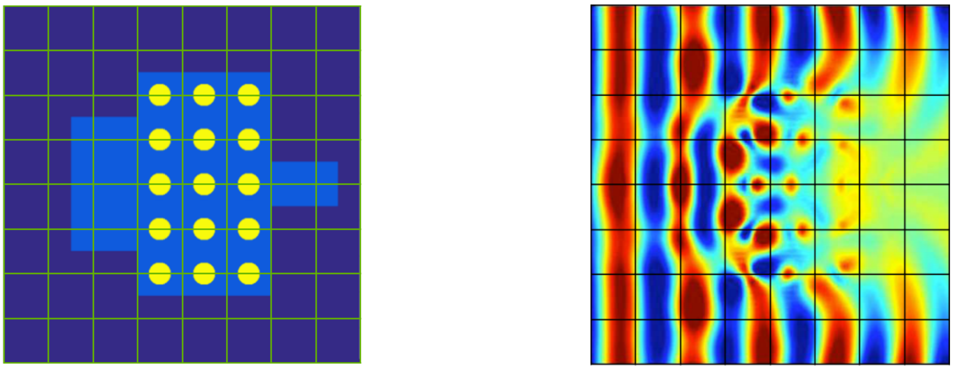


Figure 4. Light propagation in a photonic crystal structure using a MHM-DGTD method for solving the 2D Maxwell's equations. Left: quadrangular mesh. Right: contour lines of the amplitude of the electric field.

6.1.7. HDG methods for the time-domain Maxwell equations

Participants: Alexandra Christophe-Argenvillier [MIT, USA], Stéphane Descombes, Stéphane Lanteri, Georges Nehmetallah.

This study is concerned with the development of accurate and efficient solution strategies for the system of 3D time-domain Maxwell equations coupled to local dispersion models (e.g. Debye, Drude or Drude-Lorentz models) in the presence of locally refined meshes. Such meshes impose a constraint on the allowable time step for explicit time integration schemes that can be very restrictive for the simulation of 3D problems. We consider here the possibility of using an unconditionally stable implicit time or a locally implicit time integration scheme combined to a HDG discretization method. As a preliminary step, we have investigated a fully explicit HDG method generalizing the classical upwind flux-based DG method for the system of time-domain Maxwell equations. We have study the stability of this new HDG method and in particular, the influence of the stabilization parameter on the CFL condition. We are now assessing the consitions under which we can obtain a superconverging HDG method.

6.1.8. HDG methods for the frequency-domain Maxwell equations

Participants: 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 frequency-domain plasmonics

Participants: Stéphane Lanteri, Mostafa Javadzadeh Moghtader, Liang Li [UESTC, Chengdu, China], Asger Mortensen [DTU Fotonik, Technical University of Denmark], Martijn Wubs [DTU Fotonik, Technical University of Denmark].

In this collaboration 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 the 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 have been implemented and numerically assessed for two-dimensional problems. Beside, we are also considering the three-dimensional case

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, Weslley Da Silva Pereira [LNCC, Petropolis, Brazil], Frédéric Valentin [LNCC, Petropolis, Brazil].

In the context of the visit of Frédéric Valentin in the team, we have initiated a study aiming at the design of novel multiscale methods for the solution of the time-domain elastodynamic equations, in the spirit of MHM (Multiscale Hybrid-Mixed) methods previously proposed for fluid flow problems. Motivation in that direction naturally came when dealing with non homogeneous anisotropic elastic media as those encountered in geodynamics related applications, since multiple scales are naturally present when high contrast elasticity parameters define the propagation medium. Instead of solving the usual system expressed in terms of displacement or displacement velocity, and stress tensor variables, a hybrid mixed-form is derived in which an additional variable, the Lagrange multiplier, is sought as representing the (opposite) of the surface tension defined at each face of the elements of a given discretization mesh. We consider the velocity/stress formulation of the elastodynamic equations, and study a MHM method defined for a heterogeneous medium where each elastic material is considered as isotropic to begin with. If the source term (the applied given force on the medium) is time independent, and if we are given an arbitrarily coarse conforming mesh (triangulation in 2D, tetrahedrization in 3D), the proposed MHM method consists in first solving a series of fully decoupled (therefore parallelizable) local (element-wise) problems defining parts of the full solution variables which are directly related to the source term, followed by the solution of a global (coarse) problem, which yields the degrees of freedom of both the Lagrange multiplier dependent part of the full solution variables and the Lagrange multiplier itself. Finally, the updating of the full solution variables is obtained by adding each splitted solution variables, before going on the next time step of a leap-frog time integration scheme. Theoretical analysis and implementation of this MHM method where the local problems are discretized with a DG method, are underway.

6.3. High performance numerical computing

6.3.1. Porting a DGTD solver for bioelectromagnetics to the DEEP-ER architecture

Participants: Alejandro Duran [Barcelona Supercomputing Center, Spain], Stéphane Lanteri, Raphaël Léger, Damian A. Mallón [Juelich Supercomputing Center, Germany].

We are concerned here with the porting of the GERShWIN DGDT solver for computational bioelectromagnetics to the novel heterogeneous architecture proposed in the DEEP-ER european project on exascale computing. This architecture is based on a Cluster/Booster division concept (see Fig. 5). The Booster nodes are based on the Intel Many Integrated Core (MIC) architecture. Therfore, one objective of our efforts is the algorithmic adaptation of the DG kernels in order to leverage the vectorizing capabilities of the MIC processor. The other activities that are undertaken in the context of our contribution to this project aim at exploiting the software environments and tools proposed by DEEP-ER partners for implementing resiliency strategies and high performance I/O operations. In particular, the Cluster nodes are used for running some parts of the pre- and post-processing phases of the DGTD solver which do not lend themselves well to multithreading, as well as I/O intensive routines. One possibility to achieve this is to consider a model in which these less scalable and I/O phases are reverse-offloaded from Booster processes to Cluster processes in a one-to-one mapping. This is achieved by exploiting the OmpSs offload functionality, developed at Barcelona Supercomputing Center for the DEEP-ER platform.

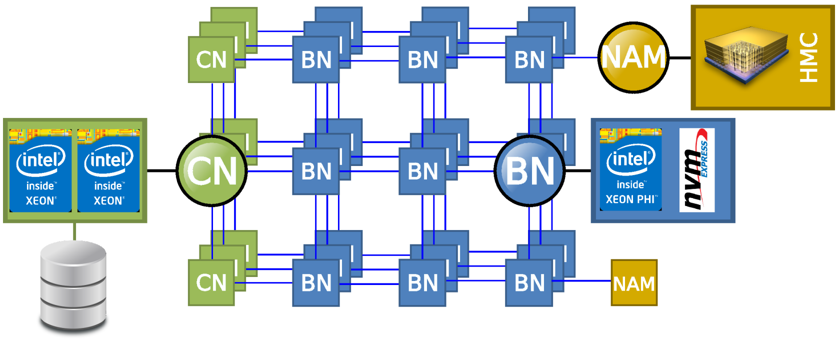


Figure 5. DEEP-ER hardware architecture sketch.

6.3.2. High order HDG schemes and domain decomposition solvers for frequency-domain electromagnetics

Participants: Emmanuel Agullo [HIEPACS project-team, Inria Bordeaux - Sud-Ouest], Luc Giraud [HIEPACS project-team, Inria Bordeaux - Sud-Ouest], Matthieu Kuhn [HIEPACS project-team, Inria Bordeaux - Sud-Ouest], Stéphane Lanteri, Ludovic Moya, Olivier Rouchon [CINES, Montpellier].

This work is undertaken in the context of the ANR TECSER project on one hand, and PRACE 4IP project on the other hand, and is concerned with the development of scalable frequency-domain electromagnetic wave propagation solvers, in the framework of the HORSE simulation software. HORSE is based on a high order HDG scheme formulated on an unstructured tetrahedral grid for the discretization of the system of three-dimensional Maxwell equations in heterogeneous media, leading to the formulation of large sparse undefinite linear system for the hybrid variable unknowns. This system is solved with domain decomposition strategies that can be either a purely algebraic algorithm working at the matrix operator level (i.e. a black-box solver), or a tailored algorithm designed at the continuous PDE level (i.e. a PDE-based solver). In the former case, we use the MaPHyS (Massively Parallel Hybrid Solver) developed in the HIEPACS project-team at Inria Bordeaux - Sud-Ouest.

6.4. Applications

6.4.1. Light transmission in subwavelength gratings

Participants: Leandro Andrade Couto Fonseca, Hugo Enrique Hernandez Figueroa [Universidade Estadual de Campinas, Sao Paulo, Brazil], Laurent Labonté [Information Quantique avec la Lumière et la Matière (QILM) team, INPHYNI, Université Nice Sophia Antipolis], Stéphane Lanteri, Jonathan Viquerat.

Silicon photonics has great potential to bringing together two technological areas that have transformed the last century, electronics and photonics. Silicon waveguides are important components for tailoring photonic functions on silicon. They have been studied extensively over the pas two decades. There are a number of waveguide geometries that have been developed in silicon. The most common are strip waveguides, rib waveguides and slot waveguides. The Bragg grating is a fundamental component in various optical devices and has applications in areas as diverse communications, laser and sensors. In the simplest configuration, a Bragg grating is a structure with periodic modulation of the effective refractive index. This modulation is commonly achieved by varying the refractive index (e.g. alternating material) or the physical dimensions of the waveguide. At each boundary, a reflection of the travelling light occurs, and the relative phase of the reflected signal is determined by the grating period and the wavelength. The repeated modulation of the refractive index results in multiple and distributed reflections. The reflected signals only interfere constructively in

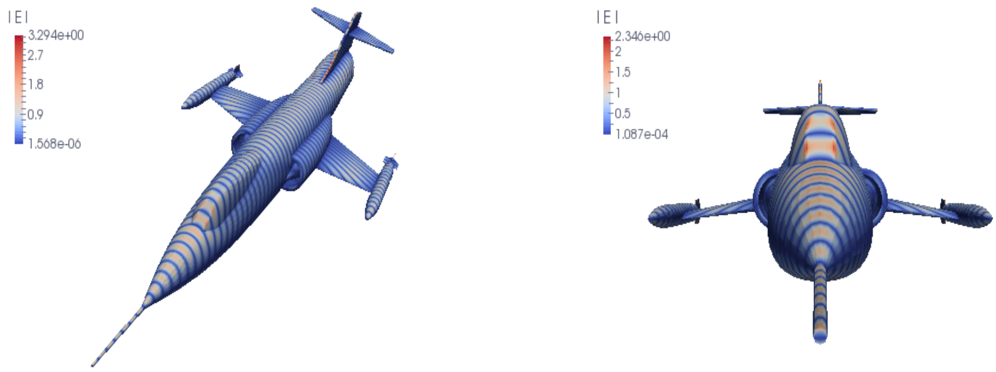


Figure 6. Scattering of a plane wave by a Lockheed F-104 Starfighter. Contour lines of the amplitude of the electric field. Simulations are performed with a HDG scheme based on a cubic interpolation of the electric and magnetic field unknowns, combined with a PDE-based domain decomposition solver.

a narrow band around one particular wavelength, namely the Bragg wavelength. Within this range, light is strongly reflected. At other wavelengths, the multiple reflections interfere destructively and cancel each other out, and as a result, light is transmitted through the grating. This is the functional principle of the concept SubWavelength Gratings (SWG). In the context of the OPENING (On-chiP wirEless quantum state eNgineerING) project of the UCA JEDI Excellence Inititiave, we collaborate with the QILM team of the INPHYNI laboratory, on the numerical modeling of light propagation in SWG waveguides, suing a high order DGTD solver from the DIOGENeS software suite. Two situations are considered: (1) in a first step, an ideal configuration corresponding to a virtual design will be simulated; (2) in a second step, several deformed configurations, which are more in line with actual designs (i .e. from lithography), are studied with the goal of identifying the main sources of performance degradation from the transmission point of view.

6.4.2. Light diffusion in nanostructured optical fibers

Participants: Wilfried Blanc [Optical Fibers team, INPHYNI, Université Nice Sophia Antipolis], Stéphane Lanteri, 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 (INPHYNI) 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.

6.4.3. Gap-plasmon confinement with gold nanocubes

Participants: Stéphane Lanteri, Antoine Moreau [Institut Pascal, Université Blaise Pascal], Armel Pitelet [Institut Pascal, Université Blaise Pascal], Claire Scheid, Nikolai Schmitt, Jonathan Viquerat.

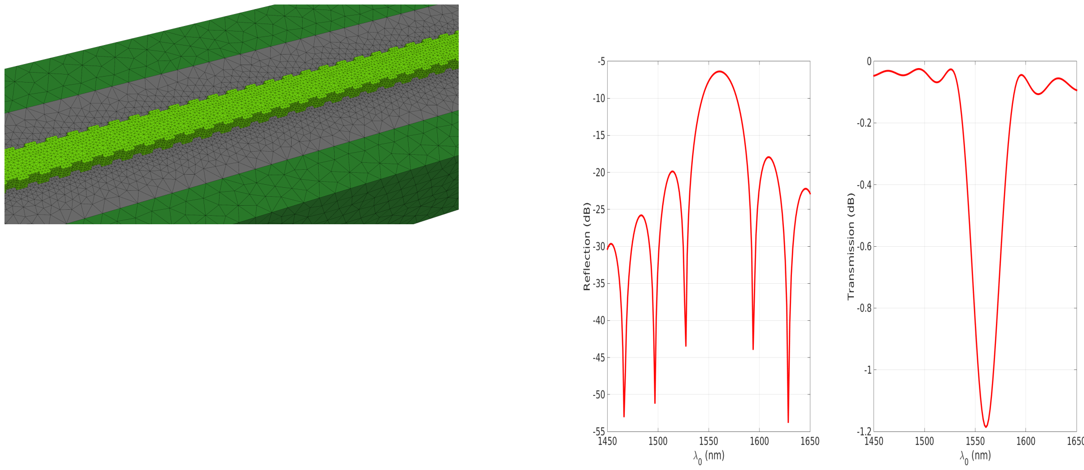


Figure 7. Partial view of a SWG wavewguide tetrahedral mesh (top left); reflection and transmission coefficients (bootom).1

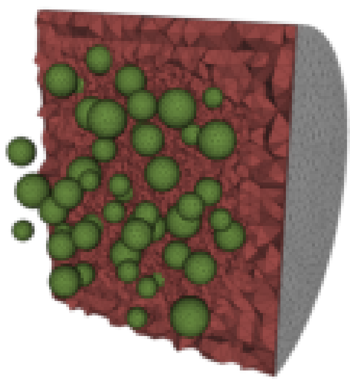


Figure 8. Unstructured tetrahdral mesh of a nanostructured optical fiber core.

The propagation of light in a slit between metals is known to give rise to guided modes. When the slit is of nanometric size, plasmonic effects must be taken into account, since most of the mode propagates inside the metal. Indeed, light experiences an important slowing-down in the slit, the resulting mode being called *gap-plasmon*. Hence, a metallic structure presenting a nanometric slit can act as a light trap, i.e. light will accumulate in a reduced space and lead to very intense, localized fields. Recently, the chemical production of random arrangements of nanocubes on gold films at low cost was proved possible by Antoine Moreau and colleagues at Institut Pascal. Nanocubes are separated from the gold substrate by a dielectric spacer of variable thickness, thus forming a narrow slit under the cube. When excited from above, this configuration is able to support gap-plasmon modes which, once trapped, will keep bouncing back and forth inside the cavity. At visible frequencies, the lossy behavior of metals will cause the progressive absorption of the trapped electromagnetic field, turning the metallic nanocubes into efficient absorbers. The frequencies at which this absorption occurs can be tuned by adjusting the dimensions of the nanocube and the spacer. In collaboration with Antoine Moreau, we propose to study numerically the impact of the geometric parameters of the problem on the behaviour of a single nanocube placed over a metallic slab (see Fig. 9). 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. 10).

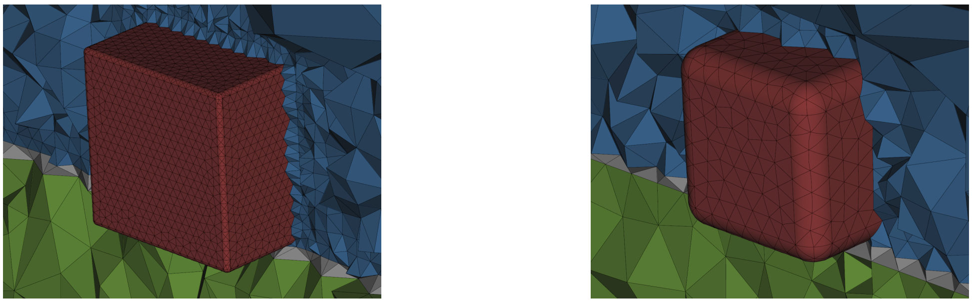
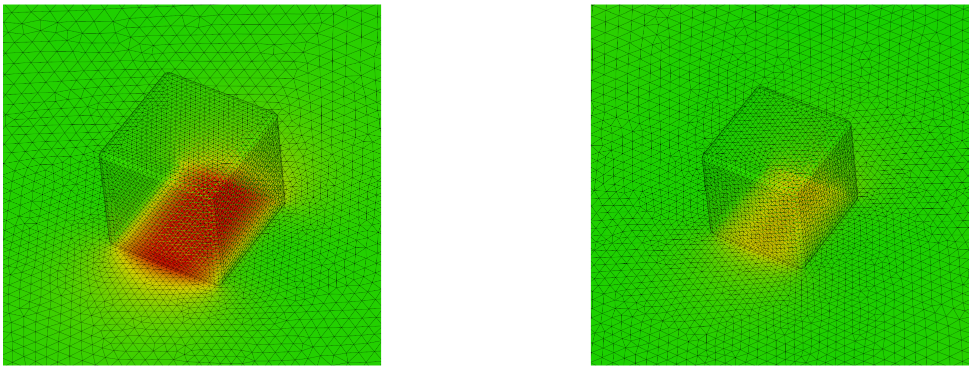


Figure 9. Meshes of rounded nanocubes with rounding radii ranging from 2 to 10 nm. Red cells correspond to the cube. The latter lies on the dielectric spacer (gray cells) and the metallic plate (green). Blue cells represent the air surrounding the device.

6.4.4. Light-trapping in nanostructured solar cells

Participants: Urs Aeberhard [IEK5 - Photovoltaik, Forschungszentrum Juelich GmbH, German], Karsten Bittkau [IEK5 - Photovoltaik, Forschungszentrum Juelich GmbH, German], Alexis Gobé, Stéphane Lanteri.

This work is undertaken in the context of the EoCoE Center of Excellence in collaboration with researchers from IEK5 - Photovoltaik, Forschungszentrum Juelich GmbH, Germany. The objective is to design a scalable high order DGTD solver for the simulation of light trapping in a multi-layer solar cell with surface texture. For that purpose, we rely on the DIOGENeS software suite from which we extract a high order DGTD solver for the problem under consideration, taking into account its specificities (in particular, with regards to material models and boundary conditions). We also need to specify and develop a dedicated preprocessing tool for building topography conforming geometrical models. Simulations are performed on the Occigen PRACE system at CINES.



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

Figure 10. 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.

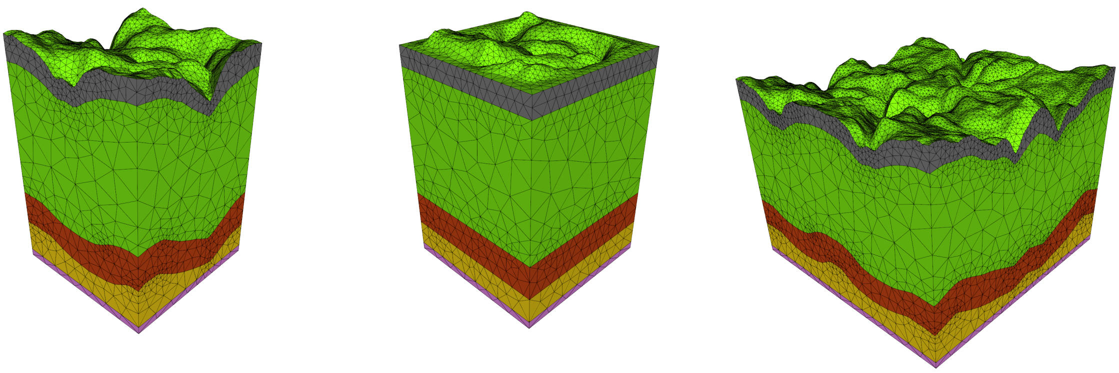


Figure 11. Simulation of light trapping in a multi-layer solar cell with surface texture using a high order DGTD fullwave solver and topography conforming geometrical models.

NEO Project-Team

7. New Results

7.1. Stochastic Modeling

Participants: Alain Jean-Marie, Hlib Mykhailenko, Eleni Vatamidou.

7.1.1. Semi-Markov Accumulation Processes

E. Vatamidou and A. Jean-Marie have introduced in [37] a new accumulation process, the Semi-Markov Accumulation Process (SMAP). This class of processes extends the framework of continuous-time Markov Additive Processes (MAPs) by allowing the underlying environmental component to be a semi-Markov process instead of a Markov process. They follow an analytic approach to derive a Master Equation formula of the Renewal type that describes the evolution of SMAPs in time. They show that under exponential holding times, a matrix exponential form analogous to the matrix exponent of a MAP is attained. Finally, they consider an application of these results where closed-form solutions are rather easy to achieve.

7.1.2. The marmoteCore platform

The development of `marmoteCore` (see Section 6.1) has been pursued. The software library is now mature enough to develop complex models, such as in [33]. Its architecture and main capabilities have been presented in [26]. `marmoteCore` provides the classes necessary to represent the state space of Markov models, from the elementary bricks that are interval or rectangular domains, simplices, or binary sequences. From there, the user easily programs the construction of probability transition matrices or infinitesimal generators. Structural analysis methods allow to identify recurrent and transient classes, and to compute the period of the model. Numerous methods allow the Monte Carlo simulation of the chain, the computation of transient and stationary distributions, as well as hitting times. `marmoteCore` is organized in a hierarchy of Markov models, from the simplest ones (Poisson process, two-state chains, ...) to the most general ones, including classes of models with a particular interest, such as QBDs. It is therefore possible to program solution methods specifically optimized and adapted to the level of structure of the model.

7.2. Random Graph and Matrix Models

Participants: Arun Kadavankandy, Konstantin Avrachenkov.

In [27] A. Kadavankandy and K. Avrachenkov in collaboration with L. Cottatellucci (EURECOM, France) and R. Sundaresan (IIS Bangalore, India) propose a local message passing algorithm based on Belief Propagation (BP) to detect a small hidden Erdös-Rényi (ER) subgraph embedded in a larger sparse ER random graph in the presence of side-information. The side-information considered is in the form of revealed subgraph nodes called cues, some of which may be erroneous. Namely, the revealed nodes may not all belong to the subgraph, and it is not known to the algorithm a priori which cues are correct and which are incorrect. The authors show that asymptotically as the graph size tends to infinity, the expected fraction of misclassified nodes approaches zero for any positive value of a parameter λ, which represents the effective Signal-to-Noise Ratio of the detection problem. Previous works on subgraph detection using BP without side-information showed that BP fails to recover the subgraph when $\lambda < 1/e$. These new results thus demonstrate the substantial gains in having even a small amount of side-information.

PageRank has numerous applications in information retrieval, reputation systems, machine learning, and graph partitioning. In [8] K. Avrachenkov and A. Kadavankandy in collaboration with L. Ostroumova and A. Raigorodskii (Yandex, Russia) study PageRank in undirected random graphs with an expansion property. The Chung-Lu random graph is an example of such a graph. They show that in the limit, as the size of the graph goes to infinity, PageRank can be approximated by a mixture of the restart distribution and the vertex degree distribution. They also extend the result to Stochastic Block Model (SBM) graphs, where they show that there is a correction term that depends on the community partitioning.

7.3. Data Analysis and Learning

Participants: Konstantin Avrachenkov, Hlib Mykhailenko, Giovanni Neglia, Dmytro Rubanov.

7.3.1. Unsupervised learning

In [21] K. Avrachenkov in collaboration with A. Kondratev and V. Mazalov (both from Petrozavodsk State Univ., Russia) apply cooperative game-theoretic methods for community detection in networks. The traditional methods for detecting community structure are based on selecting denser subgraphs inside the network. Their new approach is to use the methods of cooperative game theory that highlight not only the link density but also the mechanisms of cluster formation. Specifically, they suggest two approaches from cooperative game theory: the first approach is based on the Myerson value, whereas the second approach is based on hedonic games. Both approaches allow to detect clusters with various resolution. However, the tuning of the resolution parameter in the hedonic games approach is particularly intuitive. Furthermore, the modularity based approach and its generalizations can be viewed as particular cases of the hedonic games.

Kernels and, broadly speaking, similarity measures on graphs are extensively used in graph-based unsupervised and semi-supervised learning algorithms as well as in the link prediction problem. In [19] K. Avrachenkov and D. Rubanov in collaboration with P. Chebotarev (Trapeznikov Institute of Control Sciences, Russia) analytically study proximity and distance properties of various kernels and similarity measures on graphs. This can potentially be useful for recommending the adoption of one or another similarity measure in a machine learning method. Also, they numerically compare various similarity measures in the context of spectral clustering and observe that normalized heat-type similarity measures with log modification generally perform the best.

7.3.2. Semi-supervised learning

Graph-based semi-supervised learning for classification endorses a nice interpretation in terms of diffusive random walks, where the regularisation factor in the original optimisation formulation plays the role of a restarting probability. Recently, a new type of biased random walks for characterising certain dynamics on networks have been defined and rely on the γ-th power of the standard Laplacian matrix L. In particular, these processes embed long range transitions, the Levy flights, that are capable of one-step jumps between far-distant states (nodes) of the graph. In [24] K. Avrachenkov in collaboration with E. Bautista, S. De Nigris, P. Abry and P. Gonçalves (from DANTE Inria team and ENS Lyon) build upon these volatile random walks to propose a new version of graph based semi-supervised learning algorithms whose classification outcome could benefit from the dynamics induced by the fractional transition matrix. In [22] using the framework of Levy flights, they further improve the classification outcome, even in settings traditionally poorly performing such as unbalanced classes, and they derive a theoretical rule for classification decision.

In [6] K. Avrachenkov in collaboration with P. Chebotarev (Trapeznikov Institute of Control Sciences, Russia) and A. Mishenin (Saint Petersburg Univ., Russia) study a semi-supervised learning method based on the similarity graph and regularized Laplacian. They give convenient a optimization formulation of the regularized Laplacian method and establish its various properties. In particular, they show that the kernel of the method can be interpreted in terms of discrete and continuous-time random walks and possesses several important properties of proximity measures. Both optimization and linear algebra methods can be used for efficient computation of the classification functions. The authors demonstrate on numerical examples that the regularized Laplacian method is robust with respect to the choice of the regularization parameter and outperforms the Laplacian-based heat kernel methods.

7.3.3. Distributed computing

In distributed graph computation, graph partitioning is an important preliminary step, because the computation time can significantly depend on how the graph has been split among the different executors. In [30] H. Mykhailenko and G. Neglia, in collaboration with F. Huet (I3S) propose a framework for distributed edge partitioning based on simulated annealing. The framework can be used to optimize a large family of partitioning metrics. They provide sufficient conditions for convergence to the optimum as well as discuss which metrics can be efficiently optimized in a distributed way. They implemented these partitioners in Apache GraphX and performed a preliminary comparison with JA-BE-JA-VC, a state-of-the-art partitioner that inspired the new approach. They show that this approach can provide improvements, but further research is required to identify suitable metrics to optimize as well as to design a more efficient exploration phase for the algorithm without sacrificing convergence properties.

Because of the significant increase in size and complexity of the networks, the distributed computation of eigenvalues and eigenvectors of graph matrices has become very challenging and yet it remains as important as before. In [20] K. Avrachenkov in collaboration with P. Jacquet (Nokia Bell Labs) and J. Sreedharan (Purdue Univ., USA) develop efficient distributed algorithms to detect, with higher resolution, closely situated eigenvalues and corresponding eigenvectors of symmetric graph matrices. We model the system of graph spectral computation as physical systems with Lagrangian and Hamiltonian dynamics. The spectrum of Laplacian matrix, in particular, is framed as a classical spring-mass system with Lagrangian dynamics. The spectrum of any general symmetric graph matrix turns out to have a simple connection with quantum systems and it can be thus formulated as a solution to a Schrödinger-type differential equation. Taking into account the higher resolution requirement in the spectrum computation and the related stability issues in the numerical solution of the underlying differential equation, we propose the application of symplectic integrators to the calculation of eigenspectrum. The effectiveness of the proposed techniques is demonstrated with numerical simulations on real-world networks of different sizes and complexities.

7.4. Game Theory

Participants: Eitan Altman, Konstantin Avrachenkov.

7.4.1. Dynamic potential games

In [11] K. Avrachenkov in collaboration with V. Mazalov and A. Rettieva (both from Petrozavodsk State Univ., Russia) treat discrete-time game-theoretic models of resource exploitation as dynamic potential games. The players (countries or firms) exploit a common stock on the infinite time horizon. The main aim is to obtain a potential for the linear-quadratic games of this type. The class of games where a potential can be constructed as a quadratic form is identified. As an example, the dynamic game of bioresource management is considered and the potentials are constructed in the case of symmetric and asymmetric players.

7.4.2. A Hawk and Dove game with infinite state space

In [16], E. Altman, in collaboration with A. Aradhye and R. El-Azouzi (UAPV) consider the Hawk-Dove game in which each of infinitely many individuals, involved with pairwise encounters with other individuals, can decide whether to act aggressively (Hawk) or peacefully (Dove). Each individual is characterized by its strength. The strength distribution among the population is assumed to be fixed and not to vary in time. If both individuals involved in an interaction are Hawks, there will be a fight, the result of which will be determined by the strength of each of the individuals involved. The larger the difference between the strength of the individuals is, the larger is the cost for the weaker player involved in the fight. The goal is to study the influence of the parameters (such as the strength level distribution) on the equilibrium of the game. The authors show that for some parameters there exists a threshold equilibrium policy while for other parameters there is no equilibrium policy at all.

7.5. Applications in Telecommunications

Participants: Zaid Allybokus, Eitan Altman, Konstantin Avrachenkov, Giovanni Neglia, Sarath Pattathil, Berksan Serbetci, Alina Tuholukova.

7.5.1. Caching

As cellular network operators are struggling to keep up with the rapidly increasing traffic demand, two key directions are deemed necessary for beyond 4G networks: (i) extensive cell densification to improve spatial reuse of wavelengths, and (ii) storage of content as close to the user as possible to cope with the backhaul constraints and increased interference. However, caching has mostly been studied with an exclusive focus either on the backhaul network (e.g. the “femto-caching” line of work) or on the radio access (e.g. through coded caching or cache-aided Coordinated MultiPoint, CoMP). As a result, an understanding of the impact of edge caching on network-wide and end-to-end performance is lacking. In [32] A. Tuholukova and G. Neglia in collaboration with T. Spyropoulos (EURECOM) investigate the problem of optimal caching in a context where nearby small cells (“femto-helpers”) can coordinate not just in terms of what to cache but also to perform Joint Transmission (a type of CoMP). They show that interesting tradeoffs arise between caching policies that improve radio access and ones that improve backhaul, and propose an algorithm that provably achieves an 1/2-approximation ratio to the optimal one (which is NP-hard), and performs well in simulated scenarios.

Cache policies to minimize the content retrieval cost have been studied through competitive analysis when the miss costs are additive and the sequence of content requests is arbitrary. More recently, a cache utility maximization problem has been introduced, where contents have stationary popularities and utilities are strictly concave in the hit rates. In [29] G. Neglia in collaboration with D. Carra (Univ. of Verona) and P. Michiardi (EURECOM) bridges the two formulations, considering linear costs and content popularities. They show that minimizing the retrieval cost corresponds to solving an online knapsack problem, and we propose new dynamic policies inspired by simulated annealing, including DYNQLRU, a variant of QLRU. For such policies they prove asymptotic convergence to the optimum under the characteristic time approximation. In a real scenario, popularities vary over time and their estimation is very difficult. DYNQLRU does not require popularity estimation, and realistic, trace-driven evaluation shows that it significantly outperforms state-of-the-art policies, with up to 45% cost reduction.

Still following the idea that in large communication systems it is beneficial both for the users and for the network as a whole to store content closer to users, one particular implementation of such an approach is to co-locate caches with wireless base stations. In [5] K. Avrachenkov in collaboration with X. Bai and J. Goseling (both from Univ. of Twente, the Netherlands) study geographically distributed caching of a fixed collection of files. They model cache placement with the help of stochastic geometry and optimize the allocation of storage capacity among files in order to minimize the cache miss probability. They consider both per cache capacity constraints as well as an average capacity constraint over all caches. The case of per cache capacity constraints can be efficiently solved using dynamic programming, whereas the case of the average constraint leads to a convex optimization problem. The authors demonstrate that the average constraint leads to significantly smaller cache miss probability. Finally, they suggest a simple LRU-based policy for geographically distributed caching and show that its performance is close to the optimal.

In [7] K. Avrachenkov in collaboration with J. Goseling and B. Serbetci (both from Univ. of Twente, the Netherlands) consider caching in cellular networks in which each base station is equipped with a cache that can store a limited number of files. The popularity of the files is known and the goal is to place files in the caches such that the probability that a user at an arbitrary location in the plane will find the file that she requires in one of the covering caches is maximized. They develop distributed asynchronous algorithms for deciding which contents to store in which cache. Such cooperative algorithms require communication only between caches with overlapping coverage areas and can operate in asynchronous manner. The development of the algorithms is principally based on an observation that the problem can be viewed as a potential game. Their basic algorithm is derived from the best response dynamics. The authors demonstrate that the complexity of each best response step is independent of the number of files, linear in the cache capacity and linear in the maximum number of base stations that cover a certain area. Then, they show that the overall algorithm complexity for a discrete cache placement is polynomial in both network size and catalog size. In practical examples, the algorithm converges in just a few iterations. Also, in most cases of interest, the basic algorithm finds the best Nash equilibrium corresponding to the global optimum. Two extensions of the basic algorithm areprovided, based on stochastic and deterministic simulated annealing which find the global optimum. Finally, the authors demonstrate the hit probability evolution on real and synthetic networks numerically and show that their distributed caching algorithm performs significantly better than storing the most popular content, probabilistic content placement policy and Multi-LRU caching policies.

7.5.2. Software Defined Networks (SDN)

The performance of computer networks relies on how bandwidth is shared among different flows. Fair resource allocation is a challenging problem particularly when the flows evolve over time. To address this issue, bandwidth sharing techniques that quickly react to the traffic fluctuations are of interest, especially in large scale settings with hundreds of nodes and thousands of flows. In [17] Z. Allybokus and K. Avrachenkov in collaboration with J. Leguay and L. Maggi (both from Huawei Research, Paris) propose a distributed algorithm that tackles the fair resource allocation problem in a distributed SDN control architecture. Their algorithm continuously generates a sequence of resource allocation solutions converging to the fair allocation while always remaining feasible, a property that standard primal-dual decomposition methods often lack. Thanks to the distribution of all computer intensive operations, they demonstrate that they can handle large instances in real-time.

In [18] K. Avrachenkov in collaboration with V. Borkar and S. Pattathil (both from IIT Bombay, India) consider the Generalized Additive Increase Multiplicative Decrease (G-AIMD) dynamics for resource allocation with alpha fairness utility function. This dynamics has a number of important applications such as internet congestion control, charging electric vehicles, and smart grids. They prove indexability for the special case of MIMD model and provide an efficient scheme to compute the index. The use of index policy allows to avoid the curse of dimensionality. They also demonstrate through simulations for another special case, AIMD, that the index policy is close to optimal and significantly outperforms a natural heuristic which penalizes the strongest user.

7.5.3. Network formation games

The paper [15] deals with a network formation game while balancing multiple, possibly conflicting objectives like cost, performance, and resiliency to viruses. It is part of a collaboration between Inria (E. Altman), Delft Univ. (S. Trajanovski, F. Kuipers, P. van Mieghem) and UAPV (Y. Hayel) which started within the CONGAS European project. Each player (node) aims to minimize its cost in installing links, the probability of being infected by a virus and the sum of hop counts on its shortest paths to all other nodes. In this article the authors (1) determine the Nash Equilibria and the Price of Anarchy for the network formation game, (2) demonstrate that the Price of Anarchy (PoA) is usually low, which suggests that (near-)optimal topologies can be formed in a decentralized way, and (3) give suggestions for practitioners for those cases where the PoA is high and some centralized control/incentives are advisable.

7.5.4. User association in LTE

Within the Inria-Nokia joint labs, C.S. Chen and L. Roullet (Nokia) N. Trabelsi (former member of MAESTRO) and E. Altman, and R. El-Azouzi (UAPV) have proposed a distributed algorithm for optimizing user Association and resource allocation in LTE networks. The solution is based on a game theoretic approach, which permits to compute Cell Individual Offset (CIO) and a pattern of power transmission over frequency and time domain for each cell. Simulation results show significant benefits in the average throughput and also cell edge user throughput of 40% and 55% gains respectively. Furthermore, we also obtain a meaningful improvement in energy efficiency.

7.5.5. Matching games for solving the association problem in WIFI

Matching games are a powerful framework for formulating and for solving user association problems. In [13], M. Touati (Orange Labs) and M. Coupechoux (Telecom ParisTech), R. El-Azouzi (UAPV), E. Altman and J. M. Kelif (Orange Labs) have considered the problem of association in a particular complex context of matching games with externalities in which the ranking of various associations by a player depends on association decisions of other player. This situation occurs in multi-rate IEEE 802.11 WLANs. traditional user association based on the strongest received signal and the well known anomaly of the MAC protocol can lead to overloaded Access Points (APs), and poor or heterogeneous performance. They show that theit proposed association scheme can greatly improve the efficiency of 802.11 with heterogeneous nodes. The mechanism can be implemented as a virtual connectivity management layer to achieve efficient APs-user associations without modification of the MAC layer.

7.5.6. A stochastic game for competition over relay opportunities in DTN networks

In [12], K. P. Naveen (Indian Institute of Technology, Madras) and E. Altman in collaboration with A. Kumar (IISc Bangalore) consider an opportunistic wireless communication setting, in which two nodes (referred to as forwarders) compete to choose a relay node from a set of relays, as they ephemerally become available (e.g., wake up from a sleep state). Each relay, when it becomes available (or arrives), offers a (possibly different) " reward " to each forwarder. Each forwarder's objective is to minimize a combination of the delay incurred in choosing a relay and the reward offered by the chosen relay. As an example, the authors develop the reward structure for the specific problem of geographical forwarding over a common set of sleep-wake cycling relays. They formulate the model as a stochastic game theoretic variant of the asset selling problem studied in the Operations Research literature. They study two variants of the generic relay selection problem, namely, the completely observable and the partially observable cases. These cases are based on whether a forwarder (in addition to observing its reward) can also observe the reward offered to the other forwarder. The structure of Nash Equilibrium Policy Pairs is studied and characterized.

7.5.7. Aid for visually inpaired persons

S. Boularouk, D. Josselin (UAPV) and E. Altman pursue in [34], [35] the design of a geographic recommendation and alarm system for visually impaired persons. In [34] they propose a vocal ontology of Open-StreetMap (OSM) data for the apprehension of space by visually impaired people. They propose a simple but usable method to extract data from OSM databases in order to send them using Text To Speech technology. They focus on how to help people suffering from visual disability to plan their itinerary, to comprehend a map by querying computer and getting information about surrounding environment in a mono-modal human-computer dialogue. In [35] they further study the benefit of IoT for people with disabilities, particularly for visually impaired and blind people mobility. They propose a simple prototype using OpenStreetMap data combined to physical environment data measured from sensors connected to a Arduino board through Speech recognition.

7.5.8. Routing games over the line

In [28] A. Karouit, M. Haddad, A. El Matar (UAPV) and E. Altman study a sequential routing game where several users send traffic to a destination on a line. Each user arrives at some time epoch with a given capacity. Then, he ships its demand over time on a shared resource. The state of a player evolves according to whether he decides to transmit or not. The decision of each user is thus spatio-temporal control. The authors provide an explicit expression for the equilibrium of such systems and compare it to the global optimum case. In particular, they compute the price of anarchy of such schemes and identify a Braess-type paradox in the context of sequential routing games.

7.5.9. Multicriteria Games of congestion

In [23], A. Boukoftane and M. Haddad (UAPV) in collaboration with E. Altman and N. Oukid (Univ. de Saad Dahlab) consider a routing game in a network that contains lossy links. They consider a multi-objective problem where the players have each a weighted sum of a delay cost and a cost for losses. They compute the equilibrium and optimal solution (which are unique). They discover here in addition to the classical Kameda type paradox another paradoxical behavior in which higher loss rates have a positive impact on delay and therefore higher quality links may cause a worse performance even in the case of a single player.

7.5.10. Speed estimation in cellular networks

The paper [25], is part of a joint ongoing work within the Inria-Nokia joint lab on the SelfNet ADR which focused on speed estimation. It involved E. Altman, M. Haddad (UAPV), D.G. Herculea, C.S. Chen and V. Capdevielle (Nokia). The authors provide a new online algorithm for mobile user speed estimation in 3GPP Long Term Evolution (LTE)/LTE-Advanced networks. The proposed method leverages on uplink sounding reference signal power measurements performed at the base station, also known as eNodeB, and remains effective even under large sampling period. Extensive performance evaluation of the proposed algorithm is carried out using field traces from realistic environment. The on-line solution is proven highly efficient in terms of computational requirement, estimation delay, and accuracy.

7.6. Applications in Social Networks

Participant: Eitan Altman.

7.6.1. Posting behavior

In [10], Eitan Altman, together with A. Masson (SAFRAN Group, formerly with MAESTRO) and Y. Hayel (UAPV), pursue two objectives. First they model the posting behaviour of publishers in Social Networks which have externalities. Secondly, they propose content active filtering in order to increase content diversity from different publishers. By externalities, is meant that when the quantity of posted contents from a specific publisher impacts the popularity of other posted contents. The authors introduce a dynamical model to describe the posting behaviour of publishers taking into account these externalities. This model is based on stochastic approximations and sufficient conditions are provided to ensure its convergence to a unique rest point. A closed form of this rest point is provided, and it is shown that it can be obtained as the unique equilibrium of a non-cooperative game. Content Active Filtering (CAF) are actions taken by the administrator of the Social Network in order to promote some objectives related to the quantity of contents posted in various contents. An objective of the CAF can be maximizing the diversity of posted contents. Finally, the authors illustrate their results through numerical simulations and they validate them with real data extracted from social networks.

7.7. Applications to Renewable Resources and Energy

Participants: Sara Alouf, Alain Jean-Marie, Dimitra Politaki.

7.7.1. Stochastic models for solar power

In [31], D. Politaki and S. Alouf develop a stochastic model for the solar power at the surface of the earth. They combine a deterministic model of the clear sky irradiance with a stochastic model for the so-called clear sky index to obtain a stochastic model for the actual irradiance hitting the surface of the earth. Their clear sky index model is a 4-state semi-Markov process where state durations and clear sky index values in each state have phase-type distributions. They use per-minute solar irradiance data to tune the model, hence they are able to capture small time scales fluctuations. They compare this model with the on-off power source model developed by Miozzo et al. (2014) for the power generated by photovoltaic panels, and to a modified version that they propose. Computing the autocorrelation functions for all proposed models, they find that the irradiance model surpasses the on-off models and it is able to capture the multiscale correlations that are inherently present in the solar irradiance. The power spectrum density of generated trajectories matches closely that of measurements. This new irradiance model can be used not only in the mathematical analysis of energy harvesting systems but also in their simulation.

In [45], D. Politaki, S. Alouf and A. Jean-Marie in collaboration with F. Hermenier (Nutanix) aim at the performance analysis of a data center feb by renewable energy recources. They describe the data center system, proposing a new queuing model BMAP/PH/c which represents the queue length in a system having c servers, where arrivals are determined by a Batch Markov Arrival process and service times have a phase-type distribution. They validate this model using real traces. Next, they characterize the data center google workload traces which are available in the web and they validate that the jobs arrive to the system in groups (batches) and wait at the queue. The waiting time is diverse according to the available resources, job size etc. The authors then compute the empirical CDF of the service time and try to fit it with well-known distributions like exponential, Pareto etc. However, the Kolmogorov-Smirnov test rejects the null hypothesis at the 1% significance level which shows that service time doesn't fit with any well-known distribution.

7.7.2. Sustainable management of water consumption

Alain Jean-Marie, Mabel Tidball (INRA, Montpellier, France), Fernando Ordóñez and Victor Bucarey López (Univ. de Chile, Chile), consider in [36] a discrete time, infinite horizon dynamic game of groundwater extraction. A Water Agency charges an extraction cost to water users, and controls the marginal extraction cost so that it depends linearly on total water extraction (through a parameter n) and on rainfall (through parameter m). The water users are selfish and myopic, and the goal of the agency is to give them incentives them so as to, at the same time, improve their total welfare and improve the long-term level of the resource.

This problem is studied in two situations for a linear-quadratic model. In the first situation, the parameters n and m are considered to be fixed over time, and the Agency selects the value that maximizes the total discounted welfare of agents. A first result shows that when the Water Agency is patient (discount rate close to one), the optimal marginal extraction cost asks for strategic interactions between agents.

In the second situation, the authors look at the dynamic Stackelberg game where the Agency decides at each time what cost parameter they must announce in order to maximize the welfare function. This becomes a highly non-linear optimal control problem. Some preliminary results are presented.

STARS Project-Team

7. New Results

7.1. Introduction

This year Stars has proposed new results related to its three main research axes : perception for activity recognition, semantic activity recognition and software engineering for activity recognition.

7.1.1. Perception for Activity Recognition

Participants: François Brémond, Etienne Corvée, Antitza Dancheva, Furqan Muhammad Khan, Michal Koperski, Thi Lan Anh Nguyen, Javier Ortiz, Remi Trichet, Ujjwal Ujjwal, Srijan Das, Monique Thonnat.

The new results for perception for activity recognition are:

- Pedestrian detection: Training set optimization (see 7.2)
- Pedestrian Detection Using Deep Learning (see 7.3)
- Deep Learning applied on Embedded Systems for people detection (see 7.4)
- Facial Analysis (see 7.5)
- Multi-Object Tracking using Multi-Channel Part Appearance Representation (see 7.6)
- Tracklets Pre-Processing for Signature Computation in the Context of Multi-Shot Person Re-Identification (see 7.7)
- Multi-shot Person Re-identification in surveillance videos (see 7.8)
- Person Re-Identification using Pose-Driven Body Parts (see 7.9)
- Human Action Recognition in Videos with Local Representation (see 7.10)
- Action Detection in Untrimmed Videos (see 7.11)
- RGB-D based Action Recognition using CNNsf (see 7.12)
- Recognizing Human Actions Using RGB Sport Videos From the Web (see 7.13)

7.1.2. Semantic Activity Recognition

Participants: Carlos Fernando Crispim Junior, Kartik Kartik, Farhood Negin, Thanh Hung Nguyen, Kuan-Ru Lee, Antitza Dantcheva, Auriane Gros, Alexandra Koening, Guillaume Sacco, Philippe Robert, François Brémond, Monique Thonnat.

For this research axis, the contributions are :

- Event Recognition Based on Depth Image (see 7.14)
- Recognition of Daily Activities by Embedding Visual Features within a Semantic Language (see 7.15)
- Cognitive Assessment Using Gesture Recognition (see 7.16)
- Geometric and Visual Features Fusion for Action Recognition (see 7.17)
- Probabilistic Logic for Activity Recognition (see 7.18)
- Recognizing Retracing of Steps Using Walk Comparison (see 7.19)
- Safe & Easy Environment for Alzheimer Disease and related disorders (see 7.20)
- Early detection of cognitive disorders such as dementia on the basis of speech analysis ELEMENT (see 7.21)
- Serious Exergames for Cognitive Stimulation (see 7.22)

7.1.3. Software Engineering for Activity Recognition

Participants: Sabine Moisan, Annie Ressouche, Jean-Paul Rigault, Ines Sarray, Thanh Hung Nguyen, Daniel Gaffé, Julien Badie, Anais Ducoffe, Dorine Havyarimana, Cedric Girard-Riboulleau, François Brémond, Minh Khue Phan Tran, Philippe Robert.

The contributions for this research axis are:

- Defining an activity description language for end-users and its semantics (see 7.23)
- The Clem Workflow (see 7.24)
- Study of Temporal Properties of Neuronal Archetypes (see 7.25)
- Maintaining the engagement of older adults with dementia while interacting with serious game(see 7.26)
- Application of deep learning on healthcare (see 7.27)
- Brick & Mortar Cookies (see 7.28)

7.2. Pedestrian Detection: Training Set Optimization

Participants: Remi Trichet, Javier Ortiz.

keywords: computer vision, pedestrian detection, classifier training, data selection, data generation, data weighting, feature extraction

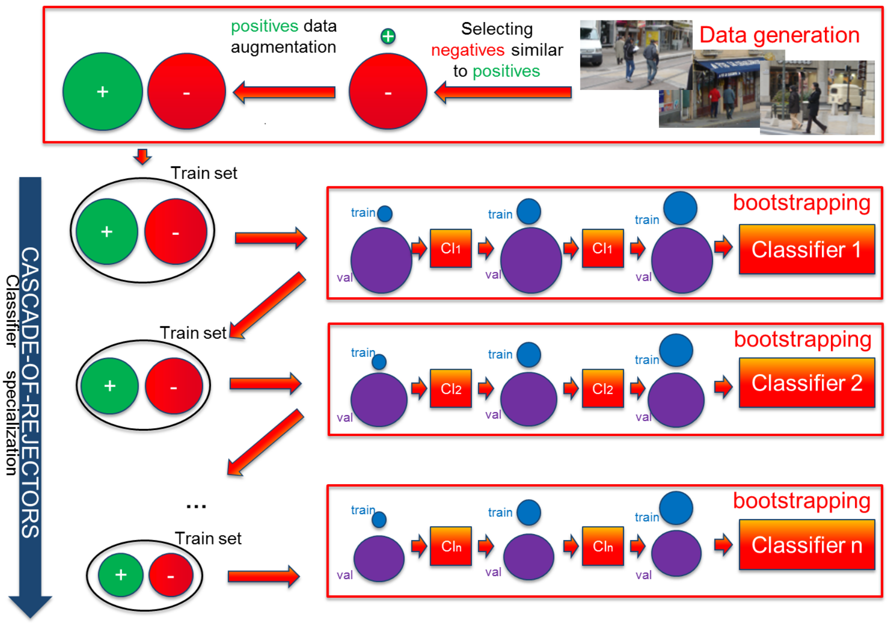


Figure 5. Training pipeline. The initial training set generation selects data while balancing negative and positive sample cardinalities. A cascade of classifiers is then trained on it, each independent classifier being learnt through bootstrapping. balanced positive and negative sets is sought all along the cascade. Each circle surface is proportional to the set's cardinality that it represents.

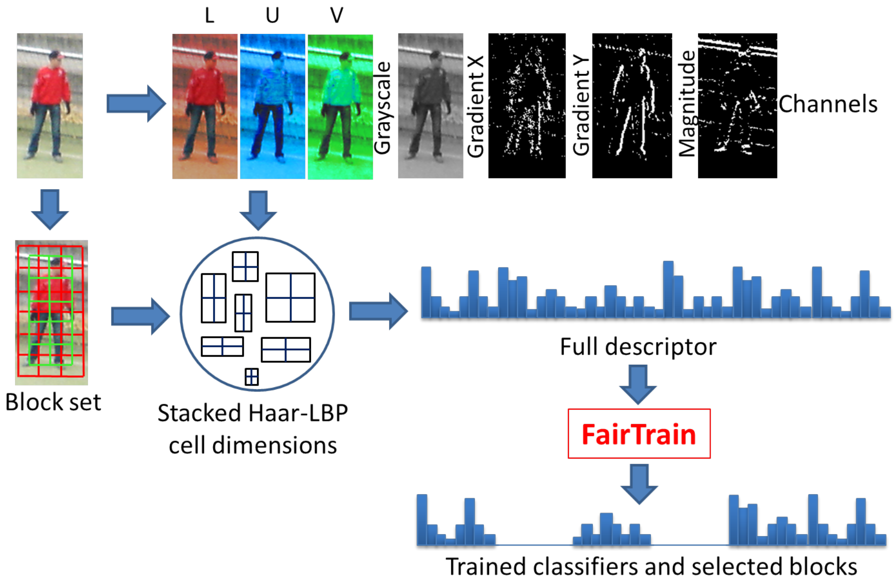


Figure 6. LBP Channel features pipeline.

This year's work builds on the near real-time pedestrian detector introduced last year. Let's recall that this detector novelty mainly focusses on our training set generation protocol, named *FairTrain*[39]. The methodology, illustrated in figure 5 , decomposes in two distinct parts: The initial training set generation and the classifier training. The initial training set generation carefully selects data from a set of images while balancing negative and positive sample cardinalities. We then train a cascade of 1 to n classifiers. This cascade could consist of a cascade-of-rejectors [57], [143], [48], [118], [122], a soft cascade [99], or both. In addition, each independent classifier is learnt through bootstrapping [59], [69] to improve performance. One key aspect is to seek balanced positive and negative sets at all time. Hence, all along the cascade, the minority class is oversampled to create balanced positive and negative sets. See [39] for details.

This year's improvement on this framework is two-fold: refined experimentation and Local Binary Pattern (LBP) channel descriptor.

In many aspects, the construction of a training set remains similar to what it was at the birth of the domain, some related problems are not well studied, and sometimes still tackled empirically. This work studies the pedestrian classifier training conditions. More than a survey of existing training techniques, our experimentation highlights impactful parameters, potential new research directions, and combination dilemmas. They allowed us to better understand and parametrized our pipeline. Second, we introduce a 12-valued filter representation based on LBP. Indeed, various improvements now allow for this texture feature to provide a very discriminative, yet compact descriptor. This new LBP-based channel descriptor outperforms channel features [65] while requiring a fraction of the original LBP memory footprint. Uniform patterns [100] and Haar-based LBP [56] are employed to shrink the filter dimension in accordance to our needs. Also, cell stacking and new filter combination restriction based on proposal window coverage are successfully applied. Finally, a more reliable feature selection technique is introduced to construct a lower dimension final descriptor without harming its discriminability. Experiments on the Inria and Caltech-USA datasets, respectively presented in tables 1 and 2 validate these progresses.

In the light of these results, combining the *FairTrain* data selection pipeline with CNN features appears like the obvious next step.

Table 1. Comparison with the state-of-the-art on the Inria dataset. Near real-time methods are separated from others. Ours is in bold. Deep learning techniques are in red. Computation times (CPU/GPU) are calculated according to 640×480 resolution frames. The used metric is the log-average miss rate (the lower the better). Best viewed in color.

Evaluation method	Log-average miss rate	Speed(CPU/*GPU*)
HoG [59]	46%	0.5fps
HoG-LBP [127]	39%	Not provided
MultiFeatures [129]	36%	$<$ 1fps
FeatSynth [45]	31%	$<$ 1fps
MultiFeatures+CSS [123]	25%	No
Channel Features [65]	21%	0.5fps
FPDW [64]	21%	2-5fps
DPM [70]	20%	$<$ 1fps
RF local experts [95]	15.4%	3fps
PCA-CNN [81]	14.24%	$<$ 0.1fps
CrossTalk cascades [66]	18.98%	30-60fps
VeryFast [46]	18%	8/*135fps*
WordChannels [57]	17%	0.5/*8fps*
SSD [92]	15%	*56fps*
LBP-Channels full	**14.3%**	**0.5/ *7.5fps***
LBP-Channels selected	**13.6%**	**0.7/ *10fps***
FRCNN [110]	13%	*7fps*
RPN+PF [140]	7%	*6fps*

Table 2. Comparison with the state-of-the-art on the Caltech dataset. Near real-time methods are separated from others. Ours is in bold. Deep learning techniques are in red. Computation times (CPU/GPU) are calculated according to 640×480 resolution frames. The used metric is the log-average miss rate (the lower the better). Best viewed in color.

Evaluation method	Log-average miss rate	Speed(CPU/*GPU*)
HoG [59]	69%	0.5fps
DPM [70]	63.26%	$<$ 1fps
FeatSynth [45]	60.16%	$<$ 1fps
MultiFeatures+CSS [123]	60.89%	No
FPDW [64]	57.4%	2-5fps
Channel Features [64]	56.34%	0.5fps
Roerei [46]	48.35%	1 fps
MOCO [54]	45.5%	$<$ 1fps
JointDeep [103]	39.32%	$<$ 1fps
SquaresChnFtrs [47]	34.8%	$<$ 1fps
InformedHaar [137]	34.6%	$<$ 0.63fps
Spatial pooling [104]	29.2%	$<$ 1fps
Checkboards [138]	24.4%	$<$ 1fps
FRCNN [110]	56%	*7fps*
CrossTalk cascades [66]	53.88%	30-60fps
WordChannels [57]	42.3%	0.5/*8fps*
LBP-Channels full	**39.1%**	**0.5/ *7.5fps***
LBP-Channels selected	**35.9%**	**0.7/ *10fps***
SSD [92]	34%	*56fps*
RPN+PF [140]	10%	*6fps*

7.3. Detection of Pedestrians Using Deep Learning

Participants: Ujwal Ujwal, Frederic Precioso, Nagi Aly, François Brémond.

keywords: Deep learning, CNN

7.3.1. Introduction

The problem of pedestrian detection shares many important characteristics with the scenario of general object detection, its applications have much more practical and widespread ramifications. This includes areas such as surveillance, monitoring and autonomous vehicles. Traditional approaches such as HoG-based detection [59], [60] and Deformable Parts Model(DPM) [71], [102] based detection have been reasonably successful. However in the wake of recent interests in autonomous vehicles where the need of safety is utmost, it is pertinent to expect a much higher degree of performance from pedestrian detection systems.

The advent and popularity of deep learning beckons us to investigate it in search for such a high-performance system. Deep learning has been very successful in object detection problems of a more general taste as reflected by a large number of very successful systems. In our work, we focus upon investigating deep learning for designing high-performance pedestrian detection systems.

This work has been done in collaboration with Bertrand Leroy (VEDECOM)

7.3.2. State-of-the-art investigations

This year, we continued our investigations into the state-of-the-art deep learning based systems which have been proposed or have been applied to pedestrian detection. Deep learning has yet been without much theoretical foundations. The vastly practical and experimental playground of deep learning makes it very important to investigate existing systems [75], [92], [140] through thorough experiments in order to better comprehend their behavior in a vast variety of scenarios where pedestrian detection might be desired. Our investigations offered us insights such as the following :

1. **Performance limitations of current systems**: We were able to conclude a number of important scenarios where present state-of-art systems stutter in their detection performance. This primarily includes the following instances :
   - *Small-scale People*: This refers to people who are far away from the camera; thus appearing small in size. We also refer to such instances as far-range people, who are often missed.
   - *Occluded People*: People in urban environments are often occluded or semi-occluded by various entities such as lamp-posts and other vehicles to name a few.
   - *Seated People*: Very often people who are either in a sitting position or riding a vehicle are often missed. This effect is much more pronounced in coupling with the previously mentioned case of small-scale people.
2. **Suboptimal usage of CNN architectures**: Convolution Neural Network (CNN) architectures are the backbone of deep learning based object detection systems. CNNs are hierarchical layers of neurons (e.g - as in multi-layer perceptrons (MLP)) albeit with more involved operations. We observe that the lower layers of a CNN are only implicitly utilized by extracting features from the last convolutional layer. We consider this to be suboptimal owing to our observations during our experiments that lower layers of a CNN indeed detect some important features which may prove useful with respect to scenarios such as small-scale people and occluded people.

Outcome

Our investigations have enabled us to focus upon some important aspects of our problem and have thus narrowed our focus. This allows us to focus upon relevant portions of system design. We expect this to induce more productivity in our future work.

Following these state-of-art studies we plan to coalesce our findings in a review paper which we aim to submit shortly to a journal.

7.3.3. Detection of small-scale people

As mentioned before, our state-of-the-art studies enabled us to identify that CNN architectures might being used in a suboptimal way. To take this investigation further, we worked upon the design of a better system which can make use of all the hierarchies of a CNN. We are correcting some implementation issues with the aforementioned system, although in our first experiments it did provide us with a miss-rate of 13.98% as against the state-of-art miss-rate of 9%. Miss-rate refers to the number of pedestrian instances which were not detected (thus *false negative*). Hence a lower miss-rate gestures at a better performing system. In our first experiments although we have a miss-rate roughly 5% worse than the state-of-art, but we find it encouraging given that in our experiments we used a much smaller CNN. A smaller CNN gestures at a lower capacity for feature extraction. We believe that by employing a better-performing CNN, much better results may be warranted.

Outcome

Our work in this problem is currently moving ahead of our first experiments where we demonstrated the validity of our conclusions that suboptimal usage of CNN architectures might be a possibility in existing systems. We are currently focused upon our second set of experiments which involve employing a better CNN and conducting more exhaustive investigations into the system performance and behavior.

7.4. Deep Learning applied on Embedded Systems for people detection

Participants: Juan Diego Gonzales Zuniga, Ujjwal Ujjwal, François Brémond.

keywords: Deep learning, CNN, Embedded Systems

7.4.1. Introduction

One of the problems with people detection is the amount of resources it takes for quality results. Most architectures either require big memory or large computing time to achieve a state-of-the-art position, these results are mostly achieved with dedicated hardware at data centers. The applications for an embedded hardware with these capabilities are limitless: automotive, security and surveillance, augmented reality and healthcare just to name a few. But the state-of-the-art architectures are mostly focused on accuracy than resources consumption [74] [75] [140].

The popularity of deep learning invites us to explore high-performance algorithms. In our work, we have to consider improving the systems' accuracy and reducing resources for a real-time application on people detection. This will lead towards new and efficient deep learning solutions.

7.4.2. State-of-the-art investigations

Deep learning lacks a strong theoretical background and a significant part of the knowledge is by investigating existing systems [75] [92] [140]. In order to better grasp the behavior in a different range of scenarios, we started our investigation to comprehend the nature of deep learning by diving into architectures that multi-task different activities. The combination of detection and segmentation shed light on the mutual improvements for people detection as seen in [67] and [50].

Another key part of our investigation was also to experiment with low time consuming architectures such as [109], an architecture that takes less time than [75] [92] [140] but still competitive and fairly flexible.

Our investigations offered us insights such as the following :

1. **Performance limitations of current systems**: We were able to conclude a number of important scenarios where present state-of-the-art systems stutter in their detection performance. This primarily includes the following instances :
   - *Loss function*: This refers to the feedback that will be reinserted for training. Different and more complex loss functions have different results. In other words, it is not the quantity of samples to train but more so the way they are trained.

- *Usage of filters*: It is commonly used among deep learning architectures to have a small filter size, this improves the field view of an image but also increases the number of parameters to control.
- *Time-Computation*: Most architectures with high-performance double the work to refine their precedent results, the accuracy of the solution is undeniable but the cost of computation and the memory resources also get affected.

2. **Suboptimal usage of CNN architectures**: (see section 7.3).

7.4.3. Outcome

Our investigations have showed us to focus more on the quality of training and not so much on the quantity. This allows us to focus upon relevant portions of system design. We expect this to give us clues on how to increase accuracy without compromising the resources.
Following these state-of-the-art studies we plan to coalesce our findings in a review paper which we aim to submit to a journal shortly.

This work has been done in collaboration with Serge Tissot (Kontron).

7.5. Facial Analysis

Participants: Antitza Dantcheva, Hung Thanh Nguyen, Philippe Robert, François Brémond.

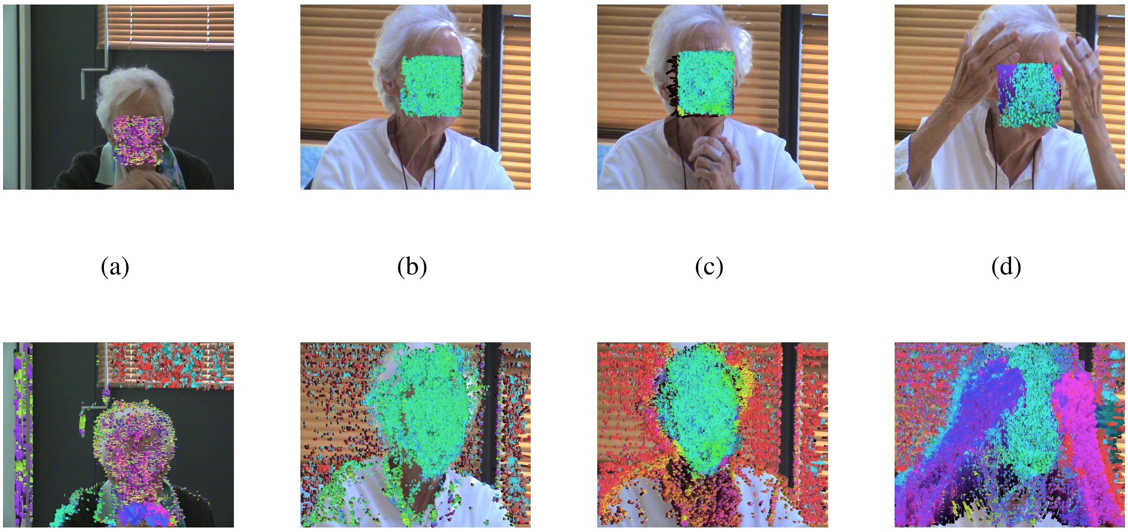
keywords: automated healthcare, healthcare monitoring, expression recognition, gender estimation, soft biometrics, biometrics, visual attributes

7.5.1. Automated Healthcare: Facial-expression-analysis for Alzheimer's patients in musical mnemotherapy

This work was done in collaboration with Piotr Bilinski (Univ. Oxford, UK), Jean-Claude Broutart (GSF Noisiez, France), Arun Ross (MSU, USA), Cunjian Chen (MSU, USA), Thomas Swearingen (MSU, USA), Ester Gonzalez-Sosa (UAM, Spain) and Julian Fierrez (UAM, Spain), Ruben Vera-Rodriguez (UAM, Spain), Jean-Luc Dugelay (Eurecom, France)

Recognizing expressions in patients with major neurocognitive disorders and specifically Alzheimer's disease (AD) is essential, since such patients have lost a substantial amount of their cognitive capacity, and some even their verbal communication ability (*e.g.*, aphasia). This leaves patients dependent on clinical staff to assess their verbal and non-verbal language, in order to communicate important messages, as of the discomfort associated to potential complications of the AD. Such assessment classically requires the patients' presence in a clinic, and time consuming examination involving medical personnel. Thus, expression monitoring is costly and logistically inconvenient for patients and clinical staff, which hinders among others large-scale monitoring. In this work, we present a novel approach for automated recognition of facial activities and expressions of severely demented patients, where we distinguish between four activity and expression states, namely *talking*, *singing*, *neutral* and *smiling*. Our approach caters to the challenging setting of current medical recordings of music-therapy sessions, which include continuous pose variations, occlusions, camera-movements, camera-artifacts, as well as changing illumination. An additional important challenge that we tackle has to do with the fact that the (elderly) patients exhibit generally less profound facial activities and expressions, which furthermore occur in combinations (e.g., talking and smiling).

Our proposed approach is based on the extension of the Improved Fisher Vectors (IFV) for videos, representing a video-sequence using both, local, as well as the related spatio-temporal features. We test our algorithm on a dataset of over 229 video sequences, acquired from 10 AD patients. We obtain the best results in *personalized facial expression and activity recognition*, where we train the proposed algorithm on video sequences related to each patient, individually. The results are promising and they have sparked substantial interest in the medical community. We believe that the proposed approach can play a key part in assessment of different therapy treatments, as well as in remote large-scale healthcare-frameworks.
Facial expression and activity recognition [37]



(a) (b) (c) (d)

(e) (f) (g) (h)

Figure 7. Example images of facial dense trajectories in video sequences related to the facial expressions and activities (a) neutral, (b) smile, (c) talking and (d) singing of a patient in the acquired dataset of AD patients.

We report the average MCA in Table 3 of the proposed algorithm and 2 further variations thereof. Specifically, we investigate as a first variation (a) the performance without face detection. The rational is that head and hands movement might contain potentially useful information in expression recognition (see Fig. 7). However, we observe that, due to a vast amount of camera-artifacts (*i.e.*, the static background containing a seemingly considerable amount of motion), the analysis of the full-frames reduces the recognition accuracy. Further, we report (b) the performance of the original IFV scheme. Our proposed algorithm significantly outperforms the original IFV-scheme from 50.83% to 53.99% (without face detection), and from 58.4% to 63.37% (with face detection). Additionally, we note that face detection significantly improves the performance of our proposed algorithm, namely from 53.99% to 63.37%.

Table 3. Average Mean Class Accuracy (MCA).

IFV, no face detection	50.83%
IFV, face detection	58.4%
Spatio-temporal IFV, no face detection	53.99%
Spatio-temporal IFV, face detection	63.37%

7.5.2. Can a smile reveal your gender?

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.

Deviating from such algorithms in [61] 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 years old 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 suggest 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.

7.5.3. Vulnerabilities of Facial Recognition Systems

Makeup can be used to alter the facial appearance of a person. Previous studies have established the potential of using makeup to obfuscate the identity of an individual with respect to an automated face matcher. We analyzed [26] the potential of using makeup for spoofing an identity, where an individual attempts to impersonate another person's facial appearance (see Fig. 8). In this regard, we first assembled a set of face images downloaded from the internet where individuals use facial cosmetics to impersonate celebrities. We next determined the impact of this alteration on two different face matchers. Experiments suggest that automated face matchers are vulnerable to makeup-induced spoofing and that the success of spoofing is impacted by the appearance of the impersonator's face and the target face being spoofed (see Fig. 9). Further, an identification experiment was conducted to show that the spoofed faces are successfully matched at better ranks after the application of makeup. To the best of our knowledge, this was the first work that systematically studied the impact of makeup-induced face spoofing on automated face recognition.

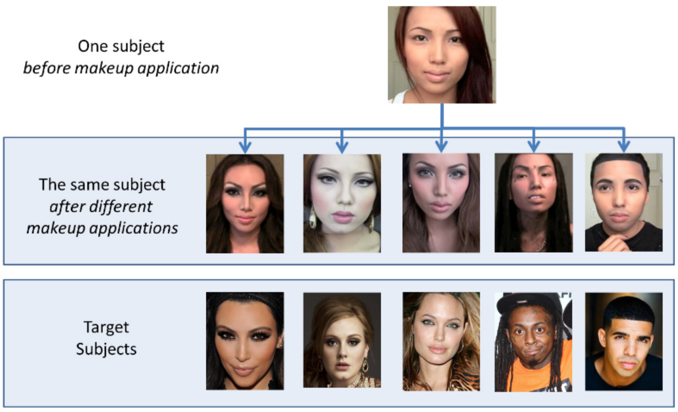
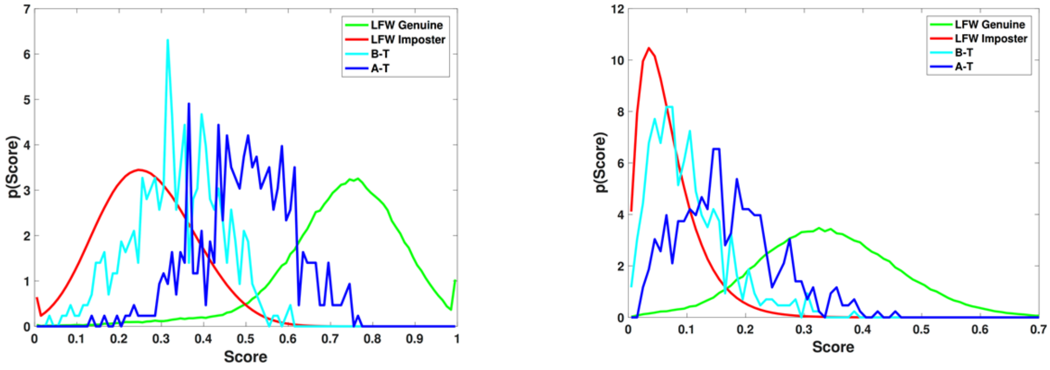


Figure 8. The subject on the top attempts to resemble identities in the bottom row (labeled "Target Subjects") through the use of makeup. The result of these attempts can be seen in the top row. Dataset available under http://antitza.com/makeup-datasets.html.

7.6. Multi-Object Tracking using Multi-Channel Part Appearance Representation

Participants: Thi Lan Anh Nguyen, Furqan Muhammad Khan, Farhood Negin, François Brémond.

Keywords: Tracklet fusion, Multi-object tracking, Appearance Representation



(a) (b)

Figure 9. Normalized histogram of similarity scores from the B-T subset (the image before makeup is matched against the target image), A-T subset (the image after makeup is matched against the target image), and the LFW dataset for the (a) COTS and (b) VGG face matchers.

Multi-object tracking (MOT) has been one of the fundamental problems in computer vision, essential for lots of applications (e.g home-care, house-care, security systems, etc.). The main objective of MOT is to estimate the states of multiple objects while identifying these objects under appearance and motion variation in time. This problem becomes very challenging due to frequent occlusion by background or other objects, object pose as well as illumination variation, etc.

Depending on the time of data association process, tracking algorithms can be categorized into 2 types: short-term and long-term tracking. Short-term trackers [108], [115] associate object detections in current frame with the most matching object trajectories in the past. These methods are able to perform online processing based on frame-to-frame association and therefore, could be applied in real-time applications. In general, short-term trackers use bipartite matching methods for short-term data association where Hungarian algorithm is the most popular method. Although these methods are computationally inexpensive, object identification could fail due to inaccurate detections (false alarms) and only short-term occlusions can be handled. Long-term trackers [139], [113] can overcome the shortcomings of short-term trackers by extension of the bipartite matching into network flow. The direct acyclic graph in [139] was formed where vertices are object detections or short tracklets and edges are the similarity links between vertices. In [113], the track of a person forms a clique and MOT is formulated as constraint maximum weight clique graph. The data association solutions for these long-term trackers are found through minimum-cost flow algorithm. However, long-term tracking methods also have their obvious drawbacks, such as: their huge computational cost due to iterative association process to generate globally optimized tracks and their pre-requirement for entire object detection in a given video.

Recently, some proposed trackers tried to combine both short-term and long-term tracking methods in a framework to perform online object tracking. The MOT methods in [44], [121] use a frame-to-frame association to generate tracklets followed by a tracklet association process with a time buffer latency. However, their performance is limited by their object features and tracklet representation. These methods utilize basic features (e.g. 2D information, color histogram or constant velocity) applied on whole body parts and use normal Gaussian distribution to describe the object. This way of representation could lose important information to discriminate objects and consequently, could fail to track objects in complex scene conditions (such as occlusion, low video resolution or insufficient lighting of environment).

On the other hand, multiple-shot person re-identification methods [89], [136] [31] gained high performances in matching objects from different camera views. In order to match a given person in a camera to the closest person in a gallery in another camera, these re-identification methods use efficient features and object representations. These methods are adapted to solve problems that involve pose and camera view setting variation. Since person Re-identification usually deals with identification of a person from different camera views, it is expected that using Re-id representation becomes even more effective in single-view multi-object tracking problem.

Therefore, we propose a robust online multi-object tracking method named MTSTracker which extends object representation and methods proposed for re-identification domain to address problems in MOT. While the re-identification works in offline mode, MTSTracker works in online mode. This method uses a time-window buffer to extract tracklets and associates tracklets in each time-window by using Re-identification techniques. MTSTracker integrates a short-term and long-term trackers in a comprehensive framework. The short-term tracker generates object trajectories called tracklets. Object features are computed for full and body parts, then, each tracklet is represented by a set of multi-modal feature distribution modeled by GMMs. The long-term tracker associates tracklets after mis-detections or occlusions based on learning Mahalanobis distance between GMM components. In order to learn this metric, KISSME [84] algorithm is adopted to learn feature transformations between different scenes by directly learning transformation between probability distributions. Experiments on two public datasets MOT2015 and ParkingLot show that MTSTracker performs well when compared to state-of-the-art tracking algorithms. This contribution has been published in the international conference AVSS 2017 [35].

7.7. Tracklets Pre-Processing for Signature Computation in the Context of Multi-Shot Person Re-Identification

Participants: Salwa Baabou, Furqan Muhammad Khan, Thi Lan Anh Nguyen, Thanh Hung Nguyen, François Brémond.

keywords: Person Re-Identification (Re-ID), tracklet, signature representation.

7.7.1. Tracklets pre-processing/representation

The person Re-Identification (Re-ID) system is divided into two steps: *i)* constructing a person's appearance signature by extracting feature representations which should be robust against pose variations, illumination changes and occlusions and *ii)* Establishing the correspondence/matching between feature representations of probe and gallery by learning similarity metrics or ranking functions (see Figure 10). However, appearance based person Re-ID is a challenging task due to disparities of human bodies and visual ambiguities across different cameras. Therefore, we focus on how to pre-process tracklets to compute the signature and represent it for Multi-shot person Re-ID to handle high appearance variance and occlusions.

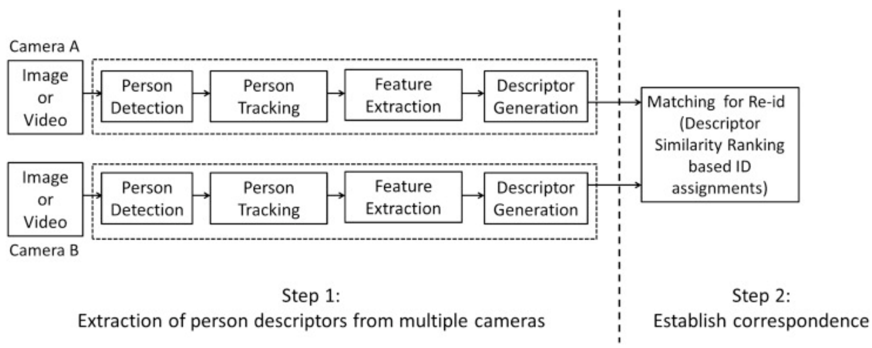
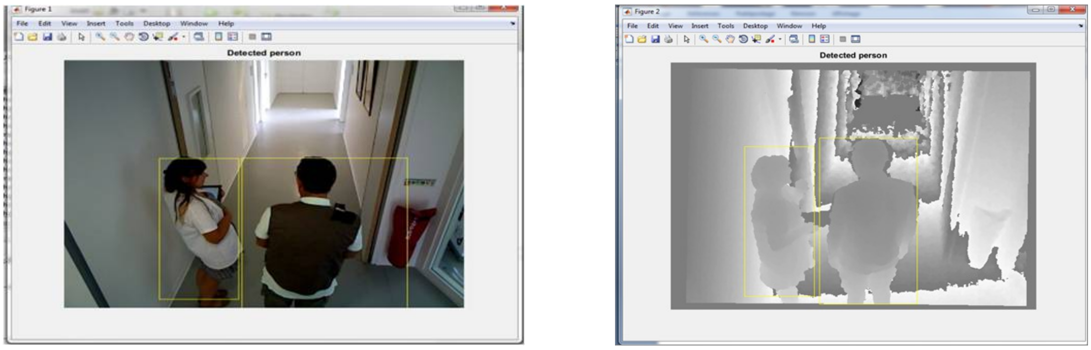


Figure 10. Re-ID Diagram

We have worked on CHU Nice dataset. First, we used the SSD detector [91] to get the detection results. Second, inspired by the Multi-Object Tracking in [35], we extracted the tracklets of persons and then we used these tracklets to compute the signatures of individuals based on Part Appearance Mixture PAM approach [31].

Figure 11 shows a visualizaton of a sample from CHU Nice dataset of the detection results.



(a) (b)

Figure 11. A visualization of a sample from CHU Nice dataset of the Detection Results

Figure 12 presents a visualization of a sample of consecutive frames from CHU Nice dataset of the tracking results.

(a) (b) (c) (d) (e) (f)

Figure 12. A visualization of a sample of frames from CHU Nice dataset of the Tracking Results

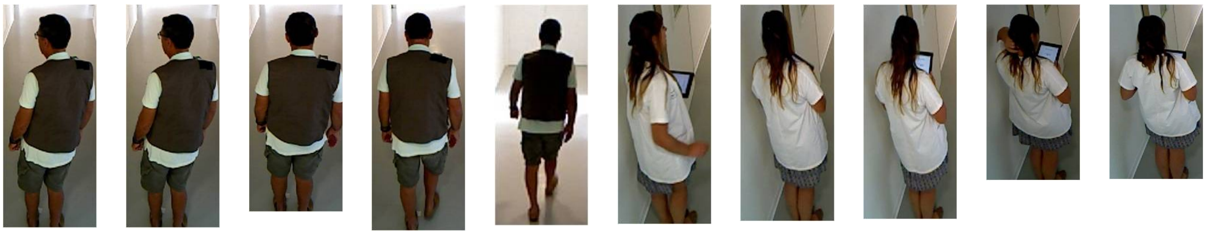
Figure 13 shows a representation of some samples of tracklets of a person from CHU Nice dataset.

7.7.2. Experimental results

CHU Nice dataset

It is an RGB-D dataset (RGB+Depth) and Collected in the hospital of Nice (CHU) in Nice, France. Most of the people recruited for this dataset were elderly people, aged 65 and above, of both genders. It contains 615 videos with 149365 frames acquired from 2 cameras: one in the corridor and another camera in the room.

Table 4 shows the recognition rate (%) at different ranks (rank-1, 5, 10, 20) of a baseline method LOMO+XQDA [89], PAM-LOMO+XQDA and PAM-LOMO+KISSME on CHU Nice dataset. From the above experiments, we notice that PAM-LOMO+KISSME achieves good performance on three datasets;



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j)

Figure 13. A sample of tracklets representation from CHU Nice Dataset

Table 4. Top ranked Recognition rates (%) on CHU Nice dataset

Methods	Rank-1	Rank-5	Rank-10	Rank-20
LOMO+XQDA	30.7	64.6	80.3	90.3
PAM-LOMO+XQDA	38.5	69.2	84.6	100.0
PAM-LOMO+KISSME	81.8	90.9	100	100

81.8% rank-1 recognition rate. This shows that our adaptation of feature descriptor LOMO [89] and metric learning KISSME [84] to PAM representation is effective.

Limitations

As shown in Figure 14 , a visualization of a selected samples from CHU Nice dataset of PAM signature representation is presented. Indeed, we visualize each GMM component by constructing a composite image. Given appearance descriptor, we compute the likelihood of an image belonging to a model component and then by summing images of corresponding person weighted by their likelihood we generate the composite image. We can say that our signature representation is able to cater variance in person's pose and orientation as well as illumination, it deals also with occlusions and is able to reduce effect of background. However, we can notice that this PAM signature representation presents some limitations, specially on our own dataset CHU Nice, which can affect the quality of our signature representation (see Figure 5). Among these challenging problems, we can cite:

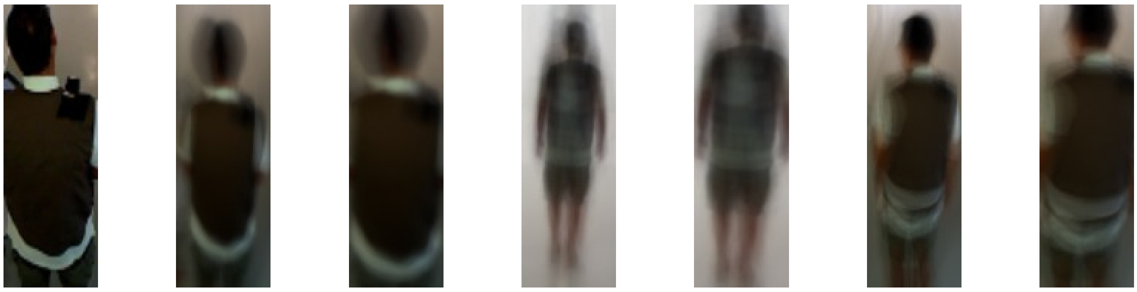
- Bad detection
- Number of frames by pose
- Number of GMM components not adequate with the number of person's pose/orientation and depends of the low-level features used.

We are actually working to improve the PAM signature representation by using the skeleton and extracting the pose machines from our dataset CHU Nice.

7.8. Multi-shot Person Re-identification in surveillance videos

Participants: Furqan Khan, Seongro Yoon, François Brémond.

keywords: person re-identification, appearance modeling, long term visual tracking



(a) (b) (c) (d) (e) (f) (g)

Figure 14. A visualization of selected samples of signature representation from CHU Nice Dataset: the first image is the input image used to learn appearance model. It's followed by the composite images, one for each component of the GMM mixture. Optimal number of GMM components for each appearance model varies between persons. GMM components focus on different pose and orientation of the person.

7.8.1. Efficient Video Summarization Using Principal Person Appearance for Video-Based Person Re-Identification

In video-based person re-identification, while most work has focused on problems of person signature representation and matching between different cameras, intra-sample variance is also a critical issue to be addressed. There are various factors that cause the intra-sample variance such as detection/tracking inconsistency, motion change and background. However, finding individual solutions for each factor is difficult and complicated. To deal with the problem collectively, we assume that it is more effective to represent a video with signatures based on a few of the most stable and representative features rather than extract from all video frames. In this work, we propose an efficient approach to summarize a video into a few of discriminative features given those challenges. Primarily, our algorithm learns principal person appearance over an entire video sequence, based on low-rank matrix recovery method. We design the optimizer considering temporal continuity of the person appearance as a constraint on the low-rank based manner. In addition, we introduce a simple but efficient method to represent a video as groups of similar frames using recovered principal appearance. Experimental results (Table 5) show that our algorithm combined with conventional matching methods outperforms state-of-the-art on publicly available datasets PRID2011 [77] and iLIDS-VID [125].

In order to get a deeper insight, Figure 15 presents some qualitative results visualizing principal appearance groups discovered by our approach without manual supervision. We compare our results with the approach of Shu *et.al.* [116] and found our results to be relatively more visually coherent and to have more groups. Details of this work can be found in our BMVC paper [36].

7.8.2. Multi-shot Person Re-identification using Part Appearance Mixture

Appearance based person re-identification in real-world video surveillance systems is a challenging problem for many reasons, including ineptness of existing low level features under significant viewpoint, illumination, or camera characteristic changes to robustly describe a person's appearance. One approach to handle appearance variability is to learn similarity metrics or ranking functions to implicitly model appearance transformation between cameras for each camera pair, or group, in the system. The alternative, that is followed in this work, is the more fundamental approach of improving appearance descriptors, called *signatures*, to cater for high appearance variance and occlusions. A novel signature representation for *multi-shot* person re-identification, called *Part Appearance Mixture* (PAM), is henceforth presented that uses multiple appearance models, each describing appearance as a probability distribution of a low-level feature for a certain portion of

Table 5. Comparison of recognition rates (%) at different ranks of various Re-ID methods on PRID and iLIDS-VID. Best results are highlighted in bold.

	PRID				iLIDS-VID			
Method	**r=1**	**r=5**	**r=10**	**r=20**	**r=1**	**r=5**	**r=10**	**r=20**
HOG3D+RankSVM [125]	19.4	44.9	59.3	77.2	12.1	29.3	41.5	56.3
Color+RankSVM [125]	29.7	49.4	59.3	71.1	16.4	37.3	48.5	62.6
DVR [125]	28.9	55.3	65.5	82.8	23.3	42.4	55.3	68.6
ColorLBP [78]+RankSVM	34.3	56.0	65.5	77.3	23.2	44.2	54.1	68.8
DVDL [80]	40.6	69.7	77.8	85.6	25.9	48.2	57.3	68.9
Color+LFDA [106]	43.0	73.1	82.9	90.3	28.0	55.3	70.6	88.0
AFDA [88]	43.0	72.7	84.6	91.9	37.5	62.7	73.0	81.8
DSVR [126]	40.0	71.1	84.5	92.2	39.5	61.1	71.7	81.0
MTL-LORAE [119]	-	-	-	-	43.0	60.1	70.3	85.3
STFV3D+KISSME [93]	64.1	87.3	89.9	92.0	43.8	69.3	80.0	90.0
CNN+KISSME [142]	69.9	90.6	-	98.2	48.8	75.6	-	92.6
RFA-Net+RankSVM [131]	58.2	85.8	93.4	97.9	49.3	76.8	85.3	90.0
CNN+XQDA [142]	77.3	93.5	-	99.3	53.0	81.4	-	95.1
APR+XQDA [73]	68.6	94.6	97.4	98.9	55.0	87.5	93.8	97.2
TDL [133]	56.7	80.0	87.6	93.6	56.3	87.6	95.6	98.3
RCNN [96]	70.0	90.0	95.0	97.0	58.0	84.0	91.0	96.0
PPA+Euclidean	66.6	90.1	93.5	96.7	29.6	55.7	67.6	79.7
PPA+KISSME	85.7	98.9	**99.9**	**100.0**	65.7	92.3	96.8	99.1
PPA+XQDA	**87.6**	**99.2**	99.6	99.9	**66.8**	**93.9**	**97.8**	**99.8**

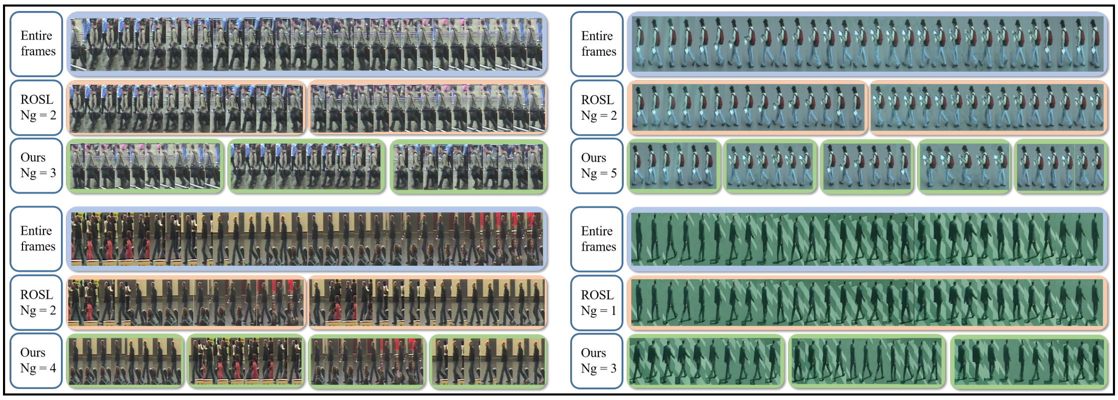


Figure 15. Visualization of principal appearance groups. Examples of our algorithm result are shown in comparison with ROSL [116] for the same process. The top and bottom on the left column are ID:218 and ID:016 of iLIDS-VID [125], and the top and bottom on the right column are ID:001 and ID:185 of PRID [77], respectively. N_g means the number of image groups.

an individual's body. It caters for high variance in a person's appearance by automatically trading compactness with variability as can be visually seen in the results presented in Figure 16 .

Signature representation has probabilistic interpretation of appearance signatures that allows for application of information theoretic similarity measures. A signature is acquired over coarsely localized body regions of a person in a computationally efficient manner instead of reliance on fine parts localization. We also define a Mahalanobis based distance measure to compute similarity between two signatures. The metric is also amenable to existing metric learning methods and appearance transformation between different scenes can be learned directly using proposed signature representation. Combined with metric learning, rank-1 recognition rates of 92.5% and 79.5% are achieved on PRID2011 [77] and iLIDS-VID [125] datasets, respectively, which establish a new state-of-the-art on both the datasets. Detailed comparisons with other contemporary unsupervised and supervised re-identification methods are presented in table 6 and table 7 .

Table 6. Recognition rates (%) at different ranks for unsupervised methods. Best results are highlighted in bold.

Spatiotemporal Methods								
	PRID2011				iLIDS-VID			
Method	r=1	r=5	r=10	r=20	r=1	r=5	r=10	r=20
HOG3D [93]	20.7	44.5	57.1	76.8	8.3	28.7	38.3	60.7
FV3D [93]	38.7	71.0	80.6	90.3	25.3	54.0	68.3	87.7
STFV3D [93]	42.1	71.9	84.4	91.6	**37.0**	**64.3**	**77.0**	**86.9**
Spatial Methods								
	PRID2011				iLIDS-VID			
Method	r=1	r=5	r=10	r=20	r=1	r=5	r=10	r=20
SDALF [68]	5.2	20.7	32.0	47.9	6.3	18.8	27.1	37.3
eSDC [141]	25.8	43.6	52.6	62.0	10.2	24.8	35.5	52.9
FV2D [94]	33.6	64.0	76.3	86.0	18.2	35.6	49.2	63.8
PAM-HOG	50.6	72.2	83.6	93.0	22.9	44.3	55.7	69.3
PAM-LOMO	**70.6**	**90.2**	**94.6**	**97.1**	33.3	57.8	68.5	80.5

Figure 16. Visualization of full-body appearance mixtures of HOG descriptor. For each person, first image is one of the input images used to learn appearance model. It is followed by the composite images, one for each component of the GMM. Optimal number of components for each appearance model varies between persons. (a)-(d) GMM components focus on different pose and orientation of person. (e)-(g) Transient occlusions are implicitly dealt with in appearance models as components focus on pose and orientation. (h) GMM components focus on different person alignments in the bounding box.

Table 7. Recognition rates (%) at different ranks of supervised methods. Best results are highlighted in bold.

Dictionary or Feature Learning Methods								
	PRID2011				iLIDS-VID			
Method	r=1	r=5	r=10	r=20	r=1	r=5	r=10	r=20
DVDL [80]	40.6	69.7	77.8	85.6	25.9	48.2	57.3	68.9
Color+LFDA [106]	43.0	73.1	82.9	90.3	28.0	55.3	70.6	88.0
AFDA [88]	43.0	72.7	84.6	91.9	37.5	62.7	73.0	81.8
MTL-LORAE [119]	-	-	-	-	43.0	60.1	70.3	85.3
RCNN [96]	70.0	90.0	95.0	97.0	58.0	84.0	91.0	96.0
Metric or Rank Learning Methods								
	PRID2011				iLIDS-VID			
Method	r=1	r=5	r=10	r=20	r=1	r=5	r=10	r=20
HOG3D+RankSVM [125]	19.4	44.9	59.3	77.2	12.1	29.3	41.5	56.3
Color+RankSVM [125]	29.7	49.4	59.3	71.1	16.4	37.3	48.5	62.6
ColorLBP [78]+RankSVM	34.3	56.0	65.5	77.3	23.2	44.2	54.1	68.8
DVR [125]	28.9	55.3	65.5	82.8	23.3	42.4	55.3	68.6
DSVR [126]	40.0	71.1	84.5	92.2	39.5	61.1	71.7	81.0
STFV3D+KISSME [93]	64.1	87.3	89.9	92.0	43.8	69.3	80.0	90.0
LOMO+XQDA [90]	-	-	-	-	53.0	78.5	86.9	93.4
LOMO+SBSR+XQDA [53]	-	-	-	-	68.5	87.9	93.0	96.3
RFA-Net+RankSVM [131]	58.2	85.8	93.4	97.9	49.3	76.8	85.3	90.0
CNN+KISSME [142]	69.9	90.6	-	98.2	48.8	75.6	-	92.6
CNN+XQDA [142]	77.3	93.5	-	99.3	53.0	81.4	-	95.1
PAM-HOG+KISSME	55.3	80.7	90.2	95.6	33.9	60.0	70.2	79.1
PAM-LOMO+KISSME	**92.5**	**99.3**	**100.0**	**100.0**	**79.5**	**95.1**	**97.6**	**99.1**

For further details, please refer to our paper [31].

7.9. Person Re-Identification using Pose-Driven Body Parts

Participants: Behzad Mirmahboub, Furqan Khan, François Brémond.

keywords: appearance-based person re-identification, pose estimation, human body parts, mask.

7.9.1. Introduction

Person re-identification is the problem of recognizing persons between several non-overlapped cameras. The main assumption is that the persons don't change their clothings between cameras. General approach is to extract discriminating color and texture features form images and calculate their distances as a measure of similarity. Most of the works consider whole body to extract descriptors. However, human body may be occluded or seen from different views that prevents correct matching between persons. We propose to use a reliable pose estimation algorithm to extract meaningful body parts and extract descriptor from each part separately.

7.9.2. Body Parts

"OpenPose" [52] is a state-of-the-art pose estimation algorithm that detects 15 body joints as shown in Fig. 17 (a). An example of pose estimation result on MARS dataset [142] is shown in Fig. 17 (b). We used joint positions to define 12 body parts as shown in Fig. 17 (c). Our idea is to extract image descriptor from each part and calculate their distances separately. Distance between two images can be computed by weighted average of all distances between body parts.

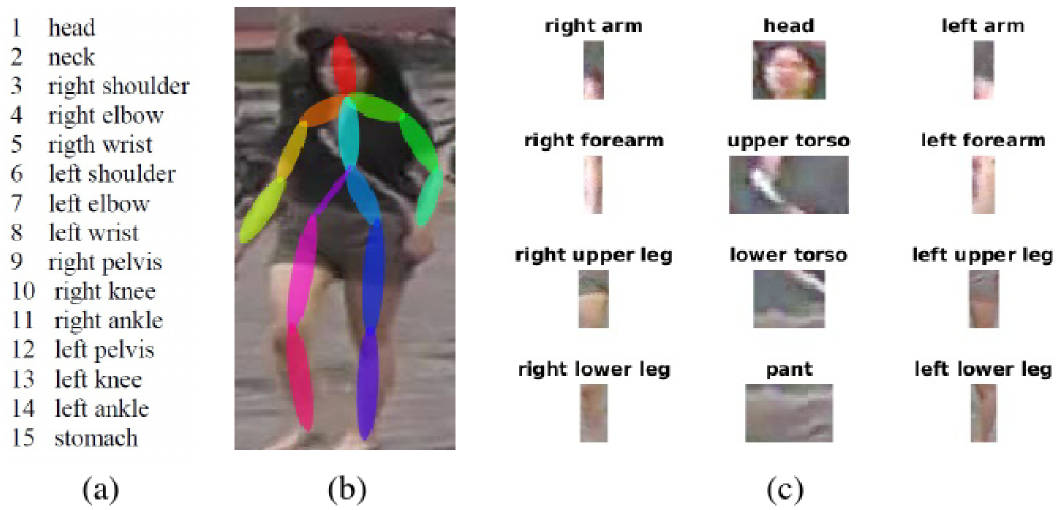


Figure 17. Human body joints and parts (a) Body joints that are detected with pose estimation algorithm (b) An example image from MARS dataset with estimated pose (c) Different body parts that we defined for feature extraction.

LOMO [90] is a famous descriptor for person re-identification that divides each image into horizontal stripes and finds the maximum bins of color and texture histograms in each stripe. We modified this code to use it on body parts.

7.9.3. Body Mask

Another challenge in person re-identification is different backgrounds between cameras. Background usually adds unnecessary information to descriptors that is not related to the person in the image, resulting in the mismatch between persons. We used the results of pose estimation algorithm to find a mask for whole body as can be seen in Fig. 18 . Since the masked image has many zero-value pixels that are not related to the persons, we modified LOMO descriptor to remove the effect of those zero pixels.

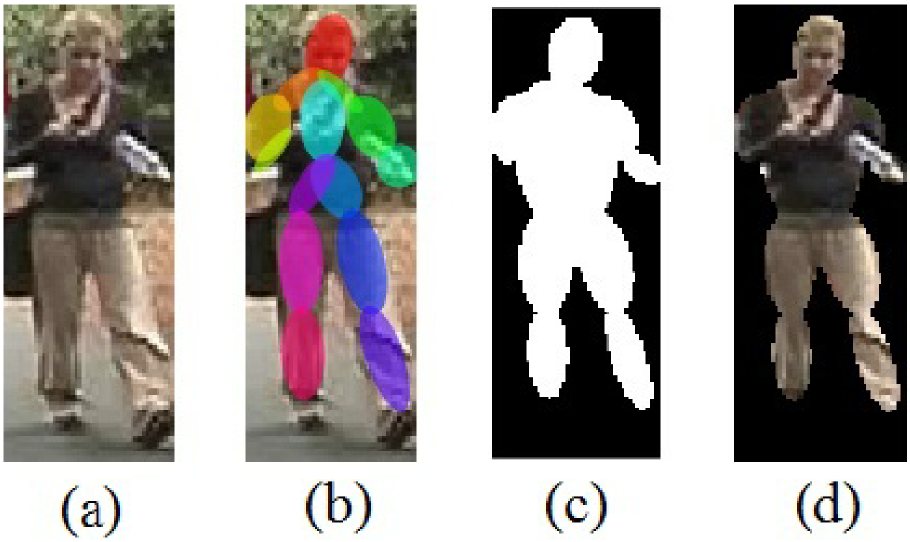


Figure 18. Generating mask from pose estimation (a) An example image from VIPeR dataset [76] (b) Result of pose estimation (c) Mask that we define based on pose (d) Masked image

7.9.4. Conclusion

Preliminary experiments show some potentials of using pose estimation for ReID, but not as accurate as global signature. One shortcoming of our work may be that we relied on LOMO descriptor that is essentially designed for the whole image. Suitable descriptor such as deep features [130] should be designed for body parts. In case of proper descriptor, part-based re-identification is promising to cope with the problem of pose and view point variations. This work can also be extended to detect mid-level features or attributes [86] (such as gender, long hair, jeans, t-shirt etc.) that are more reliable than low-level descriptors (such as gradients and histogram).

7.10. Human Action Recognition in Videos with Local Representation

Participants: Michal Koperski, François Brémond.

keywords: Computer Vision, Action Recognition, Machine Learning, Deep Learning, Artificial Intelligence

This work targets recognition of human actions in videos. Action recognition can be defined as the ability to determine whether a given action occurs in the video. This problem is complicated due to the high complexity of human actions such as appearance variation, motion pattern variation, occlusions, etc.

Recent advancements in either hand-crafted or deep-learning methods significantly improved action recognition accuracy. But there are many open questions, which keep action recognition task far from being solved.

Current state-of-the-art methods achieved satisfactory results mostly based on features, which focus on a local spatio-temporal neighborhood. But human actions are complex, thus the following question that should be answered is how to model a relationship between local features, especially in spatio-temporal context.

In previous years, we proposed 2 methods which try to answer that challenging problem. In the first method [49], we proposed to measure a pairwise relationship between features with Brownian Covariance. In the second method [83], we proposed to model spatial-layout of features with respect to person bounding box, achieving better or similar results as skeleton based methods. Our methods are generic and can improve both hand-crafted and deep-learning based methods.

Another open question is whether 3D information can improve action recognition. Currently, most of the state-of-the-art methods work on RGB data, which is missing 3D information. In addition, many methods use 3D information only to obtain body joints, which is still challenging to obtain. In our previous work, we showed that 3D information can be used not only for joints detection. We proposed [82] a novel descriptor which introduces 3D trajectories computed on RGB-D information.

In this year work we provide comprehensive study of methods proposed in the previous years, which is a part of PhD thesis [22] defended on 9th November 2017. In the evaluation part, we focus particularly on daily living actions – performed by people in their daily self-care routine. In the scope of our interest are actions like eating, drinking, cooking. Recognition of such actions is particularly important for patient monitoring systems in hospitals and nursing homes. Daily living action recognition is also a key component of assistive robots.

To evaluate the methods proposed in this work we created a large-scale dataset, which consists of 160 hours of video footage of 20 senior people. The videos were recorded in 3 different rooms by 7 RGB-D sensors. We have annotated the videos with 28 action classes. The actions in the dataset are performed in un-acted and unsupervised way, thus the dataset introduces real-world challenges, absent in many public datasets.

We proposed also new GHOG descriptor which is able to capture rough static pose information from person bounding box without need of skeleton detection. In our PhD thesis we show that fusion of GHOG with descriptors, which capture dynamic information (eg. [49], [83], [82]) leads to significant recognition accuracy improvement.

Finally, we claim that ability to process a video in real-time will be a key factor in future action recognition applications. All methods proposed in this work are ready to work in real-time. We proved our claim empirically by building a real-time action detection system, which was successfully adapted by Toyota company in their robotic systems.

We have also evaluated our methods on our Smarthomes dataset as well as on publicly available datasets: CAD60, CAD120 and MSRDailyActivity3D. Our experiments show that the methods proposed in this thesis improve state-of-the-art results.

More detail description can be found in the PhD thesis [22].

7.11. Action Detection in Untrimmed Videos

Participants: Abhishek Goel, Michal Koperski, François Brémond.

7.11.1. Problem Statement

The problem addressed in this work is *Online Action Detection in Untrimmed Videos*. The task of action detection can be broken down into two major modules, namely Action Recognition module and Temporal Localization module. Action Recognition module is responsible for assigning an action label to a trimmed video clip that is having only one action from start to the end of the clip. Temporal localization module on the other hand is responsible for deciding upon the start and end of the action present in an untrimmed video. The work has been done on the Smarthomes Dataset [22].

7.11.2. Action Detection Framework

- **Recognition Module:** The recognition module used in this work, makes use of trajectory features [72], [128] for describing the input frames. These features are clustered using a 512 centroid Gaussian Mixture Model (GMM) and encoded using Fisher Vector. Finally Fisher Vectors are then used as input to SVM classifier, which is trained in a one vs all fashion. Figure 19 gives an overview of the recognition model used in this work.

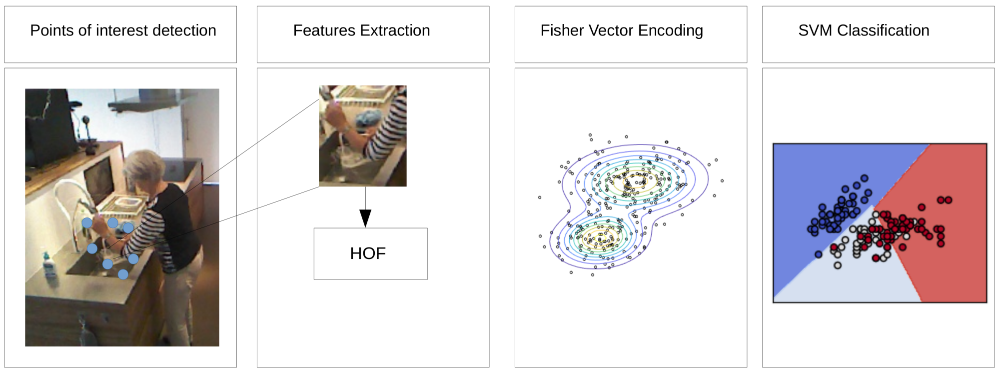


Figure 19. Steps involved in the action recognition part of the Action Detection Module. The first step is to detect the feature points in the input image. Since, in the feature detector used is Dense Trajectories [128], the feature points have been obtained using dense sampling followed by removal of points in homogeneous points. For each of the interest point, HOF descriptor is computed. These features are then clustered using GMM and encoded using fisher vectors. Finally, a SVM classifier is trained using the fisher vectors obtained for different video clips of different action class.

- **Temporal Localization Module:** The temporal localization module makes use of a sliding window architecture [72], [101], [120], [97], [134] to give candidate clips, intervals which might have action of interest, to the action recognition module to get the label for that interval.

7.11.3. Challenges

The major challenges when working with untrimmed videos in an online fashion are to identify the intervals where there are *No Action of interest* present and to identify the transition from the No Action interval to an interval containing an action of interest. In order to address these two problems, two new methods were proposed.

7.11.4. Proposed Methods

Distance Based Sliding Window

The first method, named **"Distance Based Sliding Window"** defined an actioness criterion based on the distance of a Fisher Vector from the hyperplane of a class of a trained classifier to address the problem of identifying the No Action intervals. Figure 20 gives an overview of the proposed approach.

Past and Future Windows

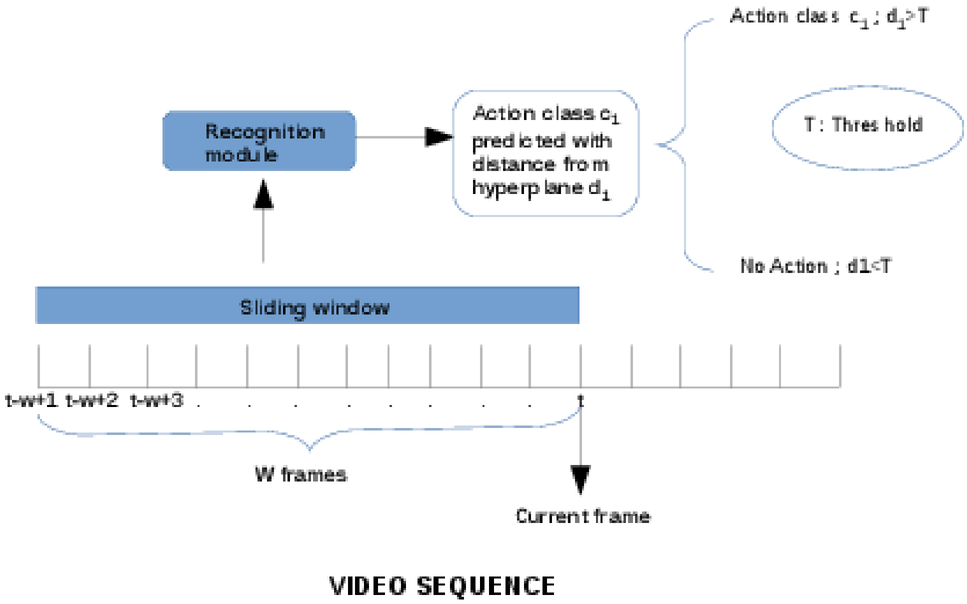


Figure 20. Approach Distance Based Sliding Window. First, a candidate, a short clip, is selected using the sliding window. This candidate is sent as an input to the action recognition system which returns the predicted class along with the distance of the fisher vector from the hyperplane of this class. Finally, if this distance is greater than a threshold T, the predicted label is that class otherwise it is No Action interval.

The second method, named **"Past and Future Windows"** addressed the second issue with a sliding window architecture which makes use of some of the future frames in order to get an action label for the current frame. The task is to perform Online Action detection in which ideally we have information only about the frames that have been seen till now and prediction for the current frame has to be done on the basis of this information. The term "future" refers to the frames which come after the frame in consideration. Since now the label is getting predicted for a frame after seeing some more frames after it, a delay is introduced in the prediction of the label. This delay is equivalent to *W* frames, where *W* is the window size. Figure 21 gives an overview of the proposed method.

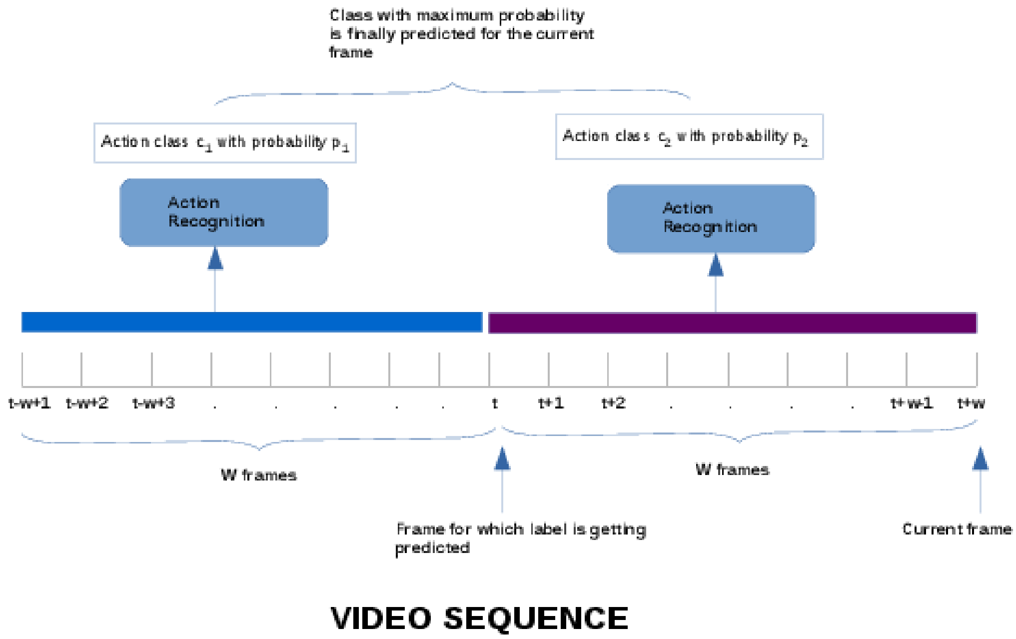


Figure 21. Past and Future windows approach. For the current frame, two temporal windows of size W frames are considered. The first window contains past frames and the second one future frames relative to the frame for which the label has to be predicted. Both the windows predict an action label with a probability with the help of an Action Recognition module. The final class label is corresponding to the class which returns the highest probability.

7.12. RGB-D based Action Recognition using CNNs

Participants: Srijan Das, Michal Koperski, François Brémond.

In the first half of the year, we focused on using the newly introduced Pose Machines [51] to extract skeletons from RGB frames. Then, our objective was to study how different skeleton extraction methods affect the performance of action recognition. For skeleton extraction from RGB data we used Pose Machines [51] and from Depth data we used Kinect sensors. Since, our final objective is to recognize actions from videos, we use an action recognition network proposed in [55]. This action network takes part patches (right hand, left hand,

upper body, full body and full image) around the joints to produce CNN features. The framework considers both the appearance flow and the optical flow so as to produce the concatenated CNN features. These features followed by a max-min aggregation are used as an input of a SVM to classify actions.
Finally, we propose a fusion of classifiers trained based on each skeleton extraction methods discussed above to improve the action recognition performance. The framework is depicted in fig. 22 . We validate our approach on CAD60, CAD120 and MSRDailyActivity3D, achieving the state-of-the-art results. We chose daily living action datasets due to its application to healthcare and robotics. The proposed framework has been published in AVSS 2017 [28].

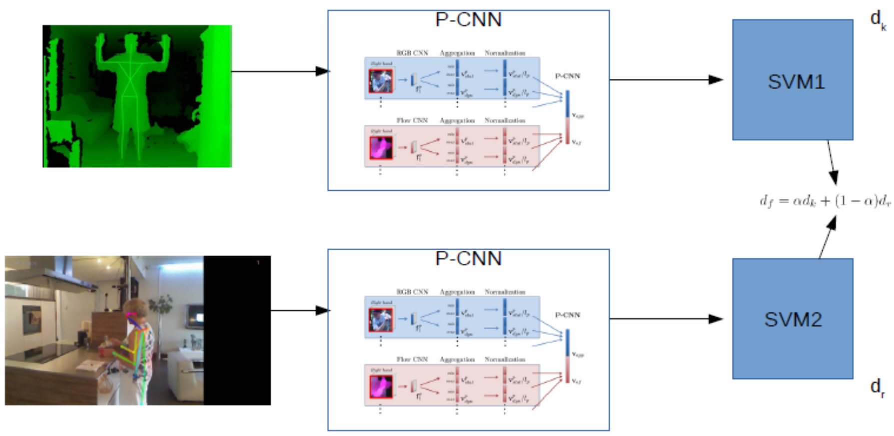


Figure 22. Framework of the proposed approach in [28]. Here, d_i represents the classifier scores for $i - th$ network.

Though our proposed approach performs well on CAD60 and MSRDailyActivity3D, it does not perform well on CAD120 because of the wrong patches detected during the skeleton extraction technique. Moreover, we also observed that sometimes noisy skeletons results in better action recognition as compared to well detected skeletons. This is because, noisy skeletons include the objects incurred in the actions since we use part patches in the action recognition network. So, now we include the object reference as well by considering extra large part patches in our modified P-CNN network for action recognition.

Now, we are focusing on how to include temporal information for action recognition. In our recent work, we discuss the limitation of not taking the temporal information into account for action recognition. Our objective is to introduce the temporal evolution of skeleton sequences with Recurrent Neural Networks (RNNs).

This work has been done in collaboration with Francesca Gianpiero (Toyota Motors Europe).

7.13. Recognizing Human Actions Using RGB Sport Videos From the Web

Participants: Amir Nazemi, François Brémond.

keywords: Action Recognition, Activity Recognition, Video Summarization, Web Sport Videos, Golf Videos.

The aim of this work is to extract sport actions from a web sport streaming video and use them for highlight detection. The sport videos which is used in this research is Golf videos. The report explains 4 steps including the data preparation, methods selection and excremental results.

7.13.1. Data Preparation

Figure 23. The output of human poses detection on one frame of Golf video dataset

Table 8. The Golf dataset.

Class names	Number of samples
Tee shot + Geometrical Features	73
Putt	70
standing	81

Table 9. The experimental results of performing two different methods on the golf dataset.

Methods	Accuracy on Golf Dataset
LSTM + Geometrical Features	91.5 %
P-CNN	97.32 %

First, from a streaming video a dataset is built. This dataset contains 3 action classes such as Tee-shot, Putt and Standing. Table 8 shows the dataset description.

7.13.2. Framework

After preparing the dataset next step is to define the solutions for the problem. Since one of the main goal of this research is to provide a general solution for sport video then we proposed a solution based on the skeleton or human poses. Our proposed framework contains human pose detection, human tracking and action recognition respectively. For human pose detection we used a recent method named open-pose [105]. For human pose tracking we used a tracking method of Inria STARS SUP framework. Finally for action recognition we did some experiments for choosing the best method.

7.13.3. Methods selection

From different methods in the field of action recognition we selected the P-CNN [55] method which is the state of the art on some data-set. Additionally for having an alternative solution which is faster than P-CNN we proposed a method based on geometrical features of human poses. We used the geometrical features in a Long Short-Term Memory (LSTM) structure to characterize the second solution.

7.13.4. Experimental Results

Table 9 shows the results of selected methods on the prepared golf dataset. As it is illustrated in the table 9 the P-CNN method works better than a method with LSTM and geometrical features.

7.14. Event Recognition Based on Depth Image

Participants: Kuan-Ru Lee, Carlos F. Crispim Junior, Yu-Feng Chen, François Brémond.

keywords: event recognition, depth image

7.14.1. Introduction

We proposed several methods to improve event recognition that are related to human and bed. Our final goal is to provide a helpful system to support the real-time observation of patients by medical personnel.

7.14.2. Experiments

The experiments were designed in several continuous steps. The first is the basic model by using time relative operator and two particular zones, the others were developed on this basic model. Theoretically, the performance of the accuracy will be increased step by step.

Basic model

The idea of the basic model is to combine the information of time and position to achieve the goal. Therefore, we create two particular zones to represent the area of the bed and the surrounding region of the bed.

$$Zone_M \textit{ before } Zone_N$$

M and N represent the bed and the surrounding area. The time relative operator was assigned as before. To distinguish the direction of the person, we can simplify the expression by switching the zones. However, the model was not able to detect the activity because the video was not completely recorded. Due to the ontology language that we had designed, what had been done by person will be initialized in this case, and we named these problems as "Frames Jump". On the other hand, our model was sensitive to the location of person. Extra detection will happen when the person who was standing next to bed, and just simply a step backward but not sitting on the bed. By integrating the above problems, we decided to develop a new method to replace the function that is used to distinguish the direction of the person.

Distance Analysis between the Person and the Bed

To recognize the events get-in-bed and get-out-bed, we compute the vertical distance between the person and a line of reference, which is horizontally passing from the center of the bed. To avoid the noise influencing the instance value of the distance, we used majority voting rules to represent the general direction of the moving person.

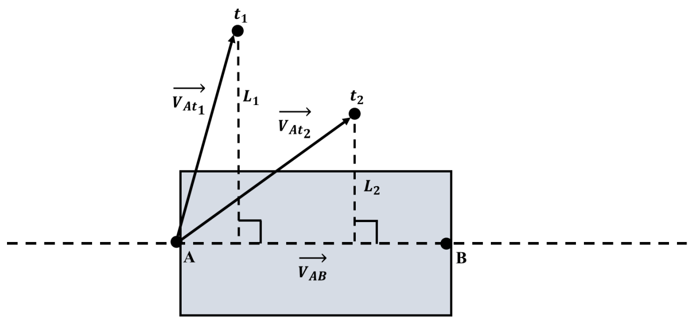


Figure 24. Schematic diagram of the proposed method

In Figure 24 , the rectangle represents the zone of bed, and a horizontal line cross through the reference points A and B. The point t_i represents the position of the person at frame i while i $\in\{1, 2, ..., N\}$. To project t_i on the reference line, the distance between t_i and the reference line, L_i, can be easily calculated. The majority voting rules can provide an average value representing the final distance.

7.14.3. Frame Jump

Due to the detection process, the system will start to detect the person while he or she moves. In this case, some frames may be lost when the person is still on the bed but in the getting out processes. Based on our ontology language, we designed a new model which just focused on those events which happened surrounding the bed area.

7.14.3.1. Performance

Table 10. Contingency table of two events

	Get in Bed					Get out Bed				
Method	TP	FP	FN	Pr.	Re.	TP	FP	FN	Pr.	Re.
A	6	14	10	0.3	0.37	7	9	8	0.43	0.46
B	9	2	8	0.81	0.52	7	5	8	0.58	0.46
B + C	12	6	5	0.6	0.70	14	10	1	0.58	0.93

In the previous section, the basic model, which we labeled as method A, faced two problems, frame jump and extra detecting. Those problems lead high false positive and false negative. To solve the unnecessary extra detecting, we propose to analyse the distance between the person and the bed with the method B.

In table 10 we can notice the improvement of TP, FP, and FN. The FP value for method B is much lower than for method A. The new approach using the average filter and majority voting rule to eliminate the noise of movement, reduces the chance of misdetection and improves the whole performance. After we considered the solution of frame jump as method C, and combined it with method B, the number of FN reduced a lot. The increments of FP are caused by the overlap detection of both methods.

7.15. Recognition of Daily Activities by Embedding Visual Features within a Semantic Language

Participants: Francesco Verrini, Carlos F. Crispim Junior, Michal Koperski, François Brémond.

keywords: Activity of Daily Living, RGBD Sensors, Activity Recognition

The recognition of complex actions is still a challenging task in Computer Vision especially in daily living scenarios where problems like occlusion and limited field of view are very common. Recognition of Activity Daily Living (ADL) could improve the quality of life and supporting independent and healthy living of older or/and impaired people by using information and communication technologies at home, at the workplace and in public spaces. A method based on the development of a scenario model with semantic logic and a priori knowledge formalism is able to take into account spatio-temporal information of the scene but falls short in identifying finer events occurring in a specific area, e.g. it identifies that the person is sitting but we cannot determine whether the person is only sitting, using a laptop, or watching television. For this method the supervision of experts is also needed [58]. In this method after detection and tracking, event recognition is performed (fig 25). On the other side, action recognition through visual words [83] improves recognition of actions with low amount of motion but contextual information of the scene is not taken into account. The goal of this work is to merge the two methods trying to use the spatio-temporal information of the ontology model to improve the results of the action recognition through visual words. The actions detected with visual words are implemented as Primitive States in the scenario and then used as Components of Composite States to merge them with spatio-temporal pattern that the people display while performing activities of daily living (e.g. Person Inside Zone Sink, Person moving between zone Entry and zone Corridor). In a challenging Dataset such as SmartHome [22] where a high variance intra-class and low variance inter-class is present results for some actions improves in precision and recall thanks to spatial information, e.g. for Clean Dishes the precision with the proposed method increases form 29% to 42% thanks to the definition of a spatial zone for the sink. A drawback of this method is that True Positive can not increase being strictly dependent on machine learning pipeline, for this reason Precision improves due to the less number of False Positive.

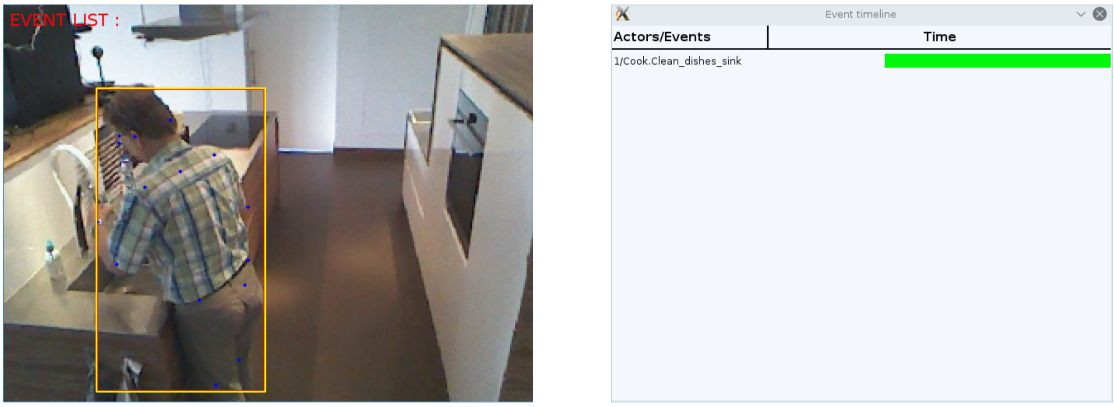


Figure 25. left:Person Performing Cook.Clean_dishes_sink, right:Timeline of the action Cook.Clean_dishes_sink

7.16. Cognitive Assessment Using Gesture Recognition

Participants: Farhood Negin, Michal Koperski, Philippe Robert, François Brémond, Pau Rodrigez, Jeremy Bourgeois.

keywords: Human computer interaction, Computer assisted diagnosis, Cybercare industry applications, Medical services, Patient monitoring, Pattern recognition.

7.16.1. The Praxis test and clinical diagnosis

Praxis test is a gesture-based diagnostic test which has been accepted as diagnostically indicative of cortical pathologies such as Alzheimer's disease. Despite being simple, this test is oftentimes skipped by the clinicians. In this study, we proposed a novel framework to investigate the potential of *static* and *dynamic* upper-body gestures based on the Praxis test and their potential in a medical framework to automatize the test procedures for computer-assisted cognitive assessment of older adults.

In order to carry out gesture recognition as well as correctness assessment of the performances we have recollected a novel challenging RGB-D gesture video dataset [0] recorded by Kinect v2, which contains 29 specific gestures suggested by clinicians and recorded from both experts and patients performing the gesture set. Moreover, we propose a framework to learn the dynamics of upper-body gestures, considering the videos as sequences of short-term clips of gestures. Our approach first uses body part detection to extract image patches surrounding the hands and then, by means of a fine-tuned convolutional neural network (CNN) [87] model, it learns deep hand features which are then linked to a long short-term memory (LSTM) [79] to capture the temporal dependencies between video frames.

We report the results of four developed methods using different modalities. The experiments show effectiveness of our deep learning based approach in gesture recognition and performance assessment tasks. Satisfaction of clinicians from the assessment reports indicates the impact of our proposed framework corresponding to the diagnosis.

7.16.2. Proposed Method

Four methods have been applied to evaluate the dataset (Figure 26). Each path (indicated with different colors) learns its representation and performs gesture recognition independently given RGB-D stream and pose information as input.

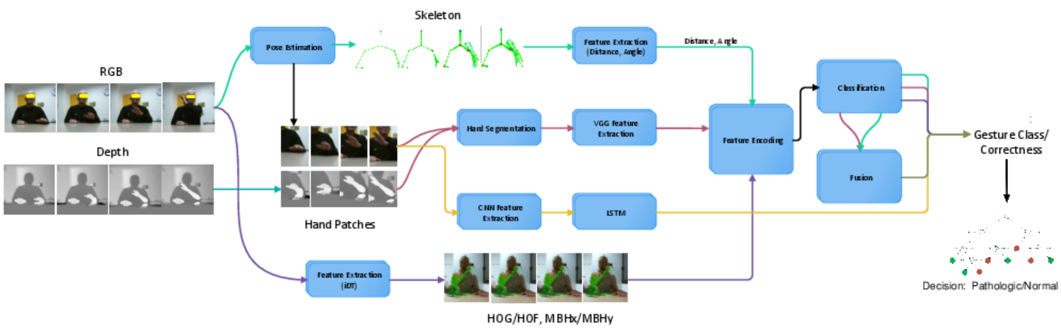


Figure 26. The data flow for the four methods applied on the Praxis dataset. Each method flow is separated by using a different color code.

Skeleton Based Method: Similar to [132] the joint angle and distance features are used to define global appearance of the poses. Prior to the classification (different from [132]), a temporal window-based method is employed to capture temporal dependencies among consecutive frames and to differentiate pose instances by notion of temporal proximity.

Multi-modal Fusion: The skeleton feature captures only global appearance of a person, while deep VGG features [117] extracted from RGB video stream acquire additional information about hand shape and dynamics of the hand motion which is important for discriminating gestures, specially the ones with similar poses. Due to sub-optimal performance of immediate concatenation of the high-dimensional features, a late fusion scheme for class probabilities is adopted.

Local Descriptor Based Method: Similar to action recognition techniques which use improved dense trajectories [128], a feature extraction step is followed by a Fisher vector-based encoding scheme.

[0] https://team.inria.fr/stars/praxis-dataset/

Deep Learning based Method: Influenced by recent advancements in representation learning methods, a convolutional neural network based representation of hands is coupled with a LSTM to effectively learn both temporal dependencies and dynamics of the hand gestures. In order to make decisions about condition of a subject (normal vs pathologic) and perform a diagnostic prediction, a decision tree is trained by taking output of gesture recognition task into account.

It should be noticed that for all the developed methods we assumed that the subjects are in a sitting position in front of the camera where only their upper-body is visible. We also assume that the gestures are already localized and the input to the system is short-term clipped videos.

		Accuracy			Correctness		
Method		Static	Dynamic	Average	Static	Dynamic	Average
Skeleton	Distance	70.04	56.99	63.51	72.04	59.93	65.98
	Angle	57.21	51.44	54.32	68.13	62.16	65.14
	Distance+Angle	61.83	55.78	58.80	70.06	61.49	65.77
Multimodal Fusion	RGB (VGG)	67.63	63.18	65.40	68.21	63.54	65.87
	RGB (VGG)+Skeleton	72.43	62.75	67.59	70.72	64.55	67.63
improved dense trajectories (iDT)	HOG/HOF	65.04	61.31	63.17	61.89	57.37	59.63
	MBHx/MBHy	70.32	75.49	72.90	55.63	72.93	64.28
Deep Learning	CNN+LSTM	**92.88**	**76.61**	**84.74**	**93.80**	**86.28**	**90.04**

Figure 27. Comparison of the obtained results for static and dynamic gestures using proposed methods in terms of accuracy of gesture classification and correctness of performance with other baseline methods (Best performances are indicated in bold).

In this work we made a stride towards non-invasive detection of cognitive disorders by means of our novel dataset and an effective deep learning pipeline that takes into account temporal variations, achieving 90% average accuracy on classifying gestures for diagnosis. The performance measurements of the applied algorithms are given in Figure 27 .

We proposed a computer-assisted solution to undergo evaluation of automatic diagnosis process with help of computer vision. The evaluations of the system can be delivered to the clinicians for further assessment in decision making processes. We have collected a unique dataset from 60 subjects targeting analysis and recognition of the challenging gestures included in the Praxis test. To better evaluate the dataset we have applied different baseline methods using different modalities. Using CNN+LSTM we have shown strong evidence that complex near range gesture and upper body recognition tasks have potential to be employed in medical scenarios. In order to be practically useful, the system will be evaluated with a larger population.

7.17. Geometric and Visual Features Fusion for Action Recognition

Participants: Adlen Kerboua, Farhood Negin, François Brémond.

keywords: skeleton, geometric features, visual features, CNN.

The proposed activity recognition system consists in the fusion of two types of features: geometric features and visual features. The geometric features are computed from the 2D/3D skeleton joints that represent the articulations of the human body, which can be extracted by modern methods of pose estimation from RGB/RGB-D images, such as DeepCut pose estimation [107] or OpenPose [51]. The visual features are extracted by a convolutional neural network CNN from RGB patches representing both hands, the main steps of this method are illustrated in Figure 28 .

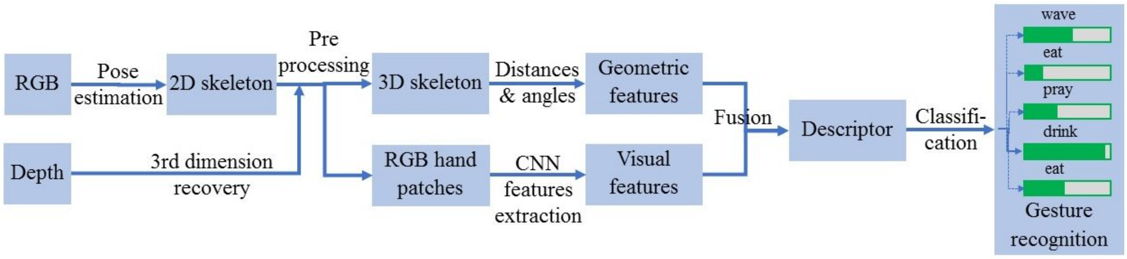


Figure 28. The data flow of our framework.

7.17.1. Geometric features

Before computing the geometrical features, we apply several preprocessing steps on the skeleton joints:

- First, we reduce noise in joints estimation by smoothing joints position over frames by applying local regression using weighted linear least squares and a 2nd degree polynomial model.
- Second, according to individual speed, similar action can be performed in different time duration by each subject resulting different number of frames, to uniform the skeleton information over frames we use cubic interpolation of the values at neighboring grid points in each respective dimension this method also permits to remove outliers joints wrongly estimated.
- Then, in order to compensate variations in body sizes which can causes intra-classes variations and confuse the classifier, we follow the method presented in [135] by imposing the same limbs (skeleton segments) lengths for skeletons of all individuals in the dataset.
- Finally, we compute rotations matrix for the first frame, then we apply same rotations for all frames in the video to remove the camera variations while keeping the over action dynamic, we also translate the skeleton to make the hip center of the first frame like the origin (figure 29).

To get the geometric features, we compute Euclidean distances and spherical coordinates (angles) between every skeleton joints pair-wise belonging to the same frame and adjacent frames.

7.17.2. Visual features

After the extraction of the skeletal joints during the precedent phase we can also extract the RGB patches representing the parts of the body most used to perform actions, which are in most cases the two hands, then we use several types of CNN (VGG16, VGG19, Resnet, ...) to extract the visual features. Different from our preliminary work of gesture recognition in the PRAXIS project, we merge those features with the geometrical one by concatenation to get the final descriptor used for classification of activities. During the test phase, a cross-subject test protocol is used to reduce the overfitting phenomenon and to obtain solutions that can be generalized.

7.17.3. Experiments

In the experimentation phase, we choose several datasets, including some properties of the STARS team, such as the PRAXIS dataset, this innovative test battery conducted on people with Alzheimer's disease is very useful to evaluate the evolution of this disease. This dataset contains more than 29 gestures divided between static and dynamic gestures, repeated several times by 58 patients, and contained a total of 3227 gestures performed in a correct manner and others in an inconsistent way. STARS also uses the most popular public datasets in the scientific community in order to evaluate the proposed methods compared to the current state of the art, such as NTU RGB+D [114] and ChaLearn [124].

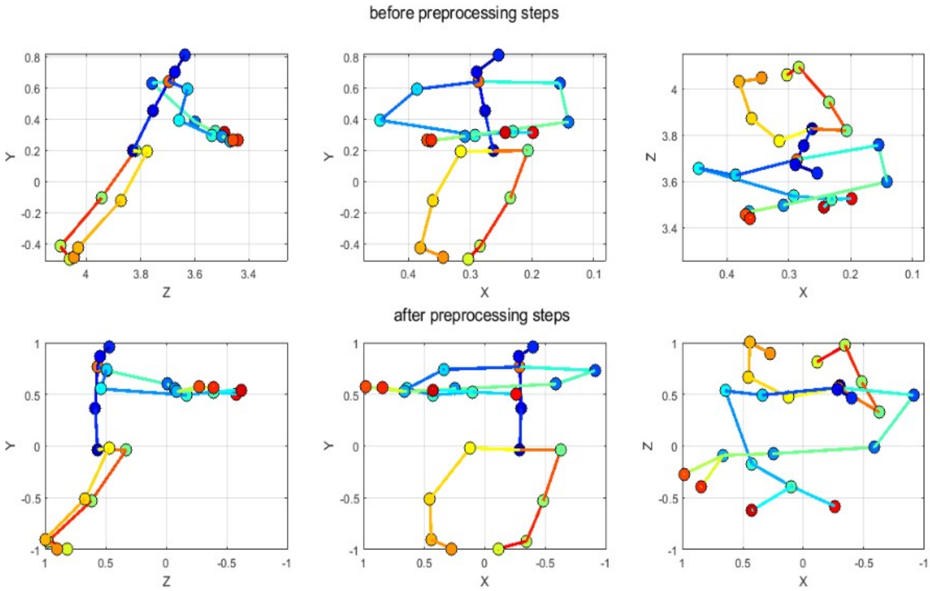


Figure 29. The data flow of our framework.

7.18. Probabilistic Logic for Activity Recognition

Participants: Carlos F. Crispim-Junior, François Brémond.

keywords: ProbLog2, Horn clauses, Probabilistic models, activity recognition, uncertainty management

In this line of investigation, we have been working on novel models to associate the robust nature of probabilistic logic to noisy observations and the knowledge representation of ontological languages. Our end goal is to design models that are capable of representing the hierarchical structure of complex events (entities, sub-events and constraints) at the same time they can handle the uncertainty of real-life settings, like noisy observations from the vision pipeline. Currently, knowledge representations underperform under noisy scenarios, while prior work in probabilistic logic has provided support either to reason about uncertainty related to entity recognition (probability of recognizing entity A) or to violation knowledge constraints (relevance of violation of constraint i to model y).

This work have been carried out in partnership with KU Leuven and the first results of this joint work have been published on the workshop entitled Assisted Computer Vision and Robotics, which was organized during the 2017 edition of the International Conference on Computer Vision. In this paper we propose BEHAVE, a person-centered pipeline for probabilistic event recognition (Fig. 30). The proposed pipeline firstly detects the set of people in a video frame, then it searches for correspondences between people in the current and previous frames (i.e., people tracking). Finally, event recognition is carried for each person using probabilistic logic models (PLMs, ProbLog2 language). PLMs represent interactions among people, home appliances and semantic regions. They also enable one to assess the probability of an event given noisy observations of the real world. BEHAVE was evaluated on the task of online (non-clipped videos) and open-set event recognition (e.g., target events plus none class) on video recordings of seniors carrying out daily tasks. Results have shown that BEHAVE improves event recognition accuracy by handling missed and partially satisfied logic models.

Future work will investigate how to extend PLMs to represent other types of relations, like temporal relations, and how to incorporate low-level information from deep architectures, like Deep Convolution Neural Networks.

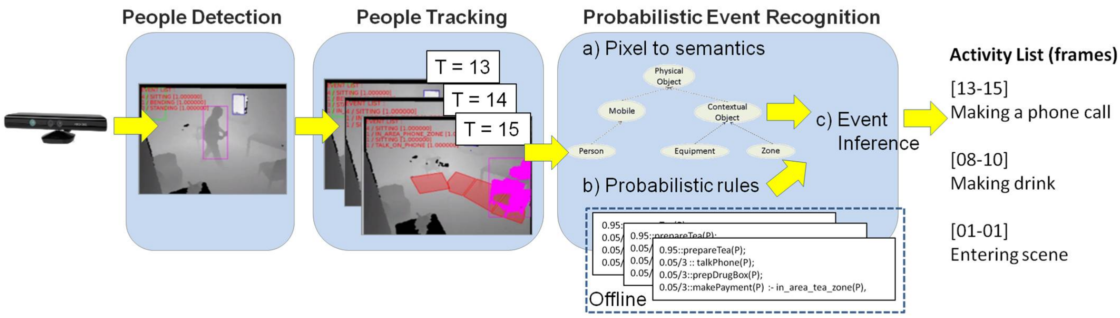


Figure 30. BEHAVE:Behavioral analysis of visual events for assisted living scenarios

7.19. Recognizing Retracing of Steps Using Walk Comparison

Participants: Kartik Kartik, Carlos F. Crispim-Junior, François Brémond.

keywords: Alzheimer, Retracing of steps, Activity Recognition

The recent advancements in the technology have paved the way to complete automation and detection of human behavior.Dementia in Alzheimer's causes memory loss and affects other mental abilities which are necessary for tasks of daily life. This discussion deals with recognizing retracing of steps in order to observe incidents or characteristics related to dementia.

7.19.1. Introduction

In recent years it has been observed a huge increase in the dementia related problems in the older population. A lot of new methodologies are being developed to recognize and observe the characteristics of people suffering from dementia. One such example is retracing the same path back and forth due to memory loss. The patient is observed walking, then stopping for a few moments or abruptly turning and then walking in the opposite direction following the same path.This discussion caters to recognition of such events using comparison between two consecutive walks. The comparison is done on the basis of position of the patient in each frame during the walk.

7.19.2. Methodology

We generate the xml1 and xml3 file by performing event recognition on SUP. SUP stands for Scene Understanding Platform which performs event and activity recognition.

In order to compute the relation between two consecutive walks that account for retracing of steps, we need to compare the positions at all points of the two walks. The information about spatial properties (2 and 3 dimensional features) are extracted from the xml1 file and accessed in python by converting the xml1 file to pandas data-frame. Similarly, the xml3 file is converted to pandas data-frame and all the frames corresponding to a walk are stored in a list.

Now, the next step is to compare every pair of frames (because they constitute a walk event) to the pair of frames prior to them.

For example g=[110, 119, 148, 178, 194, 208, 247, 295] here, 110-119 is one walk event,148-178 is another walk event and so on. So what we have to do is to compare the walk instance 147-178 to the walk instance 110-119 and walk instance 194-208 will be compared with 148-178. This comparison between the two walk instances is done on the basis of positions at each point of the walk. It has been taken into consideration to compare the positions of second walk in reverse order.

For example if frames 1325, 1350, 1367, 1397 are two walk events that correspond to retracing of footsteps, where 1325-1350 is one walk instance (going) and 1367-1397 is another walk instance (returning). We compare the positions of 1367-1397 to 1350-1325 in reverse order thus ensuring that the two walk events are a perfect candidate for step retracing.

These events are then checked for instances in which the person exits the scene and re-enters the scene following the same trajectory. Such events are of no interest from a clinical point of view hence these cases are dropped from the final list of frames that describe step retracing.

Further, to not miss the events of step retracing in a single walk,we propose to segment the walk and compare for positions using a sliding window. Each walk is compared for positions after the 20 frames of the walk. If the positions are closely related, the walk qualifies as an event of step retracing.

7.19.3. Tables

The output can be computed in the following format

	event id	event	start frame	end frame
0	0	ALLER	68967	68979
1	1	RETOUR	68989	69000
4	2	ALLER	96773	96799
5	3	RETOUR	96809	96849
8	4	ALLER	100293	100320
9	5	RETOUR	100369	100396
12	6	ALLER	121357	121369
13	7	RETOUR	121383	121396
16	8	ALLER	125693	125707
17	9	RETOUR	125718	125736
20	10	ALLER	136516	136524
21	11	RETOUR	136531	136560
24	12	ALLER	137845	137856
25	13	RETOUR	137886	137908

7.20. Safe & Easy Environment for Alzheimer Disease and related disorders

Participants: Auriane Gros, François Brémond.

As part of the SafEE project (see 9.2.1.2), we have implemented two clinical protocols, one for patients in nursing home with Alzheimer disease and the other at home for patients with a frailty syndrome. The goal was to automatically recognize emotional disorders. In nursing home, we sought to detect events specific to the quality of sleep (effective hours of sleep, awakenings at night) to provide an objective measure of sleep disorders. For this purpose, several activity analysis methods have been used to increase the accuracy of automatic recognition. The events of interest were represented by "get in bed" and "get out bed". The performance of the three models used (A; B and B + C) allowed a performance of 0.71 (F1 score). At home, we focused on anxiety-like behavior (repetitive gestures, parasitic gestures), apathy (locomotion, gestures with goals) and agitation (retracing steps, locomotion). In order to be able to identify algorithms with the greatest precision possible, clinicians have realized annotations via the Viper software. In order to annotate these events we have developed a language based on a dedicated ontology for the recognition of activity behaviors that we have deemed of interest. In order to carry out an automatic recognition of the activities of interest, files (xml1 and xml3) were generated in the Scene Understanding Platform (SUP). For the recognition of the activity "to retrace one's steps" we have calculated the relation between two consecutive walks by comparing all the position points of these walks. The spatial properties information was extracted from the xml1 file and converted to Python Pandas data to analyze and visualize the data. The first results highlighted: -a gradual increase in social interactions during the follow-up; -an increase in gestures with goals; -a decrease in retracing one's steps. The studies were conducted on 6 patients during three months of follow-up in nursing home and three patients during six months of follow-up at home.

7.21. Early detection of cognitive disorders such as dementia on the basis of speech analysis ELEMENT

Participants: Alexandra Koenig, Antitza Dantcheva, François Brémond.

This year we have contributed to the ELEMENT activity (see 9.3.2). The goal of this activity has been directed towards automated screening for cognitive decline in non-clinical settings, resulting in faster, earlier diagnosis and intervention. Inria in collaboration with the Association Innovation Alzheimer (AIA)created the French speech corpus allowing automatic detection of dementia on the basis of speech analysis. The employed speech analysis has been augmented by the means of facial expression recognition.

Due to the rapidly ageing population, the number of people with dementia in the EU will triple by 2050. The proposed speech-based screening app supports early detection and intervention, which in turn significantly reduces cost of care and preserves quality of life. The people best placed to spot early cognitive decline are carers, social workers, and family. But there is a clear lack of affordable, usable screening apps that people without medical training can use to validate these concerns and to provide actionable data for medical professionals. The approach can also be used to track mental health and other neurological conditions. The proposed solution supplements neuropsychological assessment with sophisticated and unobtrusive natural biomarkers extracted from speech data that is collected outside of medical consultations. It provides rich information about cognitive and emotional characteristics and can be used to inform clinical judgment during consultations, saving time and money. The project will bring to the European market a new product for fully-automated, reliable, unobtrusive, self-managed screening for cognitive decline, in particular dementia, and other cognitive disorders. It will allow earlier detection and, through that, more effective interventions resulting in the reduction of overall costs associated with treatment and rehabilitation. For users is will offer the comfort of flexible usage without visiting professional physicians.

The target customer group can be characterized as individuals 60+ living either at home or in residential care facilities, as well as their families, caregivers, charities, social services, other stakeholders involved in supporting older persons. The Activity will enable the first-of-that-kind product allowing implementing sophisticated and unobtrusive neuropsychological assessment within minutes right at home or at easy reachable locations without the support of professional clinicians. The initial target markets are France and UK, with the goal to start focused marketing there at the end of 2017 - beginning 2018. The focus of initial marketing will be three-fold: (1) residential care facilities as access points for groups of users, (2) social services providing homecare, and (3) pharmacies with the modern trend of turning them from sales points to service providers. Therefore, the main method of revenue generation will be corporate subscriptions purchased for specific number of users. In the middle term (2-3 years), building on the footprint at the market for corporate clients, the company will start sales for individual clients. In this case the focus of marketing strategy will be on general practitioners as major recommenders and market agents.

Inria in collaboration with AIA created the French speech corpus allowing automatic detection of dementia on the basis of speech analysis. Until now, the corpus contains samples of 149 recorded participants from which 40 Healthy controls, 40 Major cognitive disorder and 57 minor cognitive disorder, for the rest the diagnosis in missing). Data collection is ongoing and will be coupled next year systematically with the video recording.
The following shows the list of transcribed audio files :
Semantic verbal fluency : 74/149
Phonetic fluency: 36/149
Pictures: 167/ 289

Counting backwards: 7/149
Sentence repeating : 168/ 596
Postive story: 77/140
Negative story: 76/149
Motivation: 75/149
In this year, target use case scenario and user requirements were defined. ki elements UG (haftungsbeschraenkt) was established on March 15th, 2017, with the purpose of commercializing the technologies matured and integrated within the ELEMENT project. Significant efforts have been invested in the preparation of the first public demonstration of the product's prototype Delta. In collaboration with DFKI, several research papers were published on the audio data collected in Nice (see [33], [32], [25]).

7.22. Serious exergames for Cognitive Stimulation

Participants: Guillaume Sacco, Monique Thonnat.

A serious exergame is a video game combining cognitive and physical stimulation with a positive impact on patients affect. We have worked to develop and assess X-Torp, a serious exergame which is played with a Kinect™ (see Figure 31).

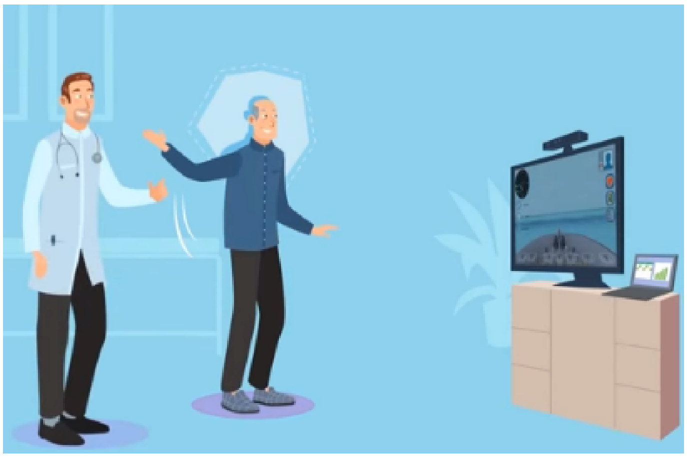


Figure 31. Illustration of the modality of use of X-Torp by a patient with a therapist

This naval battle serious exergame contains two game modes: a scenario mode and a therapist mode. The scenario mode is the core of the game. It combines exploration of an open world and mini-games. Moving in the open world (ocean with islands) corresponds to the physical exercise phase. The mini games (missions proposed on the islands) correspond to the phases of stimulation / cognitive evaluation. The game includes a system of experience points, which reflects the progression of the player in the scenario mode. The therapist mode contains direct access to the virtual versions of the neuropsychological tests proposed in the scenario mode. Therapist mode also contains a physical test that can be performed in a virtual environment.

The integration of serious exergames as a tool to manage patients with neurocognitive disorders could have a major interest in the evaluation of cognitive abilities for two reasons: the design of tests and their more ecological character. Indeed, if the serious game is regularly used by the patient (in autonomy possibly guided by an avatar but not by a therapist), we think that it can allow a much more fine and relevant evaluation of the residual cognitive functions. The first reason for this is that in patients with mild or moderate cognitive impairment, there is a variation in test performance that may be related to anxiety, but also to the variability of observable performance over the day and day to day for some patients.

The innovative aspect of our approach is both a combination of physical and cognitive activity within the same game and the use of goal-directed motor skills for physical stimulation. Indeed, the use of virtual support to guide physical activity allows a longer duration of activity and therefore a better training.

If we consider the continuum of care of patients with neurocognitive disorders at prodromal or mild stages, we find that contacts with the health care system are limited. In addition, the availability of health professionals who can offer stimulation activities remains limited compared to the massive demand generated by the large number of patients with neurocognitive disorders. The interest of our approach is that it makes it possible to free oneself largely from the healthcare professional (which intervenes only for consultations of synthesis and reassessment) and thus allows many more patient follow-up for one healthcare professional.

Thus the development of playful serious exergames, with adequate design and in sufficient numbers, available for example via online gaming platforms, would allow regular use by patients in their homes. The serious exergame would then be a tool for training cognitive functions and physical abilities. It would also be a tool for regular and objective assessment and monitoring of the cognitive and physical performance of patients. It could even be envisaged the creation of game allowing the early detection of cognitive dysfunctions directly from the home of the subjects and inviting them if necessary to consult their physician.

7.23. Activity Description Language

Participants: Daniel Gaffé, Sabine Moisan, Annie Ressouche, Jean-Paul Rigault, Ines Sarray.

Activity Recognition aims at recognizing and understanding sequences of actions and movements of mobile objects (human beings, animals or artefacts), that follow the predefined model of an activity. We propose to describe activities as a series of actions, triggered and driven by environmental events.

Due to the large range of application domains (surveillance, safety, health care ...), we propose a generic approach to design activity recognition systems that interact continously with their environment and react to its stimuli at run-time. Such recognition system must satisfy stringent requirements: dependability, real time, cost effectiveness, security and safety, correctness, completeness ... To enforce most of these properties, our approach is to base the configuration of the system as well as its execution on formal techniques. We chose the *Synchronous Approach* which provides formal bases to perform static analysis, verification and validation, but also direct implementation.

Based on the synchronous approach, we have created a new user-oriented activity description language (named ADeL) to express activities and to automatically generate recognition automata. This language relies on two formal semantics, a behavioral and an equational one. This year, we continued to work on this topic: we improved both the syntax of the ADeL language to be easier to use by non computer-scientists and its semantics to generate synchronous automata.

As the world is not synchronous and since we are working with the synchronous paradigm, we have to face the classical problem of sampling. Our systems have to deal with asynchronous events coming from the environment. This year we started to define an asynchronous/synchronous transformer component, that we call Synchronizer, to transform asynchronous sensor events into synchronous “instants”.

7.23.1. Activity Description Language (ADeL)

ADeL is a (synchronous) language that allows non-computer scientists to describe activities and behaviors to be recognized. It is a modular and hierarchical language, which means that activities can be simple or composed of one or more sub-activities. ADeL has the notions of (typed) roles, events and sub-activities, flow of control... It supports parallelism, variants (choices), and repetitions. ADeL relies on a set of formally specified control and temporal operators.

We provide our language with both a graphical and textual format. We propose a graphical tool which displays several windows, mainly to declare the scene where the activity will take place (zones, roles and equipment) and to describe the activity (expected events and “story board”). However, it may be difficult to express complex activities in a purely graphical way, thus we also provide an equivalent textual form.

This year we conducted a preliminary heuristic evaluation to define the layout of the graphical tool in collaboration with our ergonomist partners from LudoTIC. An example of a scene description window for a medical application (serious game) is shown in Fig. 32 . We made a first positive user test with a doctor, more extensive user tests are planned.

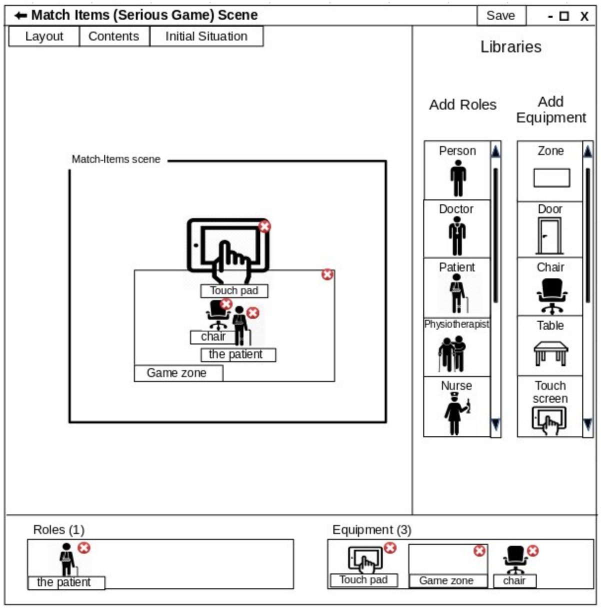


Figure 32. Graphical format of a serious game description (selection of roles and equipment)

7.23.2. Synchronizer

The main drawback of the synchronous paradigm is that the world is not synchronous in general. Thus it requires to transform asynchronous physical flows of events into a succession of discrete instants.

This year, we specified a Synchronizer component to address this issue. The Synchronizer filters physical asynchronous events, decides which ones may be considered as “simultaneous” and aggregates the latter into logical instants. The sequence of these instants constitutes the logical time of our recognition systems. In general, no exact simultaneity decision algorithm exists but several empirical strategies and heuristics may be used for determining instant boundaries. We have to take into account these parameters in the Synchronizer specification. This year we completed the UML specification of the Synchronizer and we started its first implementation.

7.23.3. Semantics

We defined two semantics for the ADeL language [34]. First, conditional rewriting rules are a classical and rather natural way to formally express the intuitive semantics. This form of *behavioral semantics* gives an abstract description and a clear interpretation of a program behavior. However it is not convenient as an implementation basis nor suitable for proofs (e.g., model-checking). Hence we also define an *equational semantics* which maps an ADeL program into a Boolean equation system representing its finite state machine. The ADeL compiler can easily translate this equation system into an efficient code not only for our runtime recognition component, but also for other tools such as model-checkers.

Since we have two different semantics, it is mandatory to establish their relationship. In fact we proved that the execution of a program based on the equational semantics also conforms to the behavioral semantics [34], [38].

7.24. The Clem Workflow

Participants: Annie Ressouche, Daniel Gaffé, Dorine Havyarimana.

Keywords: Synchronous languages, Synchronous Modeling, Model checking, Mealy machine, Logical Decision Diagram

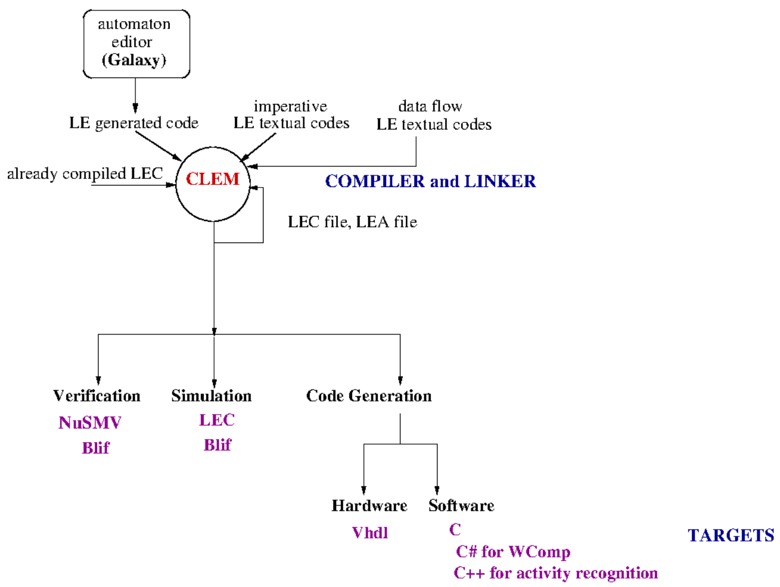


Figure 33. The Clem Toolkit

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 33) to design, simulate, verify, and generate code for programs. The novelty of the approach is the ability to manage both modularity and causality.

This year, we continued to focus on the improvement of both the LE language and compiler concerning data handling and generation of back-ends, required by other research axis of the team. We also improved the design of the simulator (developped these two last years) for LE programs which integrates the data part of the language. The simulator GUI has been designed in Qt. The simulator takes into account the values carried by signals. We implemented an external computation of data values and a communication between the compiler and the simulator through a socket mechanism. However, in this first implementation, there were no predefined types and their related methods. As a consequence, the end user must define them in external files, loaded by the simulator. To avoid the definition of such files for basic types (integer, real,...) and basic operations ($\leq$, $=$, $\geq$,...), this year we improved the simulator and the exchange mechanism to be able to integrate predefined types.

Now, we want to extend the verification side of CLEM. To this aim, this year we begin 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. During the internship of Dorine Havyarimana [41], such a LDD library has been implemented, to replace the BDD one. Then the validation mechanism of CLEM would take into account properties of integer data. However, this is a first step and the integration of a new model checking techniques (like satisfiability modulo theories model checking) is a future work.

7.25. Study of Temporal Properties of Neuronal Archetypes

Participants: Annie Ressouche, Daniel Gaffé, Cedric Girard-Riboulleau.

Keywords: biologic archetypes, Leaky Integrate and Fire Modeling, Model Coupling, Neural Spiking networks, Synchronous Languages, Model Checking Synchronous Modeling, model-checking, lustre, temporal logic, probabilistic models, network reduction.

Last year, we began a collaboration 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 with 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 these different representative archetypes and express their temporal properties, we used a synchronous programming language dedicated to reactive systems (Lustre). Then, we generated several back ends to interface different model checkers supporting data types and automatically validate these properties. We compared the respective results, that mainly depend on the underlying abstraction methods used in model checkers [63].

This year, during the internship of Thibaud l'Yvonnet [0] we tackle the next logical step and proceed to the study of the properties of their couplings. For this purpose, we rely on Leaky Integrate and Fire neuron modeling and we use the synchronous programming language Lustre to implement the neuronal archetypes and to formalize their expected properties. Then, we exploit an associated model checker called kind2 to automatically validate these behaviors. We show that when the archetypes are coupled either these behaviors are slightly modulated or they give way to a brand new behavior. We can also observe that different archetype couplings can give rise to strictly identical behaviors. Our results show that time coding modeling is more suited than rate coding modeling for this kind of studies. These results are published in [30].

On the other hand, in the framework of Cedric Girard Riboulleau internship, we formalize Boolean Probabilistic Leaky Integrate and Fire Neural Networks as Discrete-Time Markov Chains using the language PRISM. In our models, the probability for neurons to emit spikes is driven by the difference between their membrane potential and their firing threshold. The potential value of each neuron is computed taking into account both the current input signals and the past potential values. Taking advantage of this modeling, we propose a novel algorithm which aims at reducing the number of neurons and synaptical connections of a given network. The reduction preserves the desired dynamical behavior of the network, which is formalized by means of temporal logic formulas and verified thanks to the PRISM model checker.

These results are published in [29] and detailed in [40].

7.26. Maintaining the engagement of older adults with dementia while interacting with serious game

Participants: Minh Khue Phan Tran, Philippe Robert, François Brémond.

keywords: Older adults, Dementia, Engagement, Serious game,

The contribution of Phan-Tran's thesis [23] is to provide an approach that can help older adults with dementia while playing serious games. The approach proposes a set of interaction strategies to solve a difficult situation by suitable interactions. A strategy is a rule which defines a set of interactions to transfer from a situation to another one. A situation is defined and recognized by the perception on the users characteristics (position, posture, gesture, game performance). Once an interaction strategy is chosen, the approach helps the user throughout a 3D animated avatar 34 . 11 strategies are defined as well as 21 situations and 13 interactions.

[0] funded by the NeuComp project (C@UCA), in which the Stars team is involved.

Figure 34. A serious game with avatar's assistance

Three experiments have been performed with the older participants with dementia. The results shown positive impacts on the participants engagement:

- the participants can finish the game session;
- their performance while playing with the avatar's helps is similar that the one while playing with a therapist.

The proposed approach can be improved because the types of situations defined and recognized during 3 experiments are not quite so much and the difficulty level of games used in the experiment is still low. The ongoing work aims to apply the proposed approach to a more difficult game and to explore new situations.

7.27. Application of deep learning on healthcare

Participants: Thanh Hung Nguyen, François Brémond.

Healthcare standards have changed dramatically over the past 100 years. People nowadays are aware of the importance of health in their lives. The rising income has enabled them to use private healthcare services. Since the demand is growing rapidly, the physicians need tools which can help them work effeciently in terms of time and cost. Parallely, deep learning has become very popular in the recent years because of its success in computer vision. We have proposed two applications ,VISIONUM and REMINARY, as demonstration of the impact of deep learning on the healthcare.

The first application, VISIONUM (see 9.2.2.1), can detect when the patients lose their focus on the therapeutic exercise and thereby reminds them to return back to the exercise. Since the patients can correct themselves on their own, while they are doing exercises, therapists can focus more on the performance of the exercise. It also helps the therapist to keep track of multiple patients at the same time and hence, save both time and money (see Figure 35).

The second application, REMINARY (see 9.2.2.3), aims to detect the movement of people. In this application, the movement of patients is tracked and analysed. The output gives therapists an overview of the movement of their patients. This information is used by the therapist to monitor the diseases which are related to the movement and decide if there is any improvement due to the treatment. For both applications, we can also analyse emotions like happiness of patient. This information is extremely important for the design of the exercise (see Figure 36 and Figure 37).

7.28. Brick & Mortar Cookies

Participants: Julien Badie, Manikandan Bakthavatchalam, Anais Ducoffe.

Figure 35. Examples of our application VISIONUM, we detect two people in the scene, but only the person in the red bounding box is interested. This person is detected as sitting too far from the camera using depth information, he will be reminded that he should come closer so the exercise can continue.

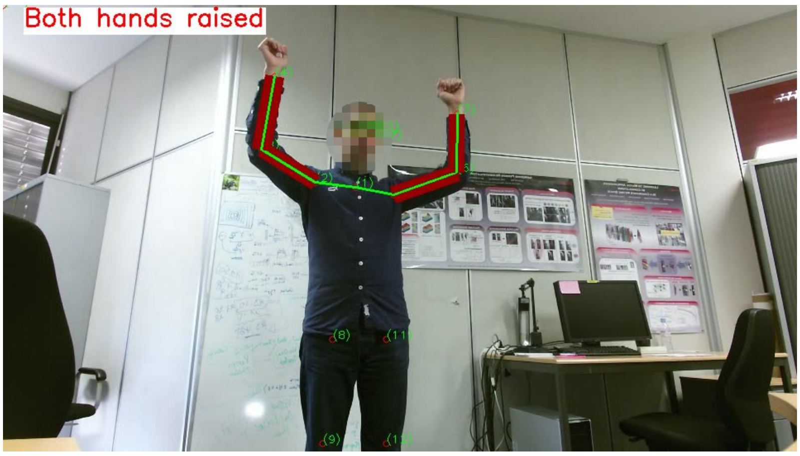


Figure 36. Examples of our application REMINARY, the actor is doing some exercise. In this case, the event that he raised both his hands is detected. The visualisation make the therapist easier to see how the system catches the event.

Figure 37. Examples of the other feature of our application REMINARY. The movement region is highlighted by a green color.

BMC is a software platform that was introduced in 2016. The goal was to create a light and easy to deploy platform in the context of gathering Business Intelligence data (BI) to help store managers monitor client trajectories and most interesting products and alleys inside a supermarket. BMC was finalized this year and had been extensively tested in real conditions with success.
The platform is divided into several modules :

- an image processing module that handles retrieving images from a camera network followed by people detection using a deep learning algorithm (SSD) and tracking. The results are stored in a MySQL database;
- a trajectory analysis module that computes statistics for BI. These statistics are computed based on the trajectories of the first module and give information regarding each alley such as the average number of customers per hour, the average time spent by the customer in the alley or the average number of stops in front of each type of product. All these data can be visualized via a web interface and are refreshed periodically;
- an automatic installation and deployment module. This module is a set of Python scripts that, given a computer with the correct hardware and OS requirements will automatically install the BMC platform and all its dependencies (OpenCV, cuda, caffe, ...). In a second time, users can enter the list of cameras they want to process with a limited set of parameters (working days and hours) and the deployment script will prepare the platform and create the CRON command line that will run BMC automatically.

An additional module was created but not included in the release : the evaluation module. It was used to find the best balance between fast processing and precise results by evaluating different parameters at the people detection level such as which model to use and which image resolution to process. After several experiments, it was decided to use a processing resolution of 480x272 to allow us to process 16 cameras simultaneously with two Nvidia GeForce GTX 980 GPU at 3-4 FPS. This framerate is sufficient for tracking in the context of a supermarket as people tends to move slowly and stops a lot. The platform was tested in a supermarket in Nice during several days and showed satisfactory results.
BMC is registered at the APP under the name BMC_1. It is intended to be used in the FUI project StoreConnect.

TITANE Project-Team

7. New Results

7.1. Analysis

7.1.1. Forest point processes for line-network extraction

Participants: Alena Schmidt, Florent Lafarge.

In collaboration with Claus Brenner, Franz Rottensteiner and Christian Heipke from the Leibniz Universitat Hannover, Germany.

We contributed a new stochastic approach for the automatic detection of network structures in raster data. We represent a network as a set of trees with acyclic planar graphs. We embed this model in the probabilistic framework of spatial point processes and determine the most probable configuration of trees by stochastic sampling. That is, different configurations are constructed randomly by modifying the graph parameters and by adding or removing nodes and edges to or from the current trees. Each configuration is evaluated based on the probabilities for these changes and an energy function describing the conformity with a predefined model. Although our main target application is the extraction of rivers and tidal channels in digital terrain models as illustrated on Figure 1 , experiments with other types of networks in images show the transferability to further applications. Qualitative and quantitative evaluations demonstrate the competitiveness of our approach with respect to existing algorithms. This work was published in the ISPRS journal [21].

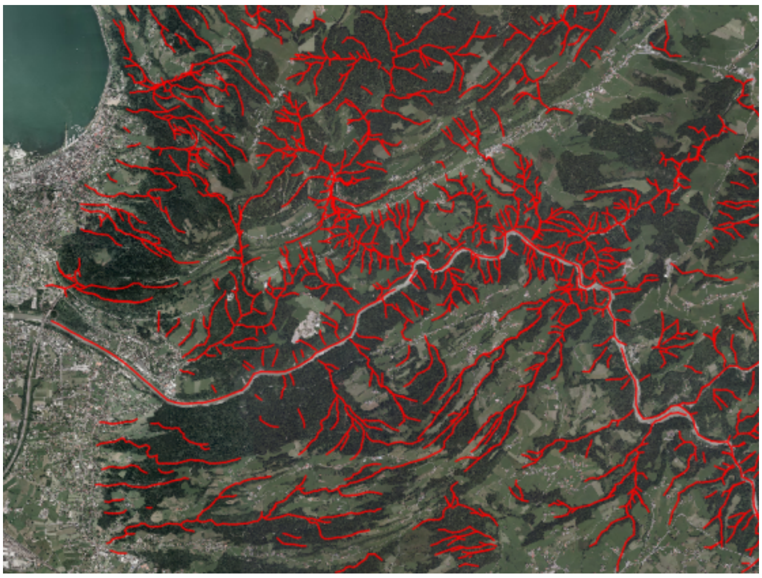


Figure 1. Extraction of line-networks by Forest point processes. River network is represented by acyclic planar graphs in red.

7.1.2. Photo2ClipArt: Image Abstraction and Vectorization Using Layered Linear Gradients

Participants: Jean-Dominique Favreau, Florent Lafarge.

In collaboration with Adrien Bousseau (GraphDeco Inria team)

We proposed a method to create vector cliparts from photographs. Our approach aims at reproducing two key properties of cliparts: they should be easily editable, and they should represent image content in a clean, simplified way. We observe that vector artists satisfy both of these properties by modeling cliparts with linear color gradients, which have a small number of parameters and approximate well smooth color variations. In addition, skilled artists produce intricate yet editable artworks by stacking multiple gradients using opaque and semi-transparent layers. Motivated by these observations, our goal is to decompose a bitmap photograph into a stack of layers, each layer containing a vector path filled with a linear color gradient. We cast this problem as an optimization that jointly assigns each pixel to one or more layer and finds the gradient parameters of each layer that best reproduce the input. Since a trivial solution would consist in assigning each pixel to a different, opaque layer, we complement our objective with a simplicity term that favors decompositions made of few, semi-transparent layers. However, this formulation results in a complex combinatorial problem combining discrete unknowns (the pixel assignments) and continuous unknowns (the layer parameters). We propose a Monte Carlo Tree Search algorithm that efficiently explores this solution space by leveraging layering cues at image junctions. We demonstrate the effectiveness of our method by reverse-engineering existing cliparts and by creating original cliparts from studio photography (see Figure 2). This work was published at ACM SIGGRAPH ASIA and in ACM Transactions on Graphics 2017 [14].

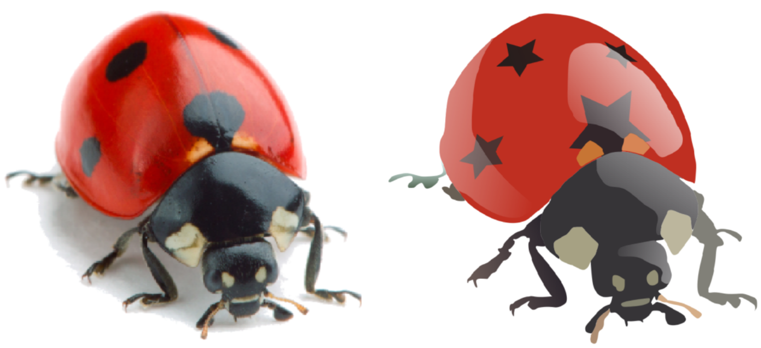


Figure 2. Photo2ClipArt. Our method generates an abstract, layered vector clipart, where each layer is filled with an opaque or semi-transparent linear color gradient. By expressing the input image (left) as a stack of linear color gradients, our vector graphics reproduce the visual style of traditional cliparts and are easy to edit. In the right example, we replaced the lady bug dots by little stars.

7.1.3. Semantic segmentation of 3D textured meshes

Participants: Florent Lafarge, Pierre Alliez.

In collaboration with Mohammad Rouhani, now at Technicolor, France.

Classifying 3D measurement data has become a core problem in photogrammetry and 3D computer vision, since the rise of modern multiview geometry techniques, combined with affordable range sensors. We introduce a Markov Random Field-based approach for segmenting textured meshes generated via multi-view stereo into urban classes of interest. The input mesh is first partitioned into small clusters, referred to as superfacets, from which geometric and photometric features are computed. A random forest is then trained to predict the class of each superfacet as well as its similarity with the neighboring superfacets. Similarity is used to assign the weights of the Markov Random Field pairwise-potential and accounts for contextual information between the classes. The experimental results illustrate the efficacy and accuracy of the proposed framework (See Figure 3). This work was published in the ISPRS journal [20].

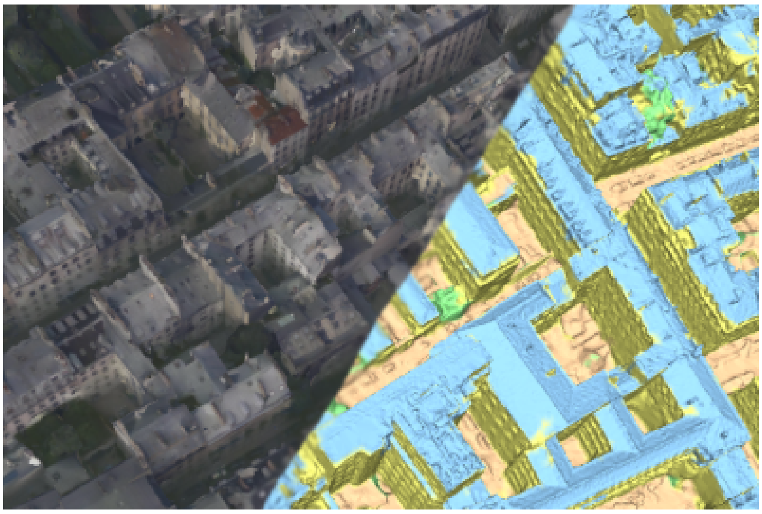


Figure 3. Semantic segmentation of 3D textured meshes. A textured mesh generated by Multiview stereo (left) is segmented into four urban classes of interest: building in blue, facade in yellow, ground in grey, and vegetation in green (right).

7.1.4. 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 (Figure 4). This work was published in IEEE Transactions on Geoscience and Remote Sensing (TGRS) [17].

7.1.5. 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

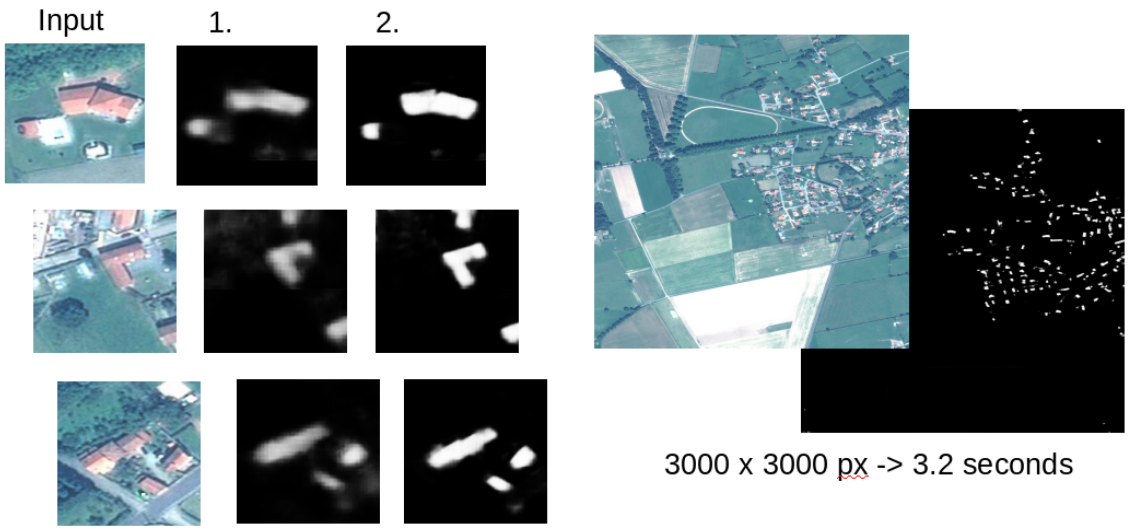


Figure 4. We train in a two-step scheme: first we train a fully convolutional network on large amounts of imperfect training data, to capture the generalities of the problem, which leads to coarse classification maps (1). In a second stage we fine-tune the network for few iterations on a precise manually labeled dataset, outputting fine classification maps as a results (2). The overall system is efficient and scalable.

these observations, we then derive a CNN framework specifically adapted to the semantic labeling problem [23], [18]. In addition to learning features at different resolutions, it learns how to combine these features (Figure 5). 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. This work was published in IEEE Transactions on Geoscience and Remote Sensing and was presented at the IEEE International Geoscience and Remote Sensing Symposium (IGARSS).

7.1.6. 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

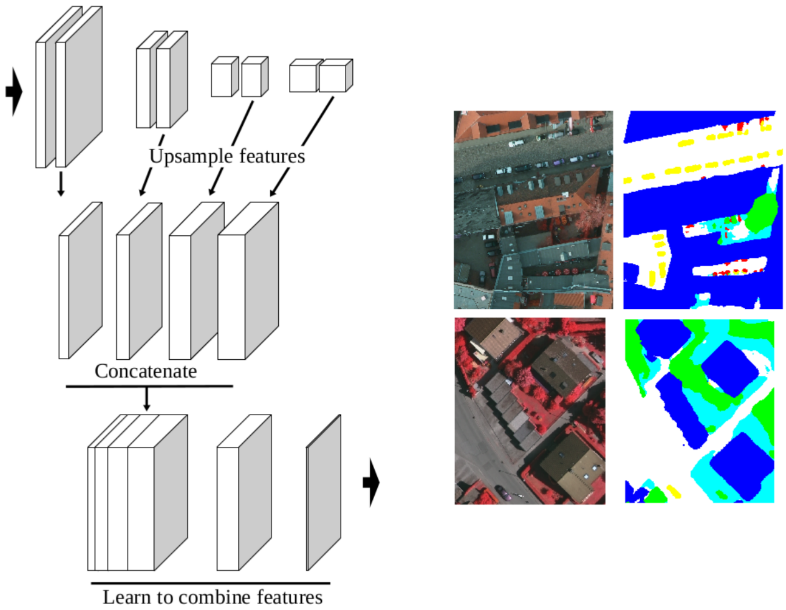


Figure 5. Our MLP network architecture (left) learns features at different resolutions and also learns how to combine those features. The technique was evaluated on the ISPRS 2D Semantic Segmentation Contest (right), providing competitive results.

classification maps (Figure 6). This work was published in IEEE Transactions on Geoscience and Remote Sensing [16].

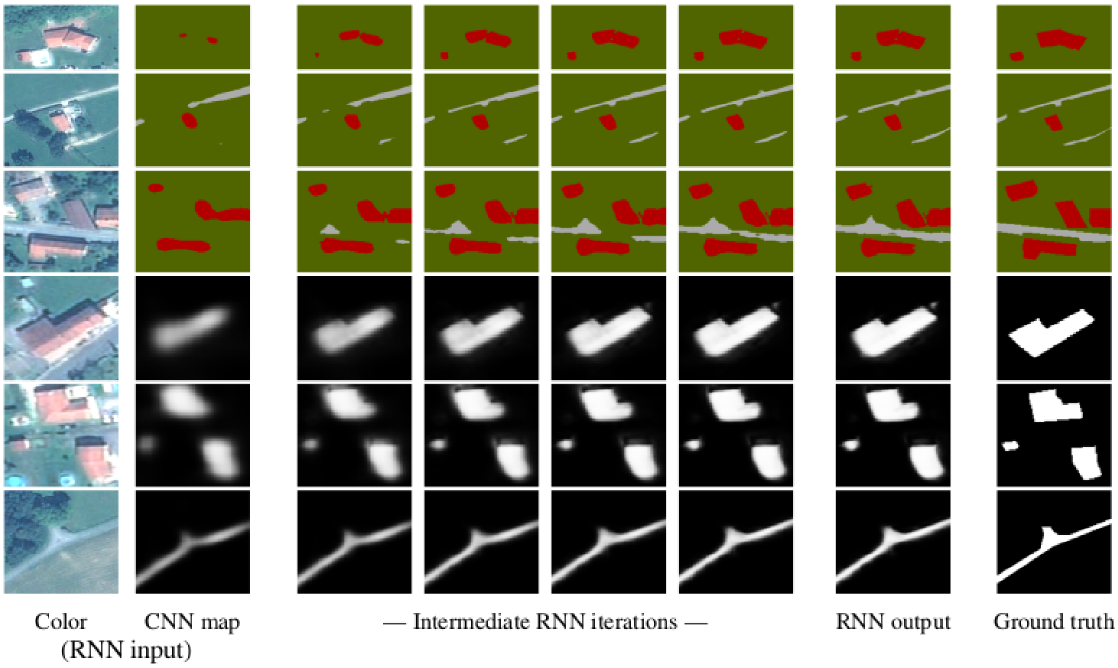


Figure 6. A recurrent neural network (RNN) learns an algorithm to iteratively correct the output of a coarse classification map. As a result, the satellite image classification maps become finer and better aligned to the real objects.

7.1.7. Can semantic labeling methods generalize to any city? The Inria Aerial Image Labeling Benchmark

Participants: Emmanuel Maggiori, Yuliya Tarabalka, Pierre Alliez.

In collaboration with Guillaume Charpiat (Inria TAO team)

New challenges in remote sensing impose the necessity of designing pixel classification methods that, once trained on a certain dataset, generalize to other areas of the earth. This may include regions where the appearance of the same type of objects is significantly different. In the literature it is common to use a single image and split it into training and test sets to train a classifier and assess its performance, respectively. However, this does not prove the generalization capabilities to other inputs. In this work, we propose an aerial image labeling dataset that covers a wide range of urban settlement appearances, from different geographic locations (see Fig. 7). Moreover, the cities included in the test set are different from those of the training set. We also experiment with convolutional neural networks on our dataset. This work was presented at the IEEE International Symposium on Geoscience and Remote Sensing (IGARSS) [22].

7.1.8. Coarse to fine non-rigid registration: a chain of scale-specific neural networks for multimodal image alignment with application to remote sensing

Participants: Armand Zampieri, Yuliya Tarabalka.

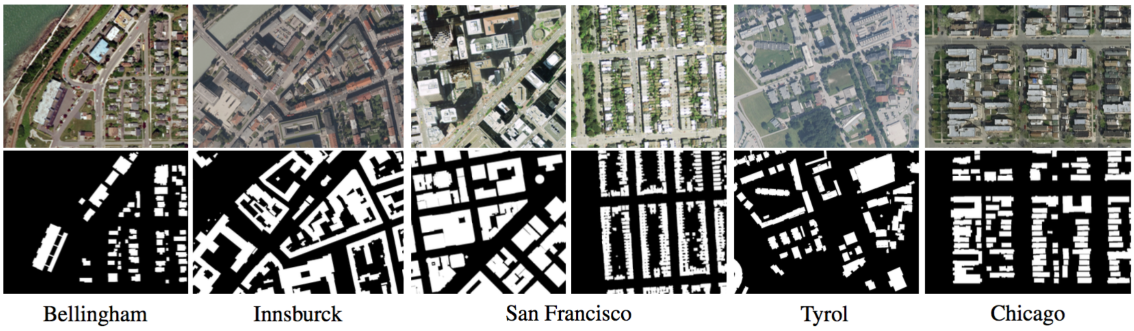


Figure 7. Close-ups of the dataset images and their corresponding reference data.

In collaboration with Guillaume Charpiat (Inria TAO team)

We tackle here the problem of multimodal image non-rigid registration, which is of prime importance in remote sensing and medical imaging. The difficulties encountered by classical registration approaches include feature design and slow optimization by gradient descent. By analyzing these methods, we note the significance of the notion of scale. We design easy-to-train, fully-convolutional neural networks able to learn scale-specific features. Once chained appropriately, they perform global registration in linear time, getting rid of gradient descent schemes by predicting directly the deformation. We show their performance in terms of quality and speed through various tasks of remote sensing multimodal image alignment. In particular, we are able to register correctly cadastral maps of buildings (see Fig. 8) as well as road polylines onto RGB images, and outperform current keypoint matching methods.

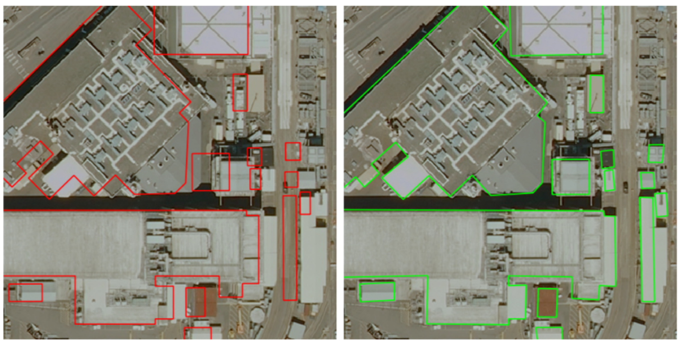


Figure 8. Example of image alignment with the proposed method. (Left) Original image and OpenStreetMap. (Right) Alignment result.

7.1.9. Models for hyperspectral image analysis: from unmixing to object-based classification

Participants: Emmanuel Maggiori, Yuliya Tarabalka.

In collaboration with Antonio Plaza (University of Extremadura)

The recent advances in hyperspectral remote sensing technology allow the simultaneous acquisition of hundreds of spectral wavelengths for each image pixel. This rich spectral information of the hyperspectral data makes it possible to discriminate different physical substances, leading to a potentially more accurate classification (see example classifications Figure 9) and thus opening the door to numerous new applications. Throughout the history of remote sensing research, numerous methods for hyperspectral image analysis have been presented. Depending on the spatial resolution of the images, specific mathematical models must be designed to effectively analyze the imagery. Some of these models operate at a sub-pixel level, trying to decompose a mixed spectral signature into its pure constituents, while others operate at a pixel or even object level, seeking to assign unique labels to every pixel or object in the scene. The spectral mixing of the measurements and the high dimensionality of the data are some of the challenging features of hyperspectral imagery. This work presents an overview of unmixing and classification methods, intended to address these challenges for accurate hyperspectral data analysis. This work was published as a book chapter [26].

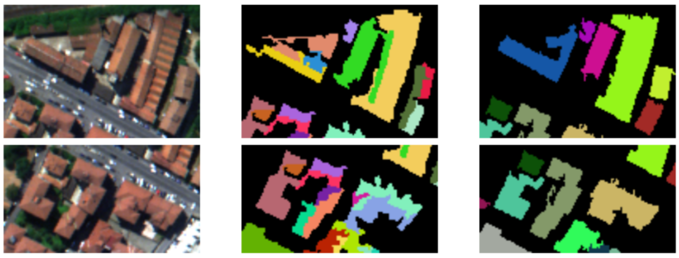


Figure 9. Example of building object-based classification using binary partition trees.

7.2. Approximation

7.2.1. Variance-Minimizing Transport Plans for Inter-surface Mapping

Participants: Pierre Alliez, Mathieu Desbrun.

In collaboration with Manish Mandad (former Ph.D. student) and Prof. Leif Kobbelt from RWTH Aachen, and with David Cohen-Steiner from the DataShape project-team.

We contribute an efficient computational method for generating dense and low distortion maps between two arbitrary surfaces of same genus [19]. Instead of relying on semantic correspondences or surface parameterization, we directly optimize a variance-minimizing transport plan between two input surfaces that defines an as-conformal-as-possible inter-surface map satisfying a user-prescribed bound on area distortion. The transport plan is computed via two alternating convex optimizations, and is shown to minimize a generalized Dirichlet energy of both the map and its inverse. Computational efficiency is achieved through a coarse-to-fine approach in diffusion geometry, with Sinkhorn iterations modified to enforce bounded area distortion. The resulting inter-surface mapping algorithm applies to arbitrary shapes robustly (figure 10), with little to no user interaction. This work has been published at the ACM SIGGRAPH conference.

7.2.2. Error-Bounded and Feature Preserving Surface Remeshing with Minimal Angle Improvement

Participant: Pierre Alliez.

In collaboration with Kaimo Hu (former post-doc) and Bedrich Benes from Purdue University, with David Bommes from RWTH Aachen and Dong-Ming Yan from the National Laboratory of Pattern Recognition, Institute of Automation, Chinese Academy of Sciences.

Figure 10. Inter-surface mapping. Our approach generates a dense, low-distortion correspondence map between non-isometric surfaces through a geometrically-derived transport map minimizing local variances of associated neighborhoods. Only two user-defined constraints were prescribed in these models, at the tip of diametrically opposed limbs. Colors are used to indicate correspondences between all the models.

Surface remeshing is a key component in many geometry processing applications. The typical goal consists in finding a mesh that is (1) geometrically faithful to the original geometry, (2) as coarse as possible to obtain a low-complexity representation and (3) free of bad elements that would hamper the desired application. Our remeshing algorithm [15] is designed to address all three optimization goals simultaneously by targeting prescribed bounds on approximation error, minimal interior angle and maximum mesh complexity. Our optimization framework applies carefully prioritized local operators in order to greedily search for the coarsest mesh with minimal interior angle and bounded approximation error. Fast runtime is enabled by a local approximation error estimation, while implicit feature preservation is obtained by specifically designed vertex relocation operators. Experiments show that our approach delivers high-quality meshes with implicitly preserved features and better balances between geometric fidelity, mesh complexity and element quality than the state-of-the-art (Figure 11). This work has been published in the IEEE Transactions on Visualization and Computer Graphics, and was presented at the EUROGRAPHICS Symposium on Geometry Processing.

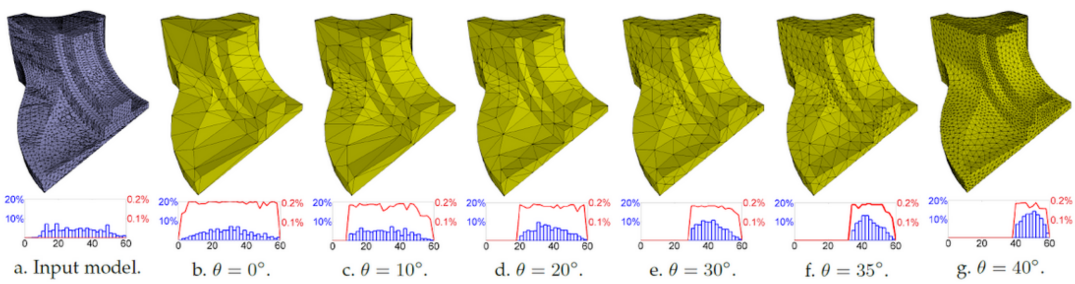


Figure 11. Examples of surface meshes generated with our approach. The input model (a) has 7.2k vertices. From (b) to (g) are the results with different minimal angle threshold. The blue histograms show the distribution of minimal angles of triangles and the red curves the corresponding approximation errors of these triangles. The error-bound threshold is set to 0.2% of the diagonal length of the input's bounding box.

TOSCA Project-Team

7. New Results

7.1. Probabilistic numerical methods, stochastic modelling and applications

Participants: Mireille Bossy, Nicolas Champagnat, Quentin Cormier, Madalina Deaconu, Olivier Faugeras, Coralie Fritsch, Pascal Helson, Antoine Lejay, Radu Maftei, Victor Martin Lac, Hector Olivero-Quinteros, Paolo Pigato, Denis Talay, Etienne Tanré, Milica Tomašević, Denis Villemonais.

7.1.1. Published works and preprints

- M. Bossy, R. Maftei and Jean-François Jabir (National Research University Higher School of Economics, Moscow) propose and analyze the convergence of a time-discretization scheme for the motion of a particle when its instantaneous velocity is drifted by the known velocity of the carrying flow, and when the motion is taking into account the collision event with a boundary wall. We propose a symetrized version of the Euler scheme and prove a convergence of order one for the weak error. The regularity analysis of the associated Kolmogorov PDE is obtained by mixed variational and stochastic flow techniques for PDE problem with specular condition [46].
- N. Champagnat and B. Henry (IECL) studied a probabilistic approach for the Hamilton-Jacobi limit of non-local reaction-diffusion models of adaptive dynamics when mutations are small. They used a Feynman-Kac interpretation of the partial differential equation and large deviation estimates to obtain a variational characterization of the limit. They also studied in detail the case of finite phenotype space with exponentially rare mutations, where they were able to obtain uniqueness of the limit [48].
- N. Champagnat and P.-E. Jabin (Univ. Maryland) completed the study of the functional spaces in the article [18], devoted to the study of strong existence and pathwise uniqueness for stochastic differential equations (SDE) with rough coefficients, typically in Sobolev spaces.
- 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, defined as the original Markov process conditioned to never be absorbed. They prove that, under the conditions of [5], in addition to the uniform exponential convergence of the 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 [22].
- N. Champagnat and D. Villemonais obtained criteria based on Lyapunov functions allowing to check the conditions of [5] which characterize the exponential uniform convergence in total variation of conditional distributions of an absorbed Markov process to a unique quasi-stationary distribution [50]. Among the various applications they give, they prove that these conditions apply to any logistic Feller diffusions in any dimension conditionned to the non extinction of all its coordinates. This question was left partly open since the first work of Cattiaux and Méléard on this topic [63].
- N. Champagnat and D. Villemonais obtained general conditions based on Foster-Lyapunov criteria ensuring the exponential convergence in total variation of the conditional distributions of an absorbed Markov process to a quasi-stationary distribution (QSD), with a speed that can depend on the initial distribution. In particular, these results provide a non-trivial subset of the domain of attraction of the minimal QSD of an absorbed process in cases where there is not uniqueness of a QSD. Similar results were only known for the very specific branching models. They also show how these criteria can be checked for a wide range of Markov processes in discrete or continuous time and in discrete

or continuous state spaces. In all these cases, they improve significantly the best known results. A particularly remarkable result is the existence of a principal eigenfunction for the generator of elliptic diffusion processes aborbed at the boundary of an open domain without any regularity assumption on the boundary of this domain [49].

- During his internship supervised by E. Tanré and R. Veltz (MATHNEURO Inria team), Q. Cormier studied numerically and theoretically a model of spiking neurons in interactions [51]. This model generalizes classical integrate and fire models: the neurons no more spike after hitting a deterministic threshold but spikes with a rate given as a function of the membrane potential (see e.g. [64]). He showed existence and uniqueness of the corresponding limit equation, and was able to extend those results in the case of excitatory and inhibitory neurons. He is now studying the long time behavior of the model, as part of his thesis.
- M. Deaconu and S. Herrmann studied the simulation of the hitting time of some given boundaries for Bessel processes. These problems are of great interest in many application fields as finance and neurosciences. More precisely they obtained recently a new method for the simulation of hitting times for Bessel processes with a non integer dimension. The main idea is to consider the simulation of the hitting time of Bessel processes with integer dimension and provide a new algorithm by using the additivity property of the laws of squared Bessel processes [26].
- M. Deaconu and S. Herrmann studied the Initial-Boundary Value Problem for the heat equation [25]. They construct an algorithm based on a random walk on heat balls in order to approximate the solution. Even if it represents a sophisticated 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 particular mean value formula for the heat equation and they obtained also a probabilistic formulation of this formula. They proved convergence results for this algorithm and illustrate them by numerical examples.
- M. Deaconu, S. Herrmann and S. Maire [27] introduced a new method for the simulation of the exit time and position of a δ-dimensional Brownian motion from a domain. The main interest of this method is that it avoids splitting time schemes as well as inversion of complicated series. The idea is to use the connexion between the δ-dimensional Bessel process and the δ-dimensional Brownian motion thanks to an explicit Bessel hitting time distribution associated with a particular curved boundary. This allows to build a fast and accurate numerical scheme for approximating the hitting time.
- M. Deaconu, B. Dumortier and E. Vincent (EPI Multispeech) are working with the Venathec SAS on the acoustic control of wind farms. Wind turbine noise is often annoying for humans living in close proximity to a wind farm. Reliably estimating the intensity of wind turbine noise is a necessary step towards quantifying and reducing annoyance, but it is challenging because of the overlap with background noise sources. Current approaches involve measurements with on/off turbine cycles and acoustic simulations, which are expensive and unreliable. This raises the problem of separating the noise of wind turbines from that of background noise sources and coping with the uncertainties associated with the source separation output. In their work they propose to assist a black-box source separation system with a model of wind turbine noise emission and propagation in a recursive Bayesian estimation framework. This new approach is validated on real data with simulated uncertainties using different nonlinear Kalman filters [38].
- M. Deaconu is working with L. Beznea and O. Lupaşcu (Bucharest, Romania) on the stochastic interpretation of rupture phenomena. They constructed a stochastic differential equation and a branching process for the fragmentation model. The main physical model involved in their study is the avalanche one and their model includes physical properties of the phenomenon. They introduced a new numerical algorithm issued from this study, which captures the fractal property of the avalanche [43].
- C. Fritsch, F. Campillo (Inria Sophia-Antipolis, MATHNEURO team) and O. Ovaskainen (Univ. Helsinki) proposed a numerical approach to determine mutant invasion fitness and evolutionary

singular strategies using branching processes and integro-differential models in [31]. They illustrate this method with a mass-structured individual-based chemostat model.

- P. Helson, E. Tanré and R. Veltz (MATHNEURO Inria team), have numerically and theoretically studied a model of spiking neurons in interaction with stochastic plasticity. A slow-fast analysis enabled to split the dynamic in two inhomogeneous Markov chains: one models the slow variable, the other one the fast variable. The jump rates of the slow chain is governed by the invariant distribution of the fast one. In his PhD thesis, P. Helson has proved existence and uniqueness of solution. Simple conditions for the slow variable to be recurrent and transient are given [53].
- A. Lejay, L. Lenôtre (CMAP, École Polytechnique) and G. Pichot (Inria Paris, SERENA team) have continued their work on the simulation of processes on discontinuous media [55]. A new Monte Carlo scheme, called the exponential timestepping scheme and based on closed form expression of the resolvent, is being studied.
- A. Lejay, E. Mordecki (U. de la República, Uruguay) and S. Torres (U. de Valparaíso, Chile) have continuous their work on the estimation of the parameter of the Skew Brownian motion [56].
- A. Lejay and P. Pigato have studied the estimation of the parameter of the Oscillating Brownian motion, which is a solution of a stochatic differential equation whose diffusivity takes two values [35].
- A. Lejay have given an alternative proof of the Girsanov theorem which is based on semigroups [39].
- In [60] D. Talay and M. Tomašević propose a new type of stochastic interpretation of the parabolic-parabolic Keller-Segel systems. It involves an original type of McKean-Vlasov interaction kernel. At the particle level, each particle interacts with all the past of each other particle. At the mean-field level studied here, the McKean-Vlasov limit process interacts with all the past time marginals of its probability distribution. They prove that the one-dimensional parabolic-parabolic Keller-Segel system in the whole Euclidean space and the corresponding McKean-Vlasov stochastic differential equation are well-posed for any values of the parameters of the model.
- In collaboration with Jean-François Jabir (National Research University Higher School of Economics, Moscow) D. Talay and M. Tomašević prove the well–posedness of an original singularly interacting stochastic particle system associated to the one-dimensional parabolic-parabolic Keller-Segel model. They also establish the propagation of chaos towards this model [54].
- In [44] J. Bion-Nadal (Ecole Polytechnique) and D. Talay have introduced a Wasserstein-type distance on the set of the probability distributions of strong solutions to stochastic differential equations. This new distance is defined by restricting the set of possible coupling measures. They proved that it may also be defined by means of the value function of a stochastic control problem whose Hamilton–Jacobi–Bellman equation has a smooth solution, which allows one to deduce a priori estimates or to obtain numerical evaluations. They have exhibited an optimal coupling measure and characterized it as a weak solution to an explicit stochastic differential equation, and they finally have described procedures to approximate this optimal coupling measure.

  A notable application concerns the following modeling issue: given an exact diffusion model, how to select a simplified diffusion model within a class of admissible models under the constraint that the probability distribution of the exact model is preserved as much as possible?
- E. Tanré has worked with Patricio Orio (CINV, Chile) and Alexandre Richard (Centrale-Supelec) on the modelling and measurement of long-range dependence in neuronal spike trains. They exhibit evidence of memory effect in genuine neuronal data and compared a fractional integrate-and-fire model with the existing Markovian models (paper in revision: [59]).
- D. Villemonais worked with his Research Project student William Oçafrain (École des Mines de Nancy) on an original mean-field particle system [36]. 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.

- D. Villemonais, Camille Coron (Université Paris XI) and Sylvie Méléard (École Polytechnique) proved a criterion for the integrability of paths of one-dimensional diffusion processes in [52] from which we derive new insights on allelic fixation in several situations.
- D. Villemonais obtains a lower bound for the coarse Ricci curvature of continuous time pure jump Markov processes in [61], with an emphasis on interacting particle systems. In this preprint, several models are studied, with a detailed study of the herd behavior of a simple model of interacting agents. The lower bound is shown to be sharp for birth and death processes.

7.1.2. Other works in progress

- M. Bossy, J. Fontbona (Universidad de Chile, Chile) and H. Olivero-Quinteros are working in a model for a network of neurons interacting electrically and chemically in a mean field fashion. They have proved the synchronization of the network under suitable values for the parameters of the model and a concentration result for the mean field limit.
- N. Champagnat is working with P. Vallois (IECL and Inria BIGS team) and L. Vallat (CHRU Strasbourg) on the inference of dynamical gene networks from RNAseq and proteome data.
- N. Champagnat, C. Fritsch and S. Billiard (Univ. Lille) are working on food web modeling.
- N. Champagnat, C. Fritsch and D. Villemonais are working with A. Gégout-Petit, P. Vallois, A. Mueller-Gueudin (IECL and Inria BIGS team), A. Kurtzmann (IECL), A. Harlé, J.-L. Merlin (ICL and CRAN) and E. Pencreac'h (CHRU Strasbourg) within an ITMO Cancer project on modeling and parametric estimation of dynamical models of circulating tumor DNA (ctDNA) of tumor cells, divided into resistant and sensitive ctDNA depending on whether they hold mutations known to provide resistance to a given targeted therapy or not. The goal of the project is to predict sooner and more accurately the emergence of resistance to the targeted therapy in a patient's tumor, so that the patient's therapy can be modulated more efficiently.
- M. Deaconu and S. Herrmann are working on numerical approaches for hitting times of some general stochastic differential equations.
- M. Deaconu, O. Lupaşcu and L. Beznea (Bucharest, Romania) are working on the connexion between branching processes and partial differential equations in fluid mechanics.
- M. Deaconu, B. Dumortier and E. Vincent (EPI Multispeech) are working on handling uncertainties in the wind farms model in order to design a stochastic algorithm.
- M. Deaconu and R. Stoica (Université de Lorraine, Nancy) are working on the ABC Shadow algorithm and its possible generalizations.
- O. Faugeras, E. Soret and E. Tanré are working on Mean-Field descriptions or thermodynamics limits of large populations of neurons. They study a system of EDS which describes the evolution of membrane potential of each neuron over the time when the synaptic weights are random variables (not assumed to be independent).
- O. Faugeras, James Maclaurin (Univ. of Utah) and E. Tanré have worked on the asymptotic behavior of a model of neurons in interaction with correlated gaussian synaptic weights. They have obtained the limit equation as a singular non-linear SDE and a Large Deviation Principle for the law of the finite network.
- 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.
- P. Helson, E. Tanré and R. Veltz (MATHNEURO Inria team) are working on a mathematical framework for plasticity models. The aim is to propose a 'optimized' model of memory capacity and memory lifetime.
- A. Lejay, A. Brault (Univ. Toulouse) and L. Coutin (Univ. Toulouse) are working on a non linear generalization of the sewing lemma, which is the main technical tool in the theory of rough paths.

- V. Martin Lac, H. Olivero-Quinteros and D. Talay are working on theoretical and algorithmic questions related to the simulation of large particle systems under singular interactions and to the simulation of independent random variables with heavy tails.
- C. Graham (École Polytechnique) and D. Talay are ending and polishing the second volume of their series on Mathematical Foundation of Stochastic Simulation to be published by Springer.
- P-E. Jabin (University of Maryland) and D. Talay are working on a mean-field game and developing a new technique to analyse it.
- E. Tanré is working with Nicolas Fournier (Univ. Pierre et Marie Curie, Paris 6) and Romain Veltz (MATHNEURO Inria team) on a network of spiking networks with propagation of spikes along the dendrites. Consider a large number n of neurons randomly connected. When a neuron spikes at some rate depending on its electric potential, its potential is set to a minimum value v_{min}, and this makes start, after a small delay, two fronts on the dendrites of all the neurons to which it is connected. Fronts move at constant speed. When two fronts (on the dendrite of the same neuron) collide, they annihilate. When a front hits the soma of a neuron, its potential is increased by a small value w_n. Between jumps, the potentials of the neurons are assumed to drift in $[v_{min}, \infty)$, according to some well-posed ODE. We prove the existence and uniqueness of a heuristically derived mean-field limit of the system when $n \to \infty$.
- E. Tanré is working with Alexandre Richard (Centrale-Supelec) and Soledad Torres (Universidad de Valparaíso, Chile) on a one-dimensional fractional SDE reflected on the line. The existence and uniqueness of this process is known in the case of the Hurst parameter H of the noise (fBM) is larger than 0.5. They have proved the existence of a penalization scheme (suited to numerical approximation) to approach this object. When $H \in (\frac{1}{4}, \frac{1}{2})$, they have proved the existence in the elliptic.
- D. Villemonais works in collaboration with Éliane Albuisson (CHRU of Nancy), Athanase Benetos (CHRU of Nancy), Simon Toupance (CHRU of Nancy), Daphné Germain (École des Mines de Nancy), Anne Gégout-Petit (Inria BIGS team) and Sylvain Chabanet (École des Mines de Nancy). The aim of this collaboration is to conduct a statistical study of the time evolution of telomere's length in human cells.
- D. Villemonais started a collaboration with Cécile Mailler (University of Bath) with the aim of studying the almost sure convergence of measure valued Pólya urns models.

7.2. Financial Mathematics

Participants: Madalina Deaconu, Antoine Lejay, Paolo Pigato, Khaled Salhi, Etienne Tanré.

7.2.1. Published works and preprints

- When the underlying asset price is given by a exponential Lévy model, the market is almost incomplete. Under this hypothesis, M. Deaconu, A. Lejay and K. Salhi worked 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 [28].
- A. Lejay and P. Pigato studied the estimation of the coefficients of the Geometric Oscillating Brownian motion on financial data. This stochastic process is a modification of the Black & Scholes model that takes into account leverage effect and other sudden changes in the volatility [57], [41].
- V. Reutenauer and E. Tanré have worked on extensions of the exact simulation algorithm introduced by Beskos et al. [62]. 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 ([58], paper in revision).

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.

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 [67], [58]. 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.* (Bilan Yonis-Omar, Emma Carrié, 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 [66]. 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 [53].

  An application for the reconstruction of an apple tree core collection (1000 trees) has been conducted during the internships of B. Yonis-Omar and E. Carrié in a collaboration with the AFEF Team of UMR AGAP. A protocol that minimize the number of movement of the scanner has been setup. Some first method to characterize and reconstruct architectural traits from the scan has been defined.

- *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 Cereals), 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 or establish response curve of morphogenetic processes to light environment [37]. This software framework was presented to “BMVA technical meeting: Plants in Computer Vision”.

  This research theme is supported by the PIA Phenome.

- *Tracking the growth of maize ear and silks in a high-throughput phenotyping platform using a robot-assisted imaging pipeline* (Simon Artzet, Jerome Chopard, Christian Fournier, Christophe Pradal, Nicolas Brichet [LEPSE, INRA], Llorenç Cabrera-Bosquet [LEPSE, INRA])

  In maize, silks are hundreds of filaments that simultaneously emerge from the ear for collecting pollen over a period of 1–7 days, which largely determines grain number especially under water deficit. Silk growth is a major trait for drought tolerance in maize, but its phenotyping is difficult at throughputs needed for genetic analyses.

  We have developed a reproducible pipeline [31] that follows ear and silk growths every day for hundreds of plants, based on an ear detection algorithm that drives a robotized camera for obtaining detailed images of ears and silks. We first select, among 12 whole plant side views, those best suited for detecting ear position. Images are seg mented, the stem pixels are labelled and the ear position is identified based on changes in width along the stem. A mobile camera is then automatically positioned in real time at 30 cm from the ear, for a detailed picture in which silks are identified based on texture and colour. This allows analysis of the time course of ear and silk growths of thousands of plants. The pipeline was tested on a panel of 60 maize hybrids in the PHENOARCH phenotyping platform. Over 360 plants, ear position was correctly estimated in 86% of cases, before it could be visually assessed. Silk growth rate, estimated on all plants, decreased with time consistent with literature. The pipeline allowed clear identification of the effects of genotypes and water deficit on the rate and duration of silk growth.

  The pipeline presented here, which combines computer vision, machine learning and robotics, provides a powerful tool for large scale genetic analyses of the control of reproductive growth to changes in environ mental conditions in a non invasive and automatized way. It is available as Open Source software in the OpenAlea platform.

- *Review on morphological plant modelling.* (Christophe Pradal, Mathilde Balduzzi, Alexander Bucksch [Georgia Univ., USA], Daniel H. Chitwood [Donald Danforth Plant Science Center, USA], Erin E Sparks [Univ. of Delaware, 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 [8], 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. Never has the need to model plant morphology been more imperative. Unleashing the potential of geometric and topological approaches in the plant sciences promises to transform our understanding of both plants and mathematics.

- *Qualitative and Quantitative Descriptors for Plant Morphology.* (Christophe Pradal, Mathilde Balduzzi, Alexander Bucksch [Georgia Univ., USA], Erin E Sparks [Univ. of Delaware, USA])

  An emerging challenge in plant biology is to develop qualitative and quantitative measures to describe the appearance of plants through the integration of mathematics and biology. A major hurdle in developing these metrics is finding common terminology across fields. In this review, we define approaches for analyzing plant geometry, topology, and shape, and provide examples for how these terms have been and can be applied to plants. In leaf morphological quantifications both geometry and shape have been used to gain insight into leaf function and evolution. For the analysis of cell growth and expansion, we highlight the utility of geometric descriptors for understanding sepal and hypocotyl development. For branched structures, we describe how topology has been applied to quantify root system architecture to lend insight into root function. Lastly, we discuss the importance of using morphological descriptors in ecology to assess how communities interact, function, and respond within different environments. This review [30] aims to provide a basic description of the mathematical principles underlying morphological quantifications.

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. [47], [59], [60], [57], 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" [65], "age state" [56] or "physiological age" [50]. 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 [56], [50]. 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 [21] 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 [20].

- *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. 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). One or several replications of each genotype were available.

  Three families of indices were proposed for early detection of alternation during the juvenile phase. The first family was based on a trend model and a quantification of the deviation amplitudes and dependency, with respect to the trend. The second family was based on a 2nd-order Markov chain with fixed and random effect in transition probabilities. The third family was based on entropy indices, in which flowering probabilities were corrected from fixed effects using Generalized Linear Models.

  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 these indices [43], [35].

  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. Other QTLs are expected to be found using these new indices and genetic material. However, the amount of replicate per genotype and of data per replicate is quite reduced compared to those of our previous work. This is why we will investigate the loss of power in QTL detection due to a degraded amount of data, by simulating data deletion in our reference results.

- *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]).

  Many tropical trees are affected by strong phenological asynchronisms entailing patchiness. 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. Finally, directed acyclic graphs we built for summarizing the succession of patches over time within the canopy. This statistical modeling framework was applied to young mango trees [11].

- *Simulating fruit tree phenology.* (A.S. Briand, Frédéric Boudon, Frédéric Normand [CIRAD, Hort-Sys, Réunion Island], Anaëlle Dambreville, Jean-Baptiste Durand, Pierre Fernique, Yann Guédon, Christophe Pradal, Pierre-Eric Lauri [INRA, System])

  Mango is a tropical tree characterized by strong asynchronisms within and between trees. To study more precisely the interplay between the plant structural components, we built an integrative model to simulate the plant development based on the L-system formalism and GLM to model the dependencies between events. With such model, we showed the importance of architectural and temporal factors in the development of the units of the trees, see 1 . The model also simulates the phenology of shoots and inflorescences. For this, the sizes of the different organs is modelled by statistical laws estimated from measurements that depends on their locations in the architecture. The growth speed of organs is modulated by the temperature. The model has been then coupled with an ecophysiological model of fruit growth [62], [63]. The global aim is to have a crop simulation model to predict fruit yield and quality on mango tree.

Figure 1. Simulation of the development of a mango tree over two cycles [52]. 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.

  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 various 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 [19]. A multivariate generalization of the synchronous segmentation approach was developed in the context of Marc Labadie's PhD [14], 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 [13], 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 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 [4].

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], David Claessens [ENS ULM, Paris], 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. Following the PhD of Guillaume Garin, we finalised a sensitivity analysis of the response of the severity of septoria to architectural traits, and an analysis of the influence of the wheat architecture on the competition between septoria and brown rust. These studies allowed 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], THierry Simmoneau [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 [1], 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), Yves Caraglio, 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 three-scale growth pattern with (i) at coarse scale, roughly stationary growth phases with phase changes often corresponding to cold seasons (ii) at intermediate scale, some growth fluctuations corresponding to the influence of the climatic factors (mainly temperature and cumulated rainfall) 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 a pipeline of statistical models that incorporates specific multiple change-point models (piecewise 1st-order stationary autoregressive models) for characterizing this three-scale growth pattern.

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 [10] 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.

We finalized 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). To our knowledge, it is the first time that such high-resolution 4D digital tissues have been generated taking into account the cell shapes.

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. A paper describing the whole approach has been submitted in December 2017.

- *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 [55]. 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 [54].

  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.*
  Participants: Sophie Ribes, Yassin Refahi [RDP, ENS, Sainsbury Lab], Guillaume Cerutti, Christophe Godin, Christophe Pradal, Frédéric Boudon, Gregoire Malandain [RDP, ENS], Gaël Michelin [RDP, ENS], Jan Traas [RDP, ENS], Teva Vernoux [RDP, ENS], Patrick Lemaire [CRBM, CNRS].

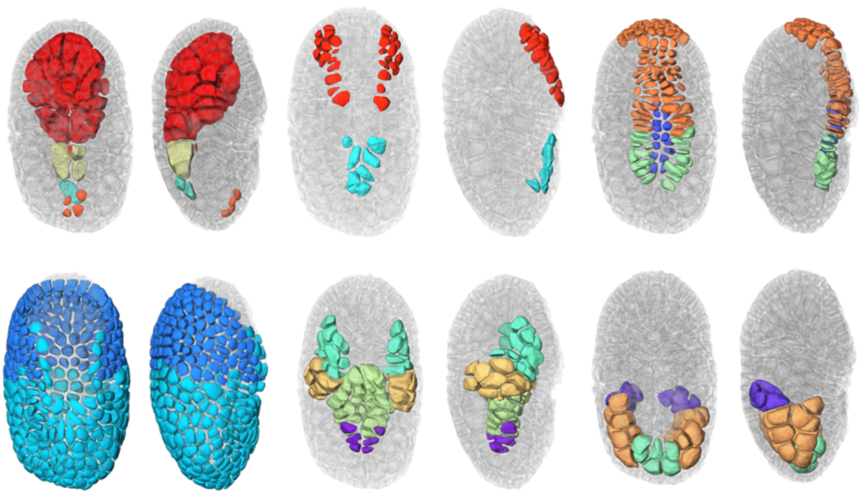


Figure 2. 3D projection of the segmented embryo at the early tailbud stage. The cells are colored by tissue type. The cells are slightly roded to allow their distinction. The other cells of the embryo are in transparent grey. The doral and lateral sides are shown.

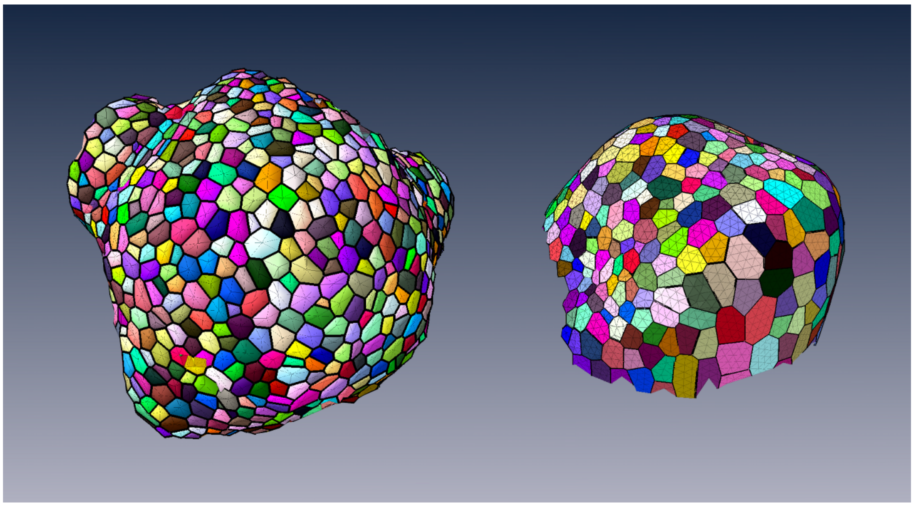


Figure 3. Triangular mesh representations of shoot apical meristem and flower meristem tissues obtained from MARS segmentations

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 [61]. 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 (a manuscript is in preparation).

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: Olivier Ali, Hadrien Oliveri, Christophe Godin, Jan Traas [ENS-Lyon].

This research theme was supported, between 2012 and 2017, by the Inria Project Lab Morphogenetics and Jan Traas's ERC.

During the previous years, we set up a multi-scale 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) with sub-cellular resolution, a detailed description of the core elements of this modelling approach has been developped in our previous reports. The aim of this project is to provide a computational framework for simulating growth of multicellular plant tissue. Several papers (and a reivew) have been published over the past few years on this work, in close collaboration with biologists: [51], [3], [26], [2].

Last year, 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 is currently under submission in a high impact factor journal.

Two years ago, 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 (tensor formalism to quantify cell polarity, ...). Ever since, Hadrien Oliveri has been studying the influence of this feedback loop on the morphogenesis of an epithelium. FEM-based simulations have been carried out on simple structures as proof of concept. This first step of the work is currently being submitted. This year, we also started to study the influence of such a mechanical-based feedback mechanism on the morphogenesis of real tissues. The specific question we want to investigate concerns flatness: How can plants produce flat organs such as leaves of sepals ? We investigate this question in the context of the sepal formation, always in close collaboration with biologists doing experiments on the very same topic.

This year, we also started in investigate to a quantitative manner the mechanical influence of inner tissues in the morphogenesis process. Indeed, up to now, our modelling approach was focused on the mechanics of the epidermis, known to be the main load-bearing layer. However, new experimental evidence suggest that inner tissues may influence and/or trigger morphogenesis processess. In order to investigate such mechanisms, our strategy relies on the use of high quality digitized tissues in 3D. Such structures, composed of triangular meshes, are produced through a workflow based on the updated version of the MARS pipeline and the DRACO-STEM module, developped within the team. Currently, numerical simulations are being carried out to analyse the mechanical equilibrium of the structures loaded with pressurized forces, see 4 . Preliminary results tend to confirm the leading mechanical role of the epidermis. Interestingly, sharp differences in the mechanical characteristics emerge between epidermal cells and inner ones.

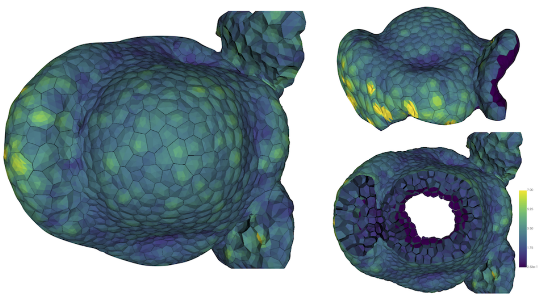


Figure 4. Heatmap of the stress tensor amplitude in a digitalized flowerbud.

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. Gene regulatory networks: Design of a genetic model of inflorescence development.

Participants: Eugenio Azpeitia, Christophe Godin, François Parcy, Etienne Farcot.

This research theme is supported by the Inria Project Lab Morphogenetics.

Modeling gene activities within cells is of primary importance since cell identities correspond to stable combination of gene expression. We studied the regulatory network that controls the flowering transition during morphogenesis. To overcome the network complexity and integrate this regulation during ontogenesis, we have developed a first model of the control of floral initiation by genes, and in particular the situation of cauliflower mutants, in which the meristem repeatedly fails in making a complete transition to the flower. The network was validated by multiple analyses, including sensibility analyses, stable state analysis, mutant analysis, among others. Once the network was validated, it was coupled with an architectural model of plant development using L-systems. The coupled model was used to study how does changes in gene dynamics and expression could change the architectural properties of plants and produce cauliflowers instead of flowers. Finally, the architectural model without the network was used to study how changes in certain parameters could generate different curd morphologies, including the normal cauliflower and the romanesco one.

We have three main types of predictions. (1) How does gene expression is modified from WT to cauliflower organisms. (2) How gene regulate plants shape in order to produce curds instead of flowers. (3) The main parameter regulating curds shapes. The predictions made using the model are currently being experimentally tested. All our results could provide a comprehensive understanding of how does genes and plant architecture are linked in a dynamical way.

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.

Our approach consists of building a programmable tissue which is able to accept different modeling components. This includes a central data structure representing the tissue in either 2-D or 3-D, which is able to grow in time, models of gene activity and regulation, models of signal exchange (physical and chemical) between cells and models of cell cycle (which includes cell division). An introduction to the modeling of some main components of such integrated system was published as a book chapter in the series of Ecole de Physique des Houches [12]. For each modeling component, one or several approaches are investigated in depth, possibly at different temporal and spatial scales, using the data available from the partners (imaging, gene networks, and expression patterns). Approaches are compared and assessed on the same data. The objective of each submodel component will be to provide plugin components, corresponding to simplified versions of their models if necessary, that can be injected in the programmable tissue platform. This work is developed in collaboration with the RDP group at ENS-Lyon [64] and the CPIB group in Nottingham, UK [49].

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. Functional-Structural Root System Models in the Context of Drought Tolerance Breeding

Participants: Mikaël Lucas [IRD], Christophe Pradal.

This research theme is supported by a PhD program at IRD.

In this work, we study the impact of hydraulic architecture on water fluxes, and we review the conception and use of functional-structural root models in the broader context of research on root-driven drought tolerance, on the basis of root system architecture (RSA) phenotyping [40]. Such models result from the integration of architectural, physiological and environmental data. Here, we consider the different phenotyping techniques allowing for root architectural and physiological study and their limits. We discuss how QTL and breeding studies support the manipulation of RSA as a way to improve drought resistance. We then go over the integration of the generated data within architectural models, how those architectural models can be coupled with functional hydraulic models, and how functional parameters can be measured to feed those models. We then consider the assessment and validation of those hydraulic models through confrontation of simulations to experimentations. Finally, we discuss the up and coming challenges facing root systems functional-structural modeling approaches in the context of breeding.

6.3.3. 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 with a modelling of growth at cell level, as described above.

As a first step in this direction, we have developed a bidimensional multicellular model that couples, on the one hand, water fluxes between cells (symplastic pathway) and between cells and intercellular space (apoplastic pathway), and on the other hand, mechanical properties of the cell walls and mechanical equilibrium of this complex system. Existing multicellular models for plant growth overlook this coupling. From a mathematical point of view, it corresponds to a coupling between (1) the ordinary differential equations that describe fluxes and cell walls properties and (2) the highly non linear system of equations that describes the mechanical equilibrium of the cell walls.

We have developed a numerical method for this coupled system, that allows to simulate in a reasonable amount of time a hundred of connected cells. Numerical simulations exhibit a highly non linear behaviour with respect to the governing parameters. Thanks to the detailed analysis of a simplified setup, we have identified two clearly distinct growth regimes: one regime that allows large growth heterogeneities by amplifying the effect of differences between cells, and conversely another regime that smoothes differences out and yields a homogeneous growth. On the biological level, the first regime is well adapted to morphogenesis, whereas the second one is well adapted to homothetic growth after the differentiated tissues have been created. A publication of these completely new results is in preparation.

We have developped a collaboration with biophysicists in RDP laboratory in Lyon (Arezki Boudaoud and Yuchen Long) in order to compare the results of this model to experiments at the microscopic scale of the meristem. A publication is in preparation.

In the longer term, we plan extend this model to the larger scale of tissues and organs in order to model fruit growth.

6.3.4. 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 was 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 [17].
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 using variable-order Markov chains.

This pipeline of analysis methods was applied to different species (maize, Pearl millet [18]) with contrasting biological objectives (study of genetic diversity for Pearl millet and of metabolic and hormonal controls of morphogenesis for maize).

6.3.5. 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

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].

This research theme has been supported by IBC.

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 [42] 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 the Life Science with Scientific workflows

Participants: Christophe Pradal, Sarah Cohen-Boulakia, Jerome Chopard.

This research theme has been supported by IBC and the GDR MADICS/ReproVirtuFlow.

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 7.2.5.3 , we study how scientific workflows can help to improve the reproducibility of computational experiment in the domain of life science [34]. 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, Pierre Fernique, 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 [41].

6.4.4. Lossy compression of tree structures

Participants: Christophe Godin, Romain Azaïs, Jean-Baptiste Durand, Alain Jean-Marie.

In in [13], 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 [48] 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 [13] 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 [4].

6.4.5. Version climber

Participants: Christophe Padal, Dennis Shasha, Sarah Cohen-Boulakia, Patrick Valduriez.

This research has been supported by the Inria International Chair of Dennis Shasha.

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.

6.4.6. Automatic generation of python bindings for C++ libraries

Participants: Pierre Fernique, Christophe Padal.

This research has been supported by the Inria ADT SCOOP

Most of Python and R scientific packages incorporate compiled scientific libraries to speed up the code and reuse legacy libraries. While several semi-automatic solutions exist to wrap these compiled libraries, the process of wrapping a large library is cumbersome and time consuming. In this paper, we introduce AutoWIG, a Python package that wraps automatically compiled libraries into high-level languages using LLVM/Clang technologies and the Mako templating engine. Our approach [46] is automatic, extensible, and applies to complex C++ libraries, composed of thousands of classes or incorporating modern meta-programming constructs.

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 and Yoann Bertrand, SPARKS, I3S, in the context of the PadDOC FUI project. Last year 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 was based on: (1) the transposal of Nielsen's heuristics and of Scapin and Bastien's ergonomic criteria to the control of personal data ; (2) the user centering of the Privacy-by-Design notion of integrated privacy; and (3) the integration of Altman's interaction approach to privacy. This year we evaluated the heuristics and the procedure by asking security specialists and HCI ergonomists to apply them to the designed PadDOC user interfaces. A not yet published report sets out the results of this evaluation together with the heuristics and the procedure.

7.1.2. 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 Raphaël Troncy (EURECOM). Our method takes into account users' exploratory search (ES) behavior and is based on a cognitive model of an ES task. We work on two applications: Discovery Hub (Wimmics project – Inria) and 3cixty (EURECOM project). During the second year of PhD, we analyzed several models of information seeking process and we compared them with our own grid of the typical characteristics of ES activities [41].

We used Ellis' model of Information Seeking as a basis for the elaboration of our model of ES process: we modified it to better suit the ES characteristics. We evaluated our model by comparing it to video records of three ES sessions on Discovery Hub [0]: we wrote down the different chains of the different model's features used by the users in their ES session. For the three records, we were able to identify the features of our model. From this analysis, we conclude that our model of ES can express the users' activity during an ES task. In this evaluation of our model, we also identified and listed the possible transitions between the model's features. These transitions do not reflect all the possible transitions in an ES session, but they express ES behaviors that all ES systems should facilitate. Based on the ES model's features and the possible transitions between them, we designed two different evaluation and design methods of ES systems which do not involve necessarily users:

- Without users: Heuristics of ES and a procedure that explains how to use them. These heuristics are principles for the interaction design. The Heuristics of ES can be used several time along the design process of the ES system (in the design and evaluation phases).
- With users: a guide for the elaboration of a customizable test protocol. The goal of the test is to analyze ES session records in order to find the model's features. In this guide, we give indications to customize the protocol and prepare users tests (e.g. the users selection). Then, we also explain how to analyze the ES sessions recorded.

We are currently testing the heuristics and the test protocol.

[0] http://discoveryhub.co/

7.1.3. User-centered Redesign of a User Interface Allowing to Remotely Control the AZKAR Robot

Participants: Thierry Bergeron, Alain Giboin, Michel Buffa.

In the context of the AZKAR project, we redesigned, with a user-centered method, the user interface allowing to remotely control the AZKAR robot. The original user interface was dedicated to the developer of the Web-RTC [0] aspects of the solution. The new interface is dedicated to end-users such as distant visitors of a museum who remotely control the robot installed in the museum.

7.1.4. Needs Analysis of the Target Users of the WASABI musical search platform

Participants: Alain Giboin, Isabelle Mirbel, Michel Buffa, Elmahdi Korfed.

In the context of the ANR project WASABI, we started an analysis of the needs of the target users of the future WASABI platform. We began with composers and musical content broadcasters. We will continue with musicologists, journalists, and sound engineers.

7.1.5. From User Goals to Process-Based Service Compositions

Participant: Isabelle Mirbel.

Complex user's needs often require heterogeneous services to be combined together. In this work, we explore a novel approach to enable flexible and dynamic composition of heterogeneous services for end users who are usually not familiar with technical process models. End-users are only required to model their goals and semantic reasoning is used for the composition itself. The possible service compositions are expressed in BPMN [0] in order to be then processed by a BPMN engine. Since the composition is built on-the-fly, this approach avoids static linking of services and therefore is much more flexible. The results of this research have been published in [39].

7.2. Communities and Social Interactions Analysis

7.2.1. Semantic Web for B2B Applications

Participants: Molka Dhouib, Catherine Faron Zucker, Andrea Tettamanzi.

This CIFRE PhD thesis is in collaboration with Silex France company, a startup that connects companies and service providers that are best suited to meet their needs through a sourcing Web service. In this thesis, we will be interested on the semantic side of the plateform in order to represent a social network of service providers and companies and recommend automatically a service provider that matches companies needs. In this thesis, we focus on three research axis: (i) Modeling of skills and activity sectors and information extraction from unstructured texts; (ii) How to match companies needs and service providers descriptions; (iii) Recommendation of service providers by reasoning on the social network.

We developed a SKOS [0] thesaurus of skills and activity sectors with the aim of semantically annotating B2B service offers, automatically categorizing them and matching them with service requests.

7.3. Vocabularies, Semantic Web and Linked Data based Knowledge Representation

7.3.1. Semantic Web for Biodiversity

Participants: Franck Michel, Catherine Faron Zucker.

[0] Real Time Communication
[0] Business Process Model and Notation
[0] Simple Knowledge Organization System, W3C recommandation.

As a continuation of the work initiated with the *Muséum National d'Histoire Naturelle* of Paris during the last two years, we have proposed a model to represent taxonomic and nomenclatural information as Linked Data, and we published the french taxonomic register on the Web along this model [0]. Furthermore, we are now leveraging this work to develop an activity related to biodiversity data sharing and integration: we presented the model and dataset in a workshop of the ISWC conference [38] as well as at the TDWG conference on biodiversity information standards [37]. We are in the process of publishing this data set on AgroPortal [0], the bioportal-based ontology repository for agronomy and agriculture. We are involved in the Bioschemas.org W3C community group with the objective of fostering the definition and adoption of common biodiversity-related markup.

7.3.2. RDF Modelization of Education Resources

Participants: Geraud Fokou Pelap, Catherine Faron Zucker, Fabien Gandon, Olivier Corby.

EduMICS (Educative Models Interactions Communities with Semantics) is a joint laboratory (LabCom, 2016-2018) between the Wimmics team and the Educlever company. Adaptive Learning, Social Learning and Linked Open Data and links between them are at the core of this LabCom. The purpose of EduMICS is both to develop research and technologies with the ultimate goal to adapt educational progressions and pedagogical resource recommendation to learner profiles.

This year, we propose a novel RDF modelisation for Educlever's Data. Once this novel modelisation have been validated, we built a migration tool to migrate Educlever data from the old model into the new one. We also performed benchmarking of the new model with Educlever's uses cases queries. In order to perform this benchmark we store RDF data in four triplestore, Corese, Allegrograph, GraphDB and Virtuoso. Next steps of the project are: perform test in real exploitation environnement, find a way to use graph database in RDF context and how to perform reasonning to recommend and adapt activities to learn. Topics covered by EduMICS include: ontology-based modeling of educational resources; ontology-based integration of heterogenous data sources; ontology-based reasoning; semantic analysis of a social network of learners; pedagogical resource recommendation adpated to learner profiles.

7.3.3. Intelliquiz Project

Participants: Oscar Rodríguez Rocha, Catherine Faron Zucker.

Intelliquiz is a research project carried out in collaboration with Qwant. The main goal of this project is to create a smart quiz game engine, able to:

1. generate credible alternative answers from a given set of questions and answers,
2. generate a multiple choice questions game based on specific subjects (initially by exploiting the non-structured dataset of the famous French multiple choice questions game "Les Incollables"),
3. generate a set of multiple choice questions and answers (quiz) about a specific subject, to be proposed to a user (a learner / player)
4. adapt the resulting quiz to the user's profile, context and past experience,
5. set up the fundamentals of an intelligent platform for education.

This work was published at EDULEARN [32].

7.3.4. Reconciling DBpedia Chapters

Participants: Serena Villata, Elena Cabrio, Fabien Gandon.

[0] http://taxref.mnhn.fr/lod/Dataset/10.0/
[0] http://agroportal.lirmm.fr/

Together with Alessio Palmero Aprosio (FBK, Italy), we addressed the issue of reconciling information obtained by querying the SPARQL endpoints of language-specific DBpedia chapters. DBpedia is a RDF triple store whose content is automatically created by extracting information from Wikipedia. Starting from a categorization of the possible relations among the resulting instances, we provide a framework to: (i) classify such relations, (ii) reconcile information using argumentation theory, (iii) rank the alternative results depending on the confidence of the source in case of inconsistencies, and (iv) explain the reasons underlying the proposed ranking. We release the resource obtained applying our framework to a set of language-specific DBpedia chapters, and integrate such framework in the Question Answering system QAKiS, that exploits such chapters as RDF datasets to be queried using a natural language interface. The results of this research have been published in the Semantic Web Journal [25].

7.3.5. Ontological Representation of Normative Requirements

Participants: Serena Villata, Elena Cabrio, Fabien Gandon.

Together with Guido Governatori (Data61, Australia), we have proposed a proof of concept for the ontological representation of normative requirements as Linked Data on the Web. Starting from the LegalRuleML ontology, we present an extension of this ontology to model normative requirements and rules. Furthermore, we define an operational formalization of the deontic reasoning over these concepts on top of the Semantic Web languages. The results of this research have been published at the JURIX 2017 conference [52].

7.3.6. LDScript Linked Data Script Language

Participants: Olivier Corby, Catherine Faron Zucker, Fabien Gandon.

LDScript is a script language for the Semantic Web of Linked Data built on top of SPARQL filter language. It enables users to define extension functions for SPARQL queries in a language that is highly compatible with SPARQL. This year we generalized and uniformized the design of the language with query in function, second order functions (map, funcall, apply, reduce), lambda expressions, *return* statement, method call. We also introduced literal extension datatypes to manage list, triple, graph and query solution mapping as RDF extended literals. This work was published at ISWC and listed as *spotlight paper* in the conference program [32].

7.3.7. SHACL Validator

Participant: Olivier Corby.

In the context of the SHACL W3C working group to design a Shapes Constraint Language for validating RDF graphs, we have written a SHACL validator using two languages developed in the team: STTL, SPARQL Template Transformation Language, and LDScript. An online demo server have been set up [0].

7.3.8. HAL Open Data

Participant: Olivier Corby.

The HAL open archive is provided with an Open Data SPARQL endpoint [0]. We participated, with CNRS CCSD team [0], to the design of the RDF Schema of the open data server and we developed a Linked Data Hypertext Navigator [0] on top of the HAL open data server.

7.3.9. Graph Database for the Semantic Web

Participants: Erwan Demairy, Olivier Corby.

[0] http://corese.inria.fr
[0] http://data.archives-ouvertes.fr/sparql
[0] Center for Direct Scientific Communication
[0] http://corese.inria.fr

In the context of an Inria two years grant, we conducted in collaboration with Johan Montagnat (I3S, CNRS) a study of graph databases (Orient DB, Titan DB, Neo4j) and of the TinkerPop abstract query language. The purpose of this study was to design a mapping between RDF statements and graph databases and conversely. In addition, we designed a mapping of SPARQL query patterns to TinkerPop. We have implemented with Corese a binding of a generic SPARQL interpreter on top of TinkerPop that enables us to query a RDF oriented graph database with SPARQL.

7.3.10. Mobile Linked Data Sharing in Technologically Constrained Environment

Participants: Fabien Gandon, Mahamadou Toure.

During the second year of the MoReWAIS project we finalized the state of the art report [61]. In addition to the initial points of the survey, namely caching of client-side data and cache federation, querying and sharing of data, Linked Open Data and data privacy, we have identified and added an important point for this state of the art, which is the domain of collaborative RDF graph modification. This last point raises the question of identifying the mechanisms proposed in the literature that make it possible to solve the constraints related to the availability, the processing loads balance and sources and data reliability in decentralized peer-to-peer architectures. These mechanisms make it possible to replicate, share and collaboratively modify a graph. We also worked on an architecture model (network and data) and opted for a three-tier architecture with a data model based essentially on graph replication and cooperative caching.

7.4. Analyzing and Reasoning on Heterogeneous Semantic Graphs

7.4.1. Distributed Artificial Intelligence for Linked Reviewable Data Management on the Semantic Web

Participants: Ahmed El Amine Djebri, Andrea Tettamanzi.

The aim of this PhD thesis that started this year is to study and to propose original solutions to many key aspects: Knowledge Representation in case of uncertain, incomplete and reviewable data; Uncertainty Representation in a data source, with provenance; Distributed Knowledge Revision and Propagation; Reasoning over Uncertain, Incomplete and distributed data-sources. Starting from an open Web of Data, this work tries to give the users more objective, exhaustive and certain views and information about their queries, based on distributed data sources with different levels of certainty and trustworthiness.

7.4.2. Uncertainty Management

Participant: Andrea Tettamanzi.

In collaboration with Didier Dubois and Henri Prade of IRIT, Toulouse, and Giovanni Fusco, a geographer of the ESPACE CNRS UNS laboratory, we have developed a theory of uncertain logical gates in possibilistic networks and we have illustrated their application on a problem of human geography [17].

With Giovanni Fusco, we have approached the problem of selecting among various models of a phenomenon, in the form of Bayesian networks, and we have illustrated our solution by applying it to the case of urban sprawl [35].

Finally, together with Didier Dubois and Henri Prade of IRIT, Toulouse, and Célia da Costa Pereira of I3S, we have proposed a possibilistic approach to handle topical metadata about the validity and completeness of information coming from multiple source, with the aim of aggregating it in a possibilistic belief base [45].

7.4.3. Mining the Semantic Web for OWL Axioms

Participants: Thu Huong Nguyen, Andrea Tettamanzi.

The aim of the research in this PhD thesis is to learn OWL2 ontologies from RDF data in an open world. The first task is the extraction of axioms based ontology learning techniques using the evolutionary algorithm. Then, developing the methods for OWL axioms evaluation. In the half of the year, research work has been concentrated on the Grammatical Evolution algorithm to explore the set of disjointed classes axioms in search for the ones that are best suited to describe the recorded RDF data.

7.4.4. Logical Foundations of Cognitive Agents

Participant: Andrea Tettamanzi.

Together with Célia da Costa Pereira of I3S, Beishui Liao of Zheijiang University, China, Alessandra Malerba and Antonino Rotolo of the University of Bologna, Italy, and Leendert van der Torre of the University of Luxenbourg we have proposed a computational model for legal interpretation based on fuzzy logic and argumentation, which has been presented at the 16th International Conference on Artificial Intelligence and Law [46].

7.4.5. Agent-Based Recommender Systems

Participants: Amel Ben Othmane, Nhan Le Thanh, Andrea Tettamanzi, Serena Villata.

We have proposed a spatio-temporal extension for our multi-context framework for agent-based recommender systems (CARS) [27], to which we have then added representation and algorithms to manage uncertainty, imprecision, and approximate reasoning: a paper describing this latter development has been accepted at the 10th International Conference on Agents and Artificial Intelligence (ICAART 2018), which will be held in Madeira on January 16–18, 2018.

7.4.6. RDF Mining

Participants: Catherine Faron Zucker, Fabien Gandon, Andrea Tettamanzi, Tran Duc Minh.

In collaboration with Claudia d'Amato of the University of Bari, we have carried on our investigation about extracting knowledge from RDF data, by refining our evolutionary approach to discover multi-relational rules from ontological knowledge bases exploiting the services of an OWL reasoner [42], which we have called EDMAR. In addition, we have finally developed a coherent and organic theory of possibilistic testing of OWL axioms against RDF data [22]. The intuition behind it is to evaluate the credibility of OWL 2 axioms based on the evidence available in the form of a set of facts contained in a chosen RDF dataset.

7.4.7. Argument Mining

Participants: Serena Villata, Elena Cabrio, Fabien Gandon, Mihai Dusmanu.

We have presented an argument mining approach which applies supervised classification to identify arguments on Twitter. Moreover, we present two new tasks for argument mining, namely facts recognition and source identification. We study the feasibility of the approaches proposed to address these tasks on a set of tweets related to the Grexit and Brexit news topics. The results of this research have been published at the EMNLP 2017 conference [51].

In this direction, we have also, in collaboration with the Heron Lab of the University of Montreal, presented an empirical study about the impact of emotions and mental states on the argumentation people address in online debates. The results of this research have been published on the Argument & Computation Journal [24]. Another empirical experiment with humans has been addressed to study the impact of the three persuasive argumentation strategies called Ethos, Logos and Pathos, on the emotions and mental states of debaters. The results of this research have been published at the HCI 2017 conference [28].

Moreover, Serena Villata has co-authored a vulgarization paper for the AI Magazine, about computational argumentation [16].

Finally, Serena Villata, together with Matthias Thimm (Universitat Koblenz-Landau), has reported and analyzed the results of the first Computational Argumentation Challenge (ICCMA) in a Artificial Intelligence Journal [23].

7.4.8. Mining Legal Documents

Participants: Serena Villata, Cristian Cardellino, Milagro Teruel, Laura Alonso Alemany.

We have proposed a Named Entity Recognizer, Classifier and Linker for the legal domain. More precisely, we try to improve Information Extraction in legal texts by creating a legal Named Entity Recognizer, Classifier and Linker. With this tool, it is possible to identify relevant parts of texts and connect them to a structured knowledge representation, the LKIF ontology. This tool has been developed with relatively little effort, by mapping the LKIF ontology to the YAGO ontology and through it, taking advantage of the mentions of entities in Wikipedia. These mentions are used as manually annotated examples to train the Named Entity Recognizer, Classifier and Linker. We have evaluated the approach on holdout texts from Wikipedia and also on a small sample of judgments of the European Court of Human Rights, resulting in a very good performance, i.e., around 80% F-measure for different levels of granularity. The results of this research have been published at the EACL 2017 conference [30], the FLAIRS 2017 conference [29], and the ICAIL 2017 conference [31], A poster paper has been published at ISWC 2017 [64]. This research is addressed in the context of the EU H2020 MIREL project. The ICAIL paper has been awarded as “Best Innovative Paper” of the conference.

7.4.9. Cognitive Agent-Based Modeling

Participant: Andrea Tettamanzi.

Within the framework of the multi-disciplinary Franco-Colombian TOMSA research project, in collaboration with researchers of the I3S and ESPACE CNRS UNS laboratory and of the University of the Andes, we have developed a novel agent-based modeling approach based on belief-desire-intention (BDI) agents and we have demonstrated its potential by applying it to the coupled modeling of urban segregation and growth [43].

7.4.10. Robots Autonomously Learning about Objects

Participants: Valerio Basile, Elena Cabrio, Roque Lopez Condori.

Autonomous robots that are to assist humans in their daily lives must recognize and understand the meaning of objects in their environment. However, the open nature of the world means robots must be able to learn and extend their knowledge about previously unknown objects on-line. In this third year of the project, we have investigated the problem of unknown object hypotheses generation, and employed a semantic Web-mining framework along with deep-learning-based object detectors. This allows us to make use of both visual and semantic features in combined hypotheses generation. We have experimented on data from mobile robots in real world application deployments, showing that this combination improves performance over the use of the methods in isolation.

Moreover, we have built DeKO, a large-scale RDF repository of prototypical knowledge about objects [0]. This version of DeKO provides, mainly, information about locations and typical usage of objects (e.g. Telephone LocatedAt Office, Spoon usedFor Eating). In addition, DeKO also provides an RDF explorer where users can find knowledge about objects navigating through their relations. DeKO was built by parsing natural language text with KNEWS [67] and using Distributional Semantics [68].

Frame clustering is an important module inside DeKO, since it could allow us to find representative frame instances, i.e. prototypical knowledge about objects. For frame clustering in DeKO, we followed a hierarchical clustering approach motivated mainly by two reasons: i) it does not require a pre-specified number of clusters and ii) most of these algorithms are deterministic. However, hierarchical clustering is expensive in terms of time, making it too slow for large data sets. In order to solve this problem, we applied a parallelization strategy using a map-reduce approach together with some heuristics in the preprocessing phase (e.g. filtering of frame instances). Currently, we are setting the server environments to perform the experiments over all the collection of DeKO. The following paper have been published on the topic: [44].

7.4.11. Event Identification and Classification in Short Messages

Participants: Amosse Edouard, Elena Cabrio, Nhan Le Thanh.

[0] http://deko.inria.fr/

This work investigates the potential of exploiting information from the Linked Open Data KBs to detect, classify and track events on social media, in particular Twitter. More specifically, we address 3 research questions: i) How to extract and classify messages related to events? ii) How to cluster events into fine-grained categories? and 3) Given an event, to what extent user-generated contents on social medias can contribute in the creation of a timeline of sub-events? We provide methods that rely on Linked Open Data KBs to enrich the context of social media content; we show that supervised models can achieve good generalisation capabilities through semantic linking, thus mitigating overfitting; we rely on graph theory to model the relationships between named entities and the other terms in tweets in order to cluster fine-grained events. Finally, we use domain ontologies and local gazetteers to identify relationships between actors involved in the same event, to create a timeline of sub-events. We show that enriching the named entities in the text with information provided by LOD KBs improves the performance of both supervised and unsupervised machine learning models.

The following papers have been published on the topic: [33], [34], [18].

7.4.12. NLP over Song Lyrics

Participants: Michael Fell, Elena Cabrio, Fabien Gandon.

The goal of the WASABI project is to jointly use information extraction algorithms and the Semantic Web formalisms to produce consistent musical knowledge bases. Then, Web Audio technologies are applied to explore them in depth. More specifically, textual data such as song lyrics or free text related to the songs will be used as sources to extract implicit data (such as the topics of the song, the places, people, events, dates involved, or even the conveyed emotions) using Natural Language Processing (NLP) algorithms. Jointly exploiting such knowledge, together with information contained in the audio signal, can improve the automatic extraction of musical information, including for instance the tempo, the presence and characterization of the voice, musical emotions, identify plagiarism, or even facilitate the music unmixing.

Work in the first half year has been focused on two points. First, we delivered a report on the existing literature on NLP of song lyrics. Second, our endeavors of the last months are research on the estimation of the structure of song texts.

The following paper has been published on the topic: [55].

7.4.13. 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 are 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. 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 customer advisers to focus on more difficult questions.

We considered the different questions from customers as a multi-label unbalanced classification problem. In order to improve the results of the categorization, we were interested in increasing vectors with domain specific knowledge and named entities, then by reducing these vectors with feature selection. Also, we look after the tuning of hyperparameters with Bayesian optimization.

7.4.14. HealthPredict

Participants: David Darmon, Catherine Faron Zucker, Virginie Lacroix-Hugues, Fabien Gandon, Raphaël Gazzotti.

This project is performed in collaboration with the Département d'Enseignement de Recherche en Médecine Générale (DERMG) at UNS and SynchroNext, a company located in Nice. HealthPredict is a digital health solution aimed at the early management of patients through consultation with their general practitioner and healthcare circuit. Concretely, it is a predictive artificial intelligence interface that allows to cross the data of symptoms, diagnosis and medical treatments of the population in real time to make a more accurate prognosis, choose a more adapted treatment and reduce side effects.

ZENITH Project-Team

7. New Results

7.1. Data Management

7.1.1. Top-k Query Processing Over Encrypted Data in Clouds

Participants: Sakina Mahboubi, Reza Akbarinia, Patrick Valduriez.

Cloud data outsourcing provides users and companies with powerful capabilities to store and process their data in third-party data centers. However, the privacy of the outsourced data is not guaranteed by the cloud providers. One solution for protecting the user data against security attacks is to encrypt the data before being sent to the cloud servers. Then, the main problem is to evaluate user queries over the encrypted data.

In [41], we address the problem of top-k query processing over encrypted data, and propose an efficient approach called BuckTop. Our approach uses the bucketization technique to manage the encrypted data in the remote server. It includes a top-k query processing algorithm that works on the encrypted data of the buckets, and returns a set that contains the encrypted top-k results. It also has a filtering algorithm that efficiently eliminates the false positives in the server side. We implemented BuckTop, and compared its response time for processing top-k queries over encrypted data with that of the TA algorithm over original (plaintext) data. Our results show excellent performance gains. They show that the response time of BuckTop over encrypted data is close to TA over plaintext data.

7.1.2. End-to-end Graph Mapper

Participants: Benjamin Billet, Didier Parigot, Patrick Valduriez.

The growth of linked data in web and mobile applications motivates software developers to model their business data as graphs, enabling them to leverage the capabilities of various graph databases. Going one step further, we introduce an End-to-end Graph Mapper (EGM) [22], for modeling the whole application as (i) a set of graphs representing the business data, the in-memory data structure maintained by the application and the user interface (tree of graphical components), and (ii) a set of standardized mapping operators that maps these graphs with each other. As a benefit, the application becomes a complex live query over multiple graph databases, making the development process simpler and safer, thanks to the automation of repetitive development tasks. This work has been done in collaboration with Beepeers (http://www.beepeers.com), a startup that develops and markets social network mobile applications for small communities in the context of the Triton I-lab.

7.1.3. Management of Simulation Data

Participants: Vitor Silva, Patrick Valduriez.

In complex simulations, users must track quantities of interest (residuals, errors estimates, etc.) to control as much execution as possible. However, this tracking is typically done only after the simulation ends. We are designing techniques to extract, index and relate strategic simulation data for online queries while simulation is running. We consider coupling these techniques with largely adopted libraries such as libMesh (for numerical solvers) and ParaView (for visualization), so that queries on quantities of interest are enhanced by visualization and provenance data. Interactive data analysis support is planned for post simulation and runtime as in-situ and in-transit, taking advantage of memory access at runtime.

In [21], we propose a solution (architecture and algorithms) to combine the advantages of a dataflow-aware scientific workflow management system (SWfMS) and the raw data file analysis techniques to allow for queries on raw data file elements that are related, but reside in separate files. Armful is the name of the architecture and its main components are a raw data extractor, a provenance gatherer and a query processing interface, which are all dataflow aware. We show ARMFUL instantiated with the Chiron SWfMS.

In [31], we instantiate Armful without the SWfMS, plugging the components directly in the simulation code of highly optimized parallel applications. With support of sophisticated online data analysis, scientists get a detailed view of the execution, providing insights to determine when and how to tune parameters.

We also started investigating the combination of in-transit analysis and visualization, with the development of SAVIME (Scientific Analysis and Visualization In-Memory). The system adopts a multi-dimensional data model TARS (Typed Array Schema) [29] that enables the representation of simulation output data, the topology mesh and simulation metadata. Data produced by the simulation is ingested into the system without any transformation as a Typed Array (TAR). We intend SAVIME to implement an algebra on TARs that enables simulation output analysis and direct production of visualization output.

7.2. Scientific Workflows

7.2.1. 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. Recently, some Scientific Workflow Management Systems (SWfMSs) with provenance support (e.g. Chiron) have been deployed in the cloud. However, they typically use a single cloud site.

In [16], we consider a multisite cloud, where the data and computing resources are distributed at different sites (possibly in different regions). Based on a multisite architecture of SWfMS, i.e. multisite Chiron, and its provenance model, we propose a multisite task scheduling algorithm that considers the time to generate provenance data. We performed an extensive experimental evaluation of our algorithm using Microsoft Azure multisite cloud and two real-life scientific workflows (Buzz and Montage). The results show that our scheduling algorithm is up to 49.6% better than baseline algorithms in terms of total execution time.

In [28], 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.

7.2.2. Parallel Execution of Scientific Workflows in Spark

Participants: Reza Akbarinia, Esther Pacitti.

The success of using workflows for modeling large-scale scientific applications has fostered the research on parallel execution of scientific workflows in shared-nothing clusters, in which large volumes of scientific data may be stored and processed in parallel using ordinary machines. However, most of the current scientific workflow management systems do not handle the memory and data locality appropriately. Apache Spark deals with these issues by chaining activities that should be executed in a specific node, among other optimizations such as the in-memory storage of intermediate data in RDDs (Resilient Distributed Datasets). However, to take advantage of the RDDs, Spark requires existing workflows to be described using its own API, which forces the activities to be reimplemented in Python, Java, Scala or R, and this demands a big effort from the workflow programmers.

In [24], we propose a parallel scientific workflow engine called TARDIS, whose objective is to run existing workflows inside a Spark cluster, using RDDs and smart caching, in a completely transparent way for the user, i.e., without needing to reimplement the workflows in the Spark API. We evaluated our system through experiments and compared its performance with Swift/K. The results show that TARDIS performs better (up to 138% improvement) than Swift/K for parallel scientific workflow execution.

In [32], we evaluate a parameter sweep workflow also in the Oil and Gas domain, this time using Spark to understand its scalability when having to execute legacy black-box code with a DISC system. The source code of the dataflow implementation for Spark is available on github ((github.com/hpcdb/RFA-Spark).

7.3. Data Analytics

7.3.1. Massively Distributed Indexing of Time Series

Participants: Djamel Edine Yagoubi, Reza Akbarinia, Florent Masseglia.

Indexing is crucial for many data mining tasks that rely on efficient and effective similarity query processing. Consequently, indexing large volumes of time series, along with high performance similarity query processing, have became topics of high interest. For many applications across diverse domains though, the amount of data to be processed might be intractable for a single machine, making existing centralized indexing solutions inefficient.

In [42], we propose a parallel indexing solution that scales to billions of time series, and a parallel query processing strategy that, given a batch of queries, efficiently exploits the index. Our experiments, on both synthetic and real world data, illustrate that our index creation algorithm works on 1 billion time series in less than 2 hours, while the state of the art centralized algorithms need more than 5 days. Also, our distributed querying algorithm is able to efficiently process millions of queries over collections of billions of time series, thanks to an effective load balancing mechanism.

In [43], we propose RadiusSketch, a sketch/random projection-based approach that scales nearly linearly in parallel environments, and provides high quality answers. We illustrate the performance of our approach on real and synthetic datasets of up to 1 Terabytes and 500 million time series. The sketch method, as we have implemented, is superior in both quality and response time compared with the state of the art centralized algorithm. In a parallel environment with 32 processors, on both real and synthetic data, our parallel approach improves by a factor of up to 100 in index time construction and up to 15 in query answering time. Finally, our data structure makes use of idle computing time to improve the recall and precision yet further.

7.3.2. 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 [18], 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.

7.3.3. Closed Itemset Mining in Massively Distributed Environments

Participants: Mehdi Zitouni, Reza Akbarinia, Florent Masseglia.

Data analytics in general, and data mining primitives in particular, are a major source of bottlenecks in the operation of information systems. This is mainly due to their high complexity and intensive call to IO operations, particularly in massively distributed environments. Moreover, an important application of data analytics is to discover key insights from the running traces of information system in order to improve their engineering. Mining closed frequent itemsets (CFI) is one of these data mining techniques, associated with great challenges. It allows discovering itemsets with better efficiency and result compactness.

However, discovering such itemsets in massively distributed data poses a number of issues that are not addressed by traditional methods. One solution for dealing with such characteristics is to take advantage of parallel frameworks, e.g. MapReduce. In [33], [44], we address the problem of distributed CFI mining by introducing a new parallel algorithm, called DCIM, which uses a prime number based approach. A key feature of DCIM is the deep combination of data mining properties with the principles of massive data distribution. We carried out exhaustive experiments over real world datasets to illustrate the efficiency of DCIM for large real world datasets with up to 53 million documents.

7.3.4. Optimal Data Placement for Fast Parallel Mining of Frequent Itemsets

Participants: Saber Salah, Reza Akbarinia, Florent Masseglia.

Frequent itemset mining presents one of the fundamental building blocks in data mining. However, despite the crucial recent advances that have been made in data mining literature, few of both standard and improved solutions scale. This is particularly the case when (i) the quantity of data tends to be very large or (ii) the minimum support is very low.

In [19], we address the problem of parallel frequent itemset mining (PFIM) in very large databases, and study the impact and effectiveness of using specific data placement strategies in a massively distributed environment. By offering a clever data placement and an optimal organization of the extraction algorithms, we show that the arrangement of both the data and the different processes can make the global job either completely inoperative or very effective. In this setting, we propose two different highly scalable, PFIM algorithms, namely P2S (Parallel-2-Steps) and PATD (Parallel Absolute Top Down). P2S algorithm allows discovering itemsets from large databases in two simple, yet efficient parallel jobs, while PATD renders the mining process of very large databases more simple and compact. Its mining process is made up of only one parallel job, which dramatically reduces the mining runtime, the communication cost and the energy power consumption overhead in a distributed computational platform. Our different proposed approaches have been extensively evaluated on massive real-world data sets. The experimental results confirm the effectiveness and scalability of our proposals by the important scale-up obtained with very low minimum supports compared to other alternatives.

7.4. Data Search

7.4.1. Adversarial Autoencoders For Novelty Detection

Participants: Valentin Leveau, Alexis Joly.

In this work [40], we addressed the problem of novelty detection, i.e recognizing at test time if a data item comes from the training data distribution or not. We focus on Adversarial autoencoders (AAE) that have the advantage to explicitly control the distribution of the known data in the feature space. We show that when they are trained in a (semi-)supervised way, they provide consistent novelty detection improvements compared to a classical autoencoder. We further improve their performance by introducing an explicit rejection class in the prior distribution coupled with random input images to the autoencoder.

7.4.2. Going deeper in the automated identification of Herbarium specimens

Participants: Alexis Joly, Herve Goeau.

Hundreds of herbarium collections have accumulated a valuable heritage and knowledge of plants over several centuries. Recent initiatives started ambitious preservation plans to digitize this information and make it available to botanists and the general public through web portals. However, thousands of sheets are still unidentified at the species level while numerous sheets should be reviewed and updated following more recent taxonomic knowledge. These annotations and revisions require an unrealistic amount of work for botanists to carry out in a reasonable time. Computer vision and machine learning approaches applied to herbarium sheets are promising but are still not well studied compared to automated species identification from leaf scans or pictures of plants in the field. In this work [14], we proposed to study and evaluate the accuracy with which herbarium images can be potentially exploited for species identification with deep learning technology. In addition, we proposed to study if the combination of herbarium sheets with photos of plants in the field is relevant in terms of accuracy, and finally, we explore if herbarium images from one region that has one specific flora can be used to do transfer learning to another region with other species; for example, on a region under-represented in terms of collected data. This is, to our knowledge, the first study that uses deep learning to analyze a big dataset with thousands of species from herbaria. Results show the potential of Deep Learning on herbarium species identification, particularly by training and testing across different datasets from different herbaria. This could potentially lead to the creation of a semi, or even fully automated system to help taxonomists and experts with their annotation, classification, and revision works.

7.4.3. Crowdsourcing Thousands of Specialized Labels: a Bayesian active training approach

Participants: Maximilien Servajean, Alexis Joly, Dennis Shasha, Julien Champ, Esther Pacitti.

The use of crowdsourced and more generally user-generated annotations became the de facto methodology for building training data in a variety of data indexing and search tasks. When the labels correspond to well known or easy-to-learn concepts, it is straightforward to train the annotators by giving a few examples with known answers. Neither is true when there are thousands of complex domain specific labels. In this work, we focused on the particular case of crowdsourcing domain-specific annotations that usually require hard expert knowledge (such as plant species names, architectural styles, medical diagnostic tags, etc.). We considered that common knowledge is not sufficient to perform the task but any people can be taught to recognize a small subset of domain-specific concepts. In such a context, it is best to take advantage of the various capabilities of each annotator through teaching (annotators can enhance their knowledge), assignment (annotators can be focused on tasks they have the knowledge to complete) and inference (different annotator propositions can be aggregated to enhance labeling quality). In this work [20], we proposed a set of data-driven algorithms to (i) train image annotators on how to disambiguate among automatically generated candidate labels, (ii) evaluate the quality of annotators' label suggestions 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 measured the benefits of these algorithms by a live user experiment related to image-based plant identification involving around 1,000 people (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.

7.4.4. Evaluation of Content-Based Biodiversity Identification techniques

Participants: Alexis Joly, Herve Goeau, Jean-Christophe Lombardo.

We ran a new edition of the LifeCLEF evaluation campaign [26] with the involvement of 15 research teams working on content-based biodiversity identification worldwide. The main novelties of the 2017 edition of LifeCLEF compared to the previous years were the following:

- **Scalability**: To fully reach its objective, an evaluation campaign such as LifeCLEF requires a long term research effort so as to (i) encourage non incremental contributions, (ii) measure consistent performance gaps and (iii), progressively scale up the problem. Therefore, the number of species was increased considerably between the 2016 and 2017 editions. The plant task, in particular, made a big jump with 10,000 species instead of 1,000 species in the training set. This makes it one of the largest image classification benchmark. Besides, the data set of the bird task was increased by 50% up to 1,500 species which makes it the largest audio classification benchmark as well.
- **Noisy vs. clean data**: The focus of the plant task this year was to study the impact of training identification systems on noisy Web data rather then clean data [35]. Collecting clean data massively is actually prohibitive in terms of human cost whereas noisy Web data can be collected at a very cheap cost. Therefore, we built two large-scale datasets illustrating the same 10K species: one with clean labels coming from the Web platform Encyclopedia Of Life, and one with a high degree of noise - domain noise as well as category noise - crawled from the Web without any filtering. The main conclusion of our evaluation was that convolutional neural networks (CNN) appear to be amazingly effective in the presence of noise in the training set. All networks trained solely on the noisy dataset did outperform the same models trained on the trusted data. Even at a constant number of training

iterations (i.e. at a constant number of images passed to the network), it was more profitable to use the noisy training data. This means that diversity in the training data is a key factor to improve the generalization ability of deep learning. The noise itself seems to act as a regularization of the model. Beyond technical aspects, this conclusion is of high importance in botany and biodiversity informatics in general. Data quality and data validation issues are of crucial importance in these fields and our conclusion is somehow disruptive.

- **Time-coded soundscapes**: As the soundscapes data appeared to be very challenging in 2016 (with an accuracy below 15%), we introduced in 2017 new soundscape recordings containing time-coded bird species annotations thanks to the involvement of expert ornithologists. In total, 4,5 hours of audio recordings were collected and annotated manually with more than 2000 identified segments. The main outcome of our evaluation [36], was that the best performing system on that data was based on a purely image-based convolutional neural network architecture (Inception V4) applied to a standard time-frequency representation. This shows the convergence of the best performing methods whatever the targeted domain.
- **New organisms and identification scenarios**: The SeaCLEF task was extended with novel scenarios involving new organisms, i.e (i) salmons detection for the monitoring of water turbine, and (ii), marine animal species recognition using weakly-labeled images and relevance ranking.

7.4.5. Pl@ntNet Business Venture proposal

Participants: Alexis Joly, Herve Goeau, Antoine Affouard, Jean-Christophe Lombardo.

The ACM Multimedia conference (rank A) introduced in 2017 a new "Business Venture Track" soliciting business venture proposals that combine multimedia technology. The aim is to bridge the gap between academia and industry on multimedia research, innovation and application. The track was open for submissions by all multimedia researchers and entrepreneurs. In this context, we have been working on a business venture proposal around the Pl@ntNet project that has been accepted for publication [25]. Our business proposal is to allow enterprises or organizations to set up their own private collaborative workflow within Pl@ntNet information system. The main added value is to allow them to work on their own business object (e.g. plant disease diagnostic, deficiency measurements, railway lines maintenance, etc.) and with their own community of contributors and end-users (employees, sales representatives, clients, observers network, etc.). This business idea answers to a growing demand in agriculture and environmental economics. Actors in these domains acknowledge that machine learning techniques are mature enough but the lack of training data and efficient tools to collect them remains a major problem. A collaborative platform like Pl@ntNet extended with the technical innovations presented in this paper is the ideal tool to bridge this gap. It will initiate a powerful positive feedback loop boosting the production of training data while improving the work of the employees.