Activity Report Grenoble - Rhône-Alpes 2016

Edition: 2017-06-08

List of Inria's Research Teams

Project-Team AIRSEA

Mathematics and computing applied to oceanic and atmospheric flows

IN COLLABORATION WITH: Laboratoire Jean Kuntzmann (LJK)

IN PARTNERSHIP WITH:
Université Grenoble Alpes

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Earth, Environmental and Energy Sciences

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Project-Team AIRSEA

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

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1. Members

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Dang Khoi Pham [Inria, from Feb 2016 until Jun 2016]

2. Overall Objectives

2.1. Overall Objectives

The general scope of the AIRSEA project-team is to develop *mathematical and computational methods for the modeling of oceanic and atmospheric flows*. The mathematical tools used involve both *deterministic and statistical approaches*. The main research topics cover a) modeling and coupling b) model reduction for sensitivity analysis, coupling and multiscale optimizations c) sensitivity analysis, parameter estimation and risk assessment d) algorithms for high performance computing. The range of application is from climate modeling to the prediction of extreme events.

3. Research Program

3.1. Introduction

Recent events have raised questions regarding the social and economic implications of anthropic alterations of the Earth system, i.e. climate change and the associated risks of increasing extreme events. Ocean and atmosphere, coupled with other components (continent and ice) are the building blocks of the Earth system. A better understanding of the ocean atmosphere system is a key ingredient for improving prediction of such events. Numerical models are essential tools to understand processes, and simulate and forecast events at various space and time scales. Geophysical flows generally have a number of characteristics that make it difficult to model them. This justifies the development of specifically adapted mathematical methods:

- Geophysical flows are strongly non-linear. Therefore, they exhibit interactions between different scales, and unresolved small scales (smaller than mesh size) of the flows have to be **parameterized** in the equations.

- Geophysical fluids are non closed systems. They are open-ended in their scope for including and dynamically coupling different physical processes (e.g., atmosphere, ocean, continental water, etc). **Coupling** algorithms are thus of primary importance to account for potentially significant feedback.
- Numerical models contain parameters which cannot be estimated accurately either because they are difficult to measure or because they represent some poorly known subgrid phenomena. There is thus a need for **dealing with uncertainties**. This is further complicated by the turbulent nature of geophysical fluids.
- The computational cost of geophysical flow simulations is huge, thus requiring the use of **reduced models, multiscale methods** and the design of algorithms ready for **high performance computing** platforms.

Our scientific objectives are divided into four major points. The first objective focuses on developing advanced mathematical methods for both the ocean and atmosphere, and the coupling of these two components. The second objective is to investigate the derivation and use of model reduction to face problems associated with the numerical cost of our applications. The third objective is directed toward the management of uncertainty in numerical simulations. The last objective deals with efficient numerical algorithms for new computing platforms. As mentioned above, the targeted applications cover oceanic and atmospheric modeling and related extreme events using a hierarchy of models of increasing complexity.

3.2. Modeling for oceanic and atmospheric flows

Current numerical oceanic and atmospheric models suffer from a number of well-identified problems. These problems are mainly related to lack of horizontal and vertical resolution, thus requiring the parameterization of unresolved (subgrid scale) processes and control of discretization errors in order to fulfill criteria related to the particular underlying physics of rotating and strongly stratified flows. Oceanic and atmospheric coupled models are increasingly used in a wide range of applications from global to regional scales. Assessment of the reliability of those coupled models is an emerging topic as the spread among the solutions of existing models (e.g., for climate change predictions) has not been reduced with the new generation models when compared to the older ones.

Advanced methods for modeling 3D rotating and stratified flows The continuous increase of computational power and the resulting finer grid resolutions have triggered a recent regain of interest in numerical methods and their relation to physical processes. Going beyond present knowledge requires a better understanding of numerical dispersion/dissipation ranges and their connection to model fine scales. Removing the leading order truncation error of numerical schemes is thus an active topic of research and each mathematical tool has to adapt to the characteristics of three dimensional stratified and rotating flows. Studying the link between discretization errors and subgrid scale parameterizations is also arguably one of the main challenges.

Complexity of the geometry, boundary layers, strong stratification and lack of resolution are the main sources of discretization errors in the numerical simulation of geophysical flows. This emphasizes the importance of the definition of the computational grids (and coordinate systems) both in horizontal and vertical directions, and the necessity of truly multi resolution approaches. At the same time, the role of the small scale dynamics on large scale circulation has to be taken into account. Such parameterizations may be of deterministic as well as stochastic nature and both approaches are taken by the AIRSEA team. The design of numerical schemes consistent with the parameterizations is also arguably one of the main challenges for the coming years. This work is complementary and linked to that on parameters estimation described in 3.4.

Ocean Atmosphere interactions and formulation of coupled models State-of-the-art climate models (CMs) are complex systems under continuous development. A fundamental aspect of climate modeling is the representation of air-sea interactions. This covers a large range of issues: parameterizations of atmospheric and oceanic boundary layers, estimation of air-sea fluxes, time-space numerical schemes, non conforming grids, coupling algorithms ...Many developments related to these different aspects were performed over the last 10-15 years, but were in general conducted independently of each other.

The aim of our work is to revisit and enrich several aspects of the representation of air-sea interactions in CMs, paying special attention to their overall consistency with appropriate mathematical tools. We intend to work consistently on the physics and numerics. Using the theoretical framework of global-in-time Schwarz methods, our aim is to analyze the mathematical formulation of the parameterizations in a coupling perspective. From this study, we expect improved predictability in coupled models (this aspect will be studied using techniques described in 3.4). Complementary work on space-time nonconformities and acceleration of convergence of Schwarz-like iterative methods (see 7.1.2) are also conducted.

3.3. Model reduction / multiscale algorithms

The high computational cost of the applications is a common and major concern to have in mind when deriving new methodological approaches. This cost increases dramatically with the use of sensitivity analysis or parameter estimation methods, and more generally with methods that require a potentially large number of model integrations.

A dimension reduction, using either stochastic or deterministic methods, is a way to reduce significantly the number of degrees of freedom, and therefore the calculation time, of a numerical model.

Model reduction Reduction methods can be deterministic (proper orthogonal decomposition, other reduced bases) or stochastic (polynomial chaos, Gaussian processes, kriging), and both fields of research are very active. Choosing one method over another strongly depends on the targeted application, which can be as varied as real-time computation, sensitivity analysis (see e.g., section 7.3.1) or optimisation for parameter estimation (see below).

Our goals are multiple, but they share a common need for certified error bounds on the output. Our team has a 4-year history of working on certified reduction methods and has a unique positioning at the interface between deterministic and stochastic approaches. Thus, it seems interesting to conduct a thorough comparison of the two alternatives in the context of sensitivity analysis. Efforts will also be directed toward the development of efficient greedy algorithms for the reduction, and the derivation of goal-oriented sharp error bounds for non linear models and/or non linear outputs of interest. This will be complementary to our work on the deterministic reduction of parametrized viscous Burgers and Shallow Water equations where the objective is to obtain sharp error bounds to provide confidence intervals for the estimation of sensitivity indices.

Reduced models for coupling applications Global and regional high-resolution oceanic models are either coupled to an atmospheric model or forced at the air-sea interface by fluxes computed empirically preventing proper physical feedback between the two media. Thanks to high-resolution observational studies, the existence of air-sea interactions at oceanic mesoscales (i.e., at $\mathcal{O}(1km)$ scales) have been unambiguously shown. Those interactions can be represented in coupled models only if the oceanic and atmospheric models are run on the same high-resolution computational grid, and are absent in a forced mode. Fully coupled models at high-resolution are seldom used because of their prohibitive computational cost. The derivation of a reduced model as an alternative between a forced mode and the use of a full atmospheric model is an open problem.

Multiphysics coupling often requires iterative methods to obtain a mathematically correct numerical solution. To mitigate the cost of the iterations, we will investigate the possibility of using reduced-order models for the iterative process. We will consider different ways of deriving a reduced model: coarsening of the resolution, degradation of the physics and/or numerical schemes, or simplification of the governing equations. At a mathematical level, we will strive to study the well-posedness and the convergence properties when reduced models are used. Indeed, running an atmospheric model at the same resolution as the ocean model is generally too expensive to be manageable, even for moderate resolution applications. To account for important fine-scale interactions in the computation of the air-sea boundary condition, the objective is to derive a simplified boundary layer model that is able to represent important 3D turbulent features in the marine atmospheric boundary layer.

Reduced models for multiscale optimization The field of multigrid methods for optimisation has known a tremendous development over the past few decades. However, it has not been applied to oceanic and atmospheric problems apart from some crude (non-converging) approximations or applications to simplified and low dimensional models. This is mainly due to the high complexity of such models and to the difficulty in handling several grids at the same time. Moreover, due to complex boundaries and physical phenomena, the grid interactions and transfer operators are not trivial to define.

Multigrid solvers (or multigrid preconditioners) are efficient methods for the solution of variational data assimilation problems. We would like to take advantage of these methods to tackle the optimization problem in high dimensional space. High dimensional control space is obtained when dealing with parameter fields estimation, or with control of the full 4D (space time) trajectory. It is important since it enables us to take into account model errors. In that case, multigrid methods can be used to solve the large scales of the problem at a lower cost, this being potentially coupled with a scale decomposition of the variables themselves.

3.4. Dealing with uncertainties

There are many sources of uncertainties in numerical models. They are due to imperfect external forcing, poorly known parameters, missing physics and discretization errors. Studying these uncertainties and their impact on the simulations is a challenge, mostly because of the high dimensionality and non-linear nature of the systems. To deal with these uncertainties we work on three axes of research, which are linked: sensitivity analysis, parameter estimation and risk assessment. They are based on either stochastic or deterministic methods.

Sensitivity analysis Sensitivity analysis (SA), which links uncertainty in the model inputs to uncertainty in the model outputs, is a powerful tool for model design and validation. First, it can be a pre-stage for parameter estimation (see 3.4), allowing for the selection of the more significant parameters. Second, SA permits understanding and quantifying (possibly non-linear) interactions induced by the different processes defining e.g., realistic ocean atmosphere models. Finally SA allows for validation of models, checking that the estimated sensitivities are consistent with what is expected by the theory. On ocean, atmosphere and coupled systems, only first order deterministic SA are performed, neglecting the initialization process (data assimilation). AIRSEA members and collaborators proposed to use second order information to provide consistent sensitivity measures, but so far it has only been applied to simple academic systems. Metamodels are now commonly used, due to the cost induced by each evaluation of complex numerical models: mostly Gaussian processes, whose probabilistic framework allows for the development of specific adaptive designs, and polynomial chaos not only in the context of intrusive Galerkin approaches but also in a black-box approach. Until recently, global SA was based primarily on a set of engineering practices. New mathematical and methodological developments have led to the numerical computation of Sobol' indices, with confidence intervals assessing for both metamodel and estimation errors. Approaches have also been extended to the case of dependent entries, functional inputs and/or output and stochastic numerical codes. Other types of indices and generalizations of Sobol' indices have also been introduced.

Concerning the stochastic approach to SA we plan to work with parameters that show spatio-temporal dependencies and to continue toward more realistic applications where the input space is of huge dimension with highly correlated components. Sensitivity analysis for dependent inputs also introduces new challenges. In our applicative context, it would seem prudent to carefully learn the spatio-temporal dependences before running a global SA. In the deterministic framework we focus on second order approaches where the sought sensitivities are related to the optimality system rather than to the model; i.e., we consider the whole forecasting system (model plus initialization through data assimilation).
All these methods allow for computing sensitivities and more importantly a posteriori error statistics.

Parameter estimation Advanced parameter estimation methods are barely used in ocean, atmosphere and coupled systems, mostly due to a difficulty of deriving adequate response functions, a lack of knowledge of these methods in the ocean-atmosphere community, and also to the huge associated computing costs. In the presence of strong uncertainties on the model but also on parameter values, simulation and inference are closely associated. Filtering for data assimilation and Approximate Bayesian Computation (ABC) are two examples of such association.

Stochastic approach can be compared with the deterministic approach, which allows to determine the sensitivity of the flow to parameters and optimize their values relying on data assimilation. This approach is already shown to be capable of selecting a reduced space of the most influent parameters in the local parameter space and to adapt their values in view of correcting errors committed by the numerical approximation. This approach assumes the use of automatic differentiation of the source code with respect to the model parameters, and optimization of the obtained raw code.

AIRSEA assembles all the required expertise to tackle these difficulties. As mentioned previously, the choice of parameterization schemes and their tuning has a significant impact on the result of model simulations. Our research will focus on parameter estimation for parameterized Partial Differential Equations (PDEs) and also for parameterized Stochastic Differential Equations (SDEs). Deterministic approaches are based on optimal control methods and are local in the parameter space (i.e., the result depends on the starting point of the estimation) but thanks to adjoint methods they can cope with a large number of unknowns that can also vary in space and time. Multiscale optimization techniques as described in 7.2.1 will be one of the tools used. This in turn can be used either to propose a better (and smaller) parameter set or as a criterion for discriminating parameterization schemes. Statistical methods are global in the parameter state but may suffer from the curse of dimensionality. However, the notion of parameter can also be extended to functional parameters. We may consider as parameter a functional entity such as a boundary condition on time, or a probability density function in a stationary regime. For these purposes, non-parametric estimation will also be considered as an alternative.

Risk assessment Risk assessment in the multivariate setting suffers from a lack of consensus on the choice of indicators. Moreover, once the indicators are designed, it still remains to develop estimation procedures, efficient even for high risk levels. Recent developments for the assessment of financial risk have to be considered with caution as methods may differ pertaining to general financial decisions or environmental risk assessment. Modeling and quantifying uncertainties related to extreme events is of central interest in environmental sciences. In relation to our scientific targets, risk assessment is very important in several areas: hydrological extreme events, cyclone intensity, storm surges...Environmental risks most of the time involve several aspects which are often correlated. Moreover, even in the ideal case where the focus is on a single risk source, we have to face the temporal and spatial nature of environmental extreme events. The study of extremes within a spatio-temporal framework remains an emerging field where the development of adapted statistical methods could lead to major progress in terms of geophysical understanding and risk assessment thus coupling data and model information for risk assessment.

Based on the above considerations we aim to answer the following scientific questions: how to measure risk in a multivariate/spatial framework? How to estimate risk in a non stationary context? How to reduce dimension (see 3.3) for a better estimation of spatial risk?

Extreme events are rare, which means there is little data available to make inferences of risk measures. Risk assessment based on observation therefore relies on multivariate extreme value theory. Interacting particle systems for the analysis of rare events is commonly used in the community of computer experiments. An open question is the pertinence of such tools for the evaluation of environmental risk.
Most numerical models are unable to accurately reproduce extreme events. There is therefore a real need to develop efficient assimilation methods for the coupling of numerical models and extreme data.

3.5. High performance computing

Methods for sensitivity analysis, parameter estimation and risk assessment are extremely costly due to the necessary number of model evaluations. This number of simulations require considerable computational resources, depends on the complexity of the application, the number of input variables and desired quality of approximations. To this aim, the AIRSEA team is an intensive user of HPC computing platforms, particularly grid computing platforms. The associated grid deployment has to take into account the scheduling of a huge number of computational requests and the links with data-management between these requests, all of these as automatically as possible. In addition, there is an increasing need to propose efficient numerical algorithms specifically designed for new (or future) computing architectures and this is part of our scientific objectives.

According to the computational cost of our applications, the evolution of high performance computing platforms has to be taken into account for several reasons. While our applications are able to exploit space parallelism to its full extent (oceanic and atmospheric models are traditionally based on a spatial domain decomposition method), the spatial discretization step size limits the efficiency of traditional parallel methods. Thus the inherent parallelism is modest, particularly for the case of relative coarse resolution but with very long integration time (e.g., climate modeling). Paths toward new programming paradigms are thus needed. As a step in that direction, we plan to focus our research on parallel in time methods.

New numerical algorithms for high performance computing Parallel in time methods can be classified into three main groups. In the first group, we find methods using parallelism across the method, such as parallel integrators for ordinary differential equations. The second group considers parallelism across the problem. Falling into this category are methods such as waveform relaxation where the space-time system is decomposed into a set of subsystems which can then be solved independently using some form of relaxation techniques or multigrid reduction in time. The third group of methods focuses on parallelism across the steps. One of the best known algorithms in this family is parareal. Other methods combining the strengths of those listed above (e.g., PFASST) are currently under investigation in the community.

Parallel in time methods are iterative methods that may require a large number of iteration before convergence. Our first focus will be on the convergence analysis of parallel in time (Parareal / Schwarz) methods for the equation systems of oceanic and atmospheric models. Our second objective will be on the construction of fast (approximate) integrators for these systems. This part is naturally linked to the model reduction methods of section (7.2.2). Fast approximate integrators are required both in the Schwarz algorithm (where a first guess of the boundary conditions is required) and in the Parareal algorithm (where the fast integrator is used to connect the different time windows). Our main application of these methods will be on climate (i.e., very long time) simulations. Our second application of parallel in time methods will be in the context of optimization methods. In fact, one of the major drawbacks of the optimal control techniques used in 3.4 is a lack of intrinsic parallelism in comparison with ensemble methods. Here, parallel in time methods also offer ways to better efficiency. The mathematical key point is centered on how to efficiently couple two iterative methods (i.e., parallel in time and optimization methods).

4. Application Domains

4.1. The Ocean-Atmosphere System

The evolution of natural systems, in the short, mid, or long term, has extremely important consequences for both the global Earth system and humanity. Forecasting this evolution is thus a major challenge from the scientific, economic, and human viewpoints.

Humanity has to face the problem of **global warming**, brought on by the emission of greenhouse gases from human activities. This warming will probably cause huge changes at global and regional scales, in terms of climate, vegetation and biodiversity, with major consequences for local populations. Research has therefore been conducted over the past 15 to 20 years in an effort to model the Earth's climate and forecast its evolution in the 21st century in response to anthropic action.

With regard to short-term forecasts, the best and oldest example is of course **weather forecasting**. Meteorological services have been providing daily short-term forecasts for several decades which are of crucial importance for numerous human activities.

Numerous other problems can also be mentioned, like **seasonal weather forecasting** (to enable powerful phenomena like an El Niño event or a drought period to be anticipated a few months in advance), **operational oceanography** (short-term forecasts of the evolution of the ocean system to provide services for the fishing industry, ship routing, defense, or the fight against marine pollution) or the prediction of **floods**.

As mentioned previously, mathematical and numerical tools are omnipresent and play a fundamental role in these areas of research. In this context, the vocation of AIRSEA is not to carry out numerical prediction, but to address mathematical issues raised by the development of prediction systems for these application fields, in close collaboration with geophysicists.

5. Highlights of the Year

5.1. Highlights of the Year

In collaboration with M. Asch and M. Bocquet, M. Nodet published a book about Data Assimilation [30].

5.1.1. Awards

Jose R. Leon was granted by an International Inria Chair.

E. Arnaud was granted by a CRCT (Congé pour recherches ou conversions thématiques) by the CNU.

L. Debreu was awarded IMarEST Deny Medal for the best paper in journal of operational oceanography for year 2014.

6. New Software and Platforms

6.1. AGRIF

Adaptive Grid Refinement In Fortran

FUNCTIONAL DESCRIPTION AGRIF is a Fortran 90 package for the integration of full adaptive mesh refinement (AMR) features within a multidimensional finite difference model written in Fortran. Its main objective is to simplify the integration of AMR potentialities within an existing model with minimal changes. Capabilities of this package include the management of an arbitrary number of grids, horizontal and/or vertical refinements, dynamic regridding, parallelization of the grids interactions on distributed memory computers. AGRIF requires the model to be discretized on a structured grid, like it is typically done in ocean or atmosphere modelling.

- Participants: Laurent Debreu, Marc Honnorat and Cyril Mazauric
- Contact: Laurent Debreu
- URL: http://www-ljk.imag.fr/MOISE/AGRIF

6.2. BALAISE

Bilbliothèque d'Assimilation Lagrangienne Adaptée aux Images Séquencées en Environnement

KEYWORDS: Multi-scale analysis - Data assimilation - Optimal control

FUNCTIONAL DESCRIPTION

BALAISE (Bilbliothèque d'Assimilation Lagrangienne Adaptée aux Images Séquencées en Environnement) is a test bed for image data assimilation. It includes a shallow water model, a multi-scale decomposition library and an assimilation suite.

- Contact: Arthur Vidard

6.3. DiceDesign

Designs of Computer Experiments

FUNCTIONAL DESCRIPTION

This package is useful for conducting design and analysis of computer experiments.

- Contact: Céline Hartweg
- URL: https://cran.r-project.org/web/packages/DiceDesign/index.html

6.4. DiceEval

Construction and Evaluation of Metamodels

FUNCTIONAL DESCRIPTION

This package is useful for conducting design and analysis of computer experiments. Estimation, validation and prediction of models of different types : linear models, additive models, MARS,PolyMARS and Kriging.

- Contact: Céline Hartweg
- URL: https://cran.r-project.org/web/packages/DiceEval/index.html

6.5. NEMOVAR

Variational data assimilation for NEMO

KEYWORDS: Oceanography - Data assimilation - Adjoint method - Optimal control

FUNCTIONAL DESCRIPTION

NEMOVAR is a state-of-the-art multi-incremental variational data assimilation system with both 3D and 4D capabilities, and which is designed to work with NEMO on the native ORCA grids. The background error covariance matrix is modelled using balance operators for the multivariate component and a diffusion operator for the univariate component. It can also be formulated as a linear combination of covariance models to take into account multiple correlation length scales associated with ocean variability on different scales. NEMOVAR has recently been enhanced with the addition of ensemble data assimilation and multi-grid assimilation capabilities. It is used operationnaly in both ECMWF and the Met Office (UK)

- Partners: CERFACS - ECMWF - Met Office
- Contact: Arthur Vidard

6.6. Sensitivity

FUNCTIONAL DESCRIPTION

This package is useful for conducting sensitivity analysis of complex computer codes.

- Contact: Laurent Gilquin
- URL: https://cran.r-project.org/web/packages/sensitivity/index.html

7. New Results

7.1. Modeling for Oceanic and Atmospheric flows

7.1.1. Numerical Schemes for Ocean Modelling

Participants: Eric Blayo, Laurent Debreu, Florian Lemarié.

The increase of model resolution naturally leads to the representation of a wider energy spectrum. As a result, in recent years, the understanding of oceanic submesoscale dynamics has significantly improved. However, dissipation in submesoscale models remains dominated by numerical constraints rather than physical ones. Effective resolution is limited by the numerical dissipation range, which is a function of the model numerical filters (assuming that dispersive numerical modes are efficiently removed). In [20], we present a Baroclinic Jet test case set in a zonally reentrant channel that provides a controllable test of a model capacity at resolving submesoscale dynamics. We compare simulations from two models, ROMS and NEMO, at different mesh sizes (from 20 to 2 km). Through a spectral decomposition of kinetic energy and its budget terms, we identify the characteristics of numerical dissipation and effective resolution. It shows that numerical dissipation appears in different parts of a model, especially in spatial advection-diffusion schemes for momentum equations (KE dissipation) and tracer equations (APE dissipation) and in the time stepping algorithms. Effective resolution, defined by scale-selective dissipation, is inadequate to qualify traditional ocean models with low-order spatial and temporal filters, even at high grid resolution. High- order methods are better suited to the concept and probably unavoidable. Fourth-order filters are suited only for grid resolutions less than a few kilometers and momentum advection schemes of even higher-order may be justified. The upgrade of time stepping algorithms (from filtered Leapfrog), a cumbersome task in a model, appears critical from our results, not just as a matter of model solution quality but also of computational efficiency (extended stability range of predictor-corrector schemes). Effective resolution is also shaken by the need for non scale-selective barotropic mode filters and requires carefully addressing the issue of mode splitting errors. Possibly the most surprising result is that submesoscale energy production is largely affected by spurious diapycnal mixing (APE dissipation). This result justifies renewed efforts in reducing tracer mixing errors and poses again the question of how much vertical diffusion is at work in the real ocean.

7.1.2. Coupling Methods for Oceanic and Atmospheric Models

Participants: Eric Blayo, Mehdi-Pierre Daou, Laurent Debreu, Florian Lemarié, Charles Pelletier, Antoine Rousseau.

7.1.2.1. Coupling heterogeneous models in hydrodynamics

The coupling of models of different kinds is gaining more and more attention, due in particular to a need for more global modeling systems encompassing different disciplines (e.g. multi-physics) and different approaches (e.g. multi-scale, nesting). In order to develop such complex systems, it is generally more pragmatic to assemble different modeling units inside a user friendly modelling software platform rather than to develop new complex global models.

In the context of hydrodynamics, global modeling systems have to couple models of different dimensions (1D, 2D or 3D) and representing different physics (Navier-Stokes, hydrostatic Navier-Stokes, shallow water…). We have been developing coupling approaches for several years, based on so-called Schwarz algorithms. Our recent contributions address the development of absorbing boundary conditions for Navier-Stokes equations [4], and of interface conditions for coupling hydrostatic and nonhydrostatic Navier-Stokes flows [5]. In the context of our partnership with ARTELIA Group (PhD thesis of Medhi Pierre Daou), implementations of Schwarz coupling algorithms have been performed for hydrodynamics industrial codes (Mascaret, Telemac and OpenFoam), using the PALM coupling software. A first series of experiments was realized in an academic test case, and a second one in the much more realistic context of the Rusumo hydropower plant, coupling Telemac-3D (Navier-Stokes equations) with OpenFoam (diphasic solver) - see Figure 1. M.-P. Daou defended his PhD on September 27, 2016 [1].

7.1.2.2. Ocean-atmosphere coupling

Coupling methods routinely used in regional and global climate models do not provide the exact solution to the ocean-atmosphere problem, but an approximation of one [63]. For the last few years we have been actively working on the analysis of Schwarz waveform relaxation to apply this type of iterative coupling method to air-sea coupling [65], [66], [64]. In the context of the simulation of tropical cyclone, sensitivity tests to the coupling method have been carried out using ensemble simulations (through perturbations of the coupling frequency and initial conditions). We showed that the use of the Schwarz iterative coupling methods leads to a significantly reduced spread in the ensemble results (in terms of cyclone trajectory and intensity), thus suggesting that a source of error is removed w.r.t coupling methods en vogue in existing coupled models [68].

Motivated by this encouraging result, our activities over the last few years can be divided into four general topics

1. *Stability and consistency analysis of existing coupling methods*: in [63] we showed that the usual methods used in the context of ocean-atmosphere coupling are prone to splitting errors because they correspond to only one iteration of an iterative process without reaching convergence. Moreover,

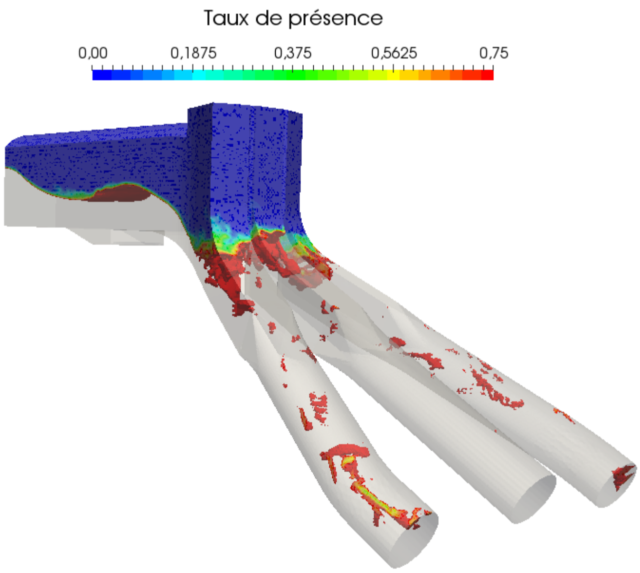

Figure 1. Biphasic simulation of the air/water flow in the Rusumo hydropower plant (PhD of M. P. Daou)

those methods have an additional condition for the coupling to be stable even if unconditionally stable time stepping algorithms are used. This last remark was further studied last year in [3] and it turned out to be a major source of instability in atmosphere-snow coupling.

2. *Study of physics-dynamics coupling*: during the PhD-thesis of Charles Pelletier (funded by Inria) the scope is on including the formulation of physical parameterizations in the theoretical analysis of the coupling, in particular the parameterization schemes to compute air-sea fluxes. To do so, a metamodel representative of the behavior of the full parameterization but with a continuous form easier to manipulate has been derived thanks to a sensitivity analysis based on Sobol' indexes This metamodel has the advantage to be more adequate to conduct the mathematical analysis of the coupling while being physically satisfactory. A publication is currently in preparation for the Quarterly Journal of the Royal Meteorological Society. In parallel we have contributed to a general review gathering the main international specialists on the topic [38].
3. *Design of a coupled single column model*: in order to focus on specific problems of ocean-atmosphere coupling, a work on simplified equation sets has been started. The aim is to implement a one-dimensional (in the vertical direction) coupled model with physical parameterizations representative of those used in realistic models. Thanks to this simplified coupled model the objective is to develop a benchmark suite for coupled models evaluation. Last year the single column oceanic and atmospheric components have been developed in the framework of the SIMBAD project and should be coupled in early 2017 (collaboration with Mercator-océan).
4. *Analysis of air-sea interactions in realistic high-resolution realistic simulations*: part of our activity has been in collaboration with atmosphericists and physical oceanographers to study the impact on some modeling assumptions (e.g. [67]) in large-scale realistic ocean-atmosphere coupled simulations [16], [15].

These four topics are addressed through strong collaborations between the applied mathematics and the climate community.

Moreover a PPR (*Projet à partenariat renforcé*) called SIMBAD (SIMplified Boundary Atmospheric layer moDel for ocean modeling purposes) is funded by Mercator-Ocean for the next three years (from march 2015 to march 2018). The aim of this project in collaboration with Meteo-France, Ifremer, LMD, and LOCEAN is to derive a metamodel to force high-resolution oceanic operational models for which the use of a full atmospheric model is not possible due to a prohibitive computational cost. Another industrial contract named ALBATROS is also funded by (from June 2016 to June 2019) to couple SIMBAD with the NEMO global ocean model and a wave model called WW3.

An ANR project COCOA (COmprehensive Coupling approach for the Ocean and the Atmosphere, P.I.: E. Blayo) has been funded in 2016 and will officially start in January 2017.

7.1.2.3. Data assimilation for coupled models

In the context of operational meteorology and oceanography, forecast skills heavily rely on proper combination of model prediction and available observations via data assimilation techniques. Historically, numerical weather prediction is made separately for the ocean and the atmosphere in an uncoupled way. However, in recent years, fully coupled ocean-atmosphere models are increasingly used in operational centers to improve the reliability of seasonal forecasts and tropical cyclones predictions. For coupled problems, the use of separated data assimilation schemes in each medium is not satisfactory since the result of such assimilation process is generally inconsistent across the interface, thus leading to unacceptable artefacts. Hence, there is a strong need for adapting existing data assimilation techniques to the coupled framework. As part of our ERACLIM2 contribution, R. Pellerej started a PhD on that topic late 2014. So far, three general data assimilation algorithms, based on variational data assimilation techniques, have been developed and applied to a simple coupled problem. The dynamical equations of the considered problem are coupled using an iterative Schwarz domain decomposition method. The aim is to properly take into account the coupling in the assimilation process in order to obtain a coupled solution close to the observations while satisfying the physical conditions across the air-sea interface. Preliminary results shows significant improvement compared to the usual approach on this simple system [28].

The aforementioned system has been recoded within the OOPS framework (Object Oriented Prediction System) in order to ease the transfer to more complex/realistic models.

7.1.3. Parameterizing subgrid scale eddy effects

Participant: Eugene Kazantsev.

Basing on the maximum entropy production principle, the influence of subgrid scales on the flow is presented as the harmonic dissipation accompanied by the backscattering of the dissipated energy. This parametrization is tested on the shallow water model in a square box. Two possible solutions of the closure problem are compared basing on the analysis of the energy dissipation-backscattering balance. Results of this model on the coarse resolution grid are compared with the reference simulation at four times higher resolution. It is shown that the mean flow is correctly recovered, as well as variability properties, such as eddy kinetic energy fields and its spectrum [40].

7.2. Model reduction / multiscale algorithms

7.2.1. Multigrid Methods for Variational Data Assimilation.

Participants: Laurent Debreu, François-Xavier Le Dimet, Arthur Vidard.

In order to lower the computational cost of the variational data assimilation process, we investigate the use of multigrid methods to solve the associated optimal control system. On a linear advection equation, we study the impact of the regularization term on the optimal control and the impact of discretization errors on the efficiency of the coarse grid correction step. We show that even if the optimal control problem leads to the solution of an elliptic system, numerical errors introduced by the discretization can alter the success of the multigrid methods. The view of the multigrid iteration as a preconditioner for a Krylov optimization method leads to a more robust algorithm. A scale dependent weighting of the multigrid preconditioner and the usual background error covariance matrix based preconditioner is proposed and brings significant improvements. This work is summarized in ([7]).

7.2.2. Intrusive sensitivity analysis, reduced models

Participants: Maëlle Nodet, Clémentine Prieur.

Another point developed in the team for sensitivity analysis is model reduction. To be more precise regarding model reduction, the aim is to reduce the number of unknown variables (to be computed by the model), using a well chosen basis. Instead of discretizing the model over a huge grid (with millions of points), the state vector of the model is projected on the subspace spanned by this basis (of a far lesser dimension). The choice of the basis is of course crucial and implies the success or failure of the reduced model. Various model reduction methods offer various choices of basis functions. A well-known method is called “proper orthogonal decomposition" or “principal component analysis". More recent and sophisticated methods also exist and may be studied, depending on the needs raised by the theoretical study. Model reduction is a natural way to overcome difficulties due to huge computational times due to discretizations on fine grids. In [61], the authors present a reduced basis offline/online procedure for viscous Burgers initial boundary value problem, enabling efficient approximate computation of the solutions of this equation for parametrized viscosity and initial and boundary value data. This procedure comes with a fast-evaluated rigorous error bound certifying the approximation procedure. The numerical experiments in the paper show significant computational savings, as well as efficiency of the error bound.

When a metamodel is used (for example reduced basis metamodel, but also kriging, regression, ...) for estimating sensitivity indices by Monte Carlo type estimation, a twofold error appears: a sampling error and a metamodel error. Deriving confidence intervals taking into account these two sources of uncertainties is of great interest. We obtained results particularly well fitted for reduced basis metamodels [62]. In [60], the authors provide asymptotic confidence intervals in the double limit where the sample size goes to infinity and the metamodel converges to the true model. These results were also adapted to problems related to more general models such as Shallow-Water equations, in the context of the control of an open channel [11].

When considering parameter-dependent PDE, it happens that the quantity of interest is not the PDE's solution but a linear functional of it. In [10], we have proposed a probabilistic error bound for the reduced output of interest (goal-oriented error bound). By probabilistic we mean that this bound may be violated with small probability. The bound is efficiently and explicitly computable, and we show on different examples that this error bound is sharper than existing ones.

A collaboration has been started with Christophe Prieur (Gipsa-Lab) on the very challenging issue of sensitivity of a controlled system to its control parameters [11]. In [32], we propose a generalization of the probabilistic goal-oriented error estimation in [10] to parameter-dependent nonlinear problems. One aims at applying such results in the previous context of sensitivity of a controlled system.

7.3. Dealing with uncertainties

7.3.1. Sensitivity Analysis for Forecasting Ocean Models

Participants: Eric Blayo, Laurent Gilquin, Céline Helbert, François-Xavier Le Dimet, Elise Arnaud, Simon Nanty, Maëlle Nodet, Clémentine Prieur, Laurence Viry, Federico Zertuche.

7.3.1.1. Scientific context

Forecasting geophysical systems require complex models, which sometimes need to be coupled, and which make use of data assimilation. The objective of this project is, for a given output of such a system, to identify the most influential parameters, and to evaluate the effect of uncertainty in input parameters on model output. Existing stochastic tools are not well suited for high dimension problems (in particular time-dependent problems), while deterministic tools are fully applicable but only provide limited information. So the challenge is to gather expertise on one hand on numerical approximation and control of Partial Differential Equations, and on the other hand on stochastic methods for sensitivity analysis, in order to develop and design innovative stochastic solutions to study high dimension models and to propose new hybrid approaches combining the stochastic and deterministic methods.

7.3.1.2. Data assimilation and second order sensitivity analysis

Sensitivity Analysis is defined by some scalar response function giving an evaluation of the state of a system with respect to parameters. By definition, sensitivity is the gradient of this response function. In the case of Variational Data Assimilation, sensitivity analysis have to be carried out on the optimality system because this is the only system in which all the information is located. An important application is the sensitivity, for instance, of the prediction with respect to observations. It's necessary to derive the optimality system and to introduce a second order adjoint.We have applied it to a simulated pollution transport problem and in the case of an oceanic model [18], [19]. More applications to water pollution using a complex hydrological model are under development.

7.3.2. Estimating variance-based sensitivity indices

Participants: Elise Arnaud, Laurent Gilquin, Clémentine Prieur, Simon Nanty, Céline Helbert, Laurence Viry.

In variance-based sensitivity analysis, a classical tool is the method of Sobol' [74] which allows to compute Sobol' indices using Monte Carlo integration. One of the main drawbacks of this approach is that the estimation of Sobol' indices requires the use of several samples. For example, in a d-dimensional space, the estimation of all the first-order Sobol' indices requires $d + 1$ samples. Some interesting combinatorial results have been introduced to weaken this defect, in particular by Saltelli [72] and more recently by Owen [70] but the quantities they estimate still require $O(d)$ samples.

In a recent work [80] we introduce a new approach to estimate all first-order Sobol' indices by using only two samples based on replicated latin hypercubes and all second-order Sobol' indices by using only two samples based on replicated randomized orthogonal arrays. This method is referred as the replicated method. We establish theoretical properties of such a method for the first-order Sobol' indices and discuss the generalization to higher-order indices. As an illustration, we propose to apply this new approach to a marine ecosystem model of the Ligurian sea (northwestern Mediterranean) in order to study the relative importance of its several parameters. The calibration process of this kind of chemical simulators is well-known to be quite intricate, and a rigorous and robust — i.e. valid without strong regularity assumptions — sensitivity analysis, as the method of Sobol' provides, could be of great help. The computations are performed by using CIGRI, the middleware used on the grid of the Grenoble University High Performance Computing (HPC) center. We are also applying these estimates to calibrate integrated land use transport models. As for these models, some groups of inputs are correlated, Laurent Gilquin extended the approach based on replicated designs for the estimation of grouped Sobol' indices [58].

We can now wonder what are the asymptotic properties of these new estimators, or also of more classical ones. In [60], the authors deal with asymptotic properties of the estimators. In [57], the authors establish also a multivariate central limit theorem and non asymptotic properties.

The use of replicated designs to estimate first-order Sobol' indices has the major advantage of reducing drastically the estimation cost as the number of runs n becomes independent of the input space dimension. The generalization to closed second-order Sobol' indices relies on the replication of randomized orthogonal arrays. However, if the input space is not properly explored, that is if n is too small, the Sobol' indices estimates may not be accurate enough.

To address this challenge, we propose approaches to render the replication method recursive, enabling the required number of evaluations to be controlled. With these approaches, more accurate Sobol' estimates are obtained while recycling previous sets of model evaluations. The estimation procedure is therefore stopped when the convergence of estimates is considered reached. One of these approaches corresponds to a recursive version of the replication method and is based on the iterative construction of stratified designs, latin hypercubes and orthogonal arrays [36]. A second approach combines the use of quasi-Monte Carlo sampling and the construction of a new stopping criterion [9], [39].

Extension of the replication method has also been proposed to face constraints arising in an application on the land use and transport model Tranus, such as the presence of dependency among the model inputs, as well as multivariate outputs [37].

7.3.2.1. Sensitivity analysis with dependent inputs

An important challenge for stochastic sensitivity analysis is to develop methodologies which work for dependent inputs. For the moment, there does not exist conclusive results in that direction. Our aim is to define an analogue of Hoeffding decomposition [59] in the case where input parameters are correlated. Clémentine Prieur supervised Gaëlle Chastaing's PhD thesis on the topic (defended in September 2013) [49]. We obtained first results [50], deriving a general functional ANOVA for dependent inputs, allowing defining new variance based sensitivity indices for correlated inputs. We then adapted various algorithms for the estimation of these new indices. These algorithms make the assumption that among the potential interactions, only few are significant. Two papers have been recently accepted [48], [51]. We also considered (see the paragraph 7.3.2) the estimation of groups Sobol' indices, with a procedure based on replicated designs. These indices provide information at the level of groups, and not at a finer level, but their interpretation is still rigorous.

Céline Helbert and Clémentine Prieur supervised the PhD thesis of Simon Nanty (funded by CEA Cadarache, and defended in October, 2015). The subject of the thesis is the analysis of uncertainties for numerical codes with temporal and spatio-temporal input variables, with application to safety and impact calculation studies. This study implied functional dependent inputs. A first step was the modeling of these inputs [14]. The whole methodology proposed during the PhD is presented in [13].

More recently, the Shapley value, from econometrics, was proposed as an alternative to quantify the importance of random input variables to a function. Owen [71] derived Shapley value importance for independent inputs and showed that it is bracketed between two different Sobol' indices. Song et al. [75] recently advocated the use of Shapley value for the case of dependent inputs. In a very recent work [42], in collaboration with Art Owen (Standford's University), we show that Shapley value removes the conceptual problems of functional ANOVA for dependent inputs. We do this with some simple examples where Shapley value leads to intuitively reasonable nearly closed form values.

7.3.3. Optimal Control of Boundary Conditions

Participants: Eric Blayo, Eugene Kazantsev, Florian Lemarié.

A variational data assimilation technique is applied to the identification of the optimal boundary conditions for a simplified configuration of the NEMO model. A rectangular box model placed in mid-latitudes, and subject to the classical single or double gyre wind forcing, is studied. The model grid can be rotated on a desired angle around the center of the rectangle in order to simulate the boundary approximated by a staircase-like coastlines. The solution of the model on the grid aligned with the box borders was used as a reference solution and as artificial observational data. It is shown in [24], [25] that optimal boundary has a rather complicated geometry which is neither a staircase, nor a straight line. The boundary conditions found in the data assimilation procedure bring the solution toward the reference solution allowing to correct the influence of the rotated grid.

Adjoint models, necessary to variational data assimilation, have been produced by the TAPENADE software, developed by the SCIPORT team. This software is shown to be able to produce the adjoint code that can be used in data assimilation after a memory usage optimization.

7.3.4. Non-Parametric Estimation for Kinetic Diffusions

Participants: Clémentine Prieur, Jose Raphael Leon Ramos.

This research is the subject of a collaboration with Venezuela and is partly funded by an ECOS Nord project.

We are focusing our attention on models derived from the linear Fokker-Planck equation. From a probabilistic viewpoint, these models have received particular attention in recent years, since they are a basic example for hypercoercivity. In fact, even though completely degenerated, these models are hypoelliptic and still verify some properties of coercivity, in a broad sense of the word. Such models often appear in the fields of mechanics, finance and even biology. For such models we believe it appropriate to build statistical non-parametric estimation tools. Initial results have been obtained for the estimation of invariant density, in conditions guaranteeing its existence and unicity [45] and when only partial observational data are available.

A paper on the non parametric estimation of the drift has been accepted recently [46] (see Samson et al., 2012, for results for parametric models). As far as the estimation of the diffusion term is concerned, a paper has been accepted [46], in collaboration with J.R. Leon (Caracas, Venezuela) and P. Cattiaux (Toulouse). Recursive estimators have been also proposed by the same authors in [47], also recently accepted. In a recent collaboration with Adeline Samson from the statistics department in the Lab, we considered adaptive estimation, that is we proposed a data-driven procedure for the choice of the bandwidth parameters. A paper has been submitted.

In [6], we focused on damping Hamiltonian systems under the so-called fluctuation-dissipation condition.

Note that Professor Jose R. Leon (Caracas, Venezuela) is now funded by an international Inria Chair, allowing to collaborate further on parameter estimation.

We recently proposed a paper on the use of the Euler scheme for inference purposes, considering reflected diffusions. This paper could be extended to the hypoelliptic framework.

7.3.5. Multivariate Risk Indicators

Participants: Clémentine Prieur, Patricia Tencaliec.

Studying risks in a spatio-temporal context is a very broad field of research and one that lies at the heart of current concerns at a number of levels (hydrological risk, nuclear risk, financial risk etc.). Stochastic tools for risk analysis must be able to provide a means of determining both the intensity and probability of occurrence of damaging events such as e.g. extreme floods, earthquakes or avalanches. It is important to be able to develop effective methodologies to prevent natural hazards, including e.g. the construction of barrages.

Different risk measures have been proposed in the one-dimensional framework . The most classical ones are the return level (equivalent to the Value at Risk in finance), or the mean excess function (equivalent to the Conditional Tail Expectation CTE). However, most of the time there are multiple risk factors, whose dependence structure has to be taken into account when designing suitable risk estimators. Relatively recent regulation (such as Basel II for banks or Solvency II for insurance) has been a strong driver for the development of realistic spatio-temporal dependence models, as well as for the development of multivariate risk measurements that effectively account for these dependencies.

We refer to [52] for a review of recent extensions of the notion of return level to the multivariate framework. In the context of environmental risk, [73] proposed a generalization of the concept of return period in dimension greater than or equal to two. Michele et al. proposed in a recent study [53] to take into account the duration and not only the intensity of an event for designing what they call the dynamic return period. However, few studies address the issues of statistical inference in the multivariate context. In [54], [56], we proposed non parametric estimators of a multivariate extension of the CTE. As might be expected, the properties of these estimators deteriorate when considering extreme risk levels. In collaboration with Elena Di Bernardino (CNAM, Paris), Clémentine Prieur is working on the extrapolation of the above results to extreme risk levels.

Elena Di Bernardino, Véronique Maume-Deschamps (Univ. Lyon 1) and Clémentine Prieur also derived an estimator for bivariate tail [55]. The study of tail behavior is of great importance to assess risk.

With Anne-Catherine Favre (LTHE, Grenoble), Clémentine Prieur supervises the PhD thesis of Patricia Tencaliec. We are working on risk assessment, concerning flood data for the Durance drainage basin (France). The PhD thesis started in October 2013 and will be defended in next February. A first paper on data reconstruction has been accepted [79]. It was a necessary step as the initial series contained many missing data. A second paper is in preparation, considering the modeling of precipitation amount with semi-parametric sparse mixtures.

7.4. Assimilation of Images

Participants: Elise Arnaud, François-Xavier Le Dimet, Maëlle Nodet, Arthur Vidard, Nelson Feyeux.

7.4.1. Direct assimilation of image sequences

At the present time the observation of Earth from space is done by more than thirty satellites. These platforms provide two kinds of observational information:

- Eulerian information as radiance measurements: the radiative properties of the earth and its fluid envelops. These data can be plugged into numerical models by solving some inverse problems.
- Lagrangian information: the movement of fronts and vortices give information on the dynamics of the fluid. Presently this information is scarcely used in meteorology by following small cumulus clouds and using them as Lagrangian tracers, but the selection of these clouds must be done by hand and the altitude of the selected clouds must be known. This is done by using the temperature of the top of the cloud.

MOISE was the leader of the ANR ADDISA project dedicated to the assimilation of images, and is a member of its follow-up GeoFluids (along with EPI FLUMINANCE and CLIME, and LMD, IFREMER and Météo-France) that ended in 2013.

During the ADDISA project we developed Direct Image Sequences Assimilation (DISA) and proposed a new scheme for the regularization of optical flow problems [77], which was recently extended [76]. Thanks to the nonlinear brightness assumption, we proposed an algorithm to estimate the motion between two images, based on the minimization of a nonlinear cost function. We proved its efficiency and robustness on simulated and experimental geophysical flows. As part of the ANR project GeoFluids, we are investigating new ways to define distance between a couple of images. One idea is to compare the gradient of the images rather than the actual value of the pixels. This leads to promising results. Another idea, currently under investigation, consists in comparing main structures within each image. This can be done using, for example, a wavelet representation of images. Both approaches have been compared, in particular their relative merits in dealing with observation errors. This work has been extended to the progressive assimilation of different scales contained in the observations [22]

In recent developments we have also used "Level Sets" methods to describe the evolution of the images. The advantage of this approach is that it permits, thanks to the level sets function, to consider the images as a state variable of the problem. We have derived an Optimality System including the level sets of the images. This approach is being applied to the tracking of oceanic oil spills [41]

7.4.2. Optimal transport for image assimilation

We investigate the use of optimal transport based distances for data assimilation, and in particular for assimilating dense data such as images. The PhD thesis of N. Feyeux studied the impact of using the Wasserstein distance in place of the classical Euclidean distance (pixel to pixel comparison). In a simplified one dimensional framework, we showed that the Wasserstein distance is indeed promising. Figure 2 illustrates the advantage of using Wasserstein over L^2 : imagine that the density ρ_0 represents the observation, ρ_1 the background, and that we wish to find the "best" interpolation of the two. The "middle point" between them in the sense of the L^2 distance does not have the correct characteristics: its amplitude is smaller, and its shape is not correct as well. On the contrary, the W^2 middle point presents a similar structure and is indeed physically a better candidate for the interpolation of ρ_0 and ρ_1. Data assimilation experiments with the Shallow Water model have been realised and confirm the interest of the Wasserstein distance. Results have been presented at ISDA conference [35] and a paper has been submitted [34]. N. Feyeux will defend his PhD thesis on Dec. 8th.

7.5. Tracking of Mesoscale Convective Systems

Participant: Clémentine Prieur.

We are interested in the tracking of mesoscale convective systems.A particular region of interest is West Africa. Data and hydrological expertise is provided by T. Vischel and T. Lebel (LTHE, Grenoble).

A first approach involves adapting the multiple hypothesis tracking (MHT) model originally designed by the NCAR (National Centre for Atmospheric Research) for tracking storms [78] to the data for West Africa. With A. Makris (working on a post-doctoral position), we proposed a Bayesian approach [69], which consists in considering that the state at time t is composed on one hand by the events (birth, death, splitting, merging) and on the other hand by the targets' attributes (positions, velocities, sizes, ...). The model decomposes the state into two sub-states: the events and the targets positions/attributes. The events are updated first and are

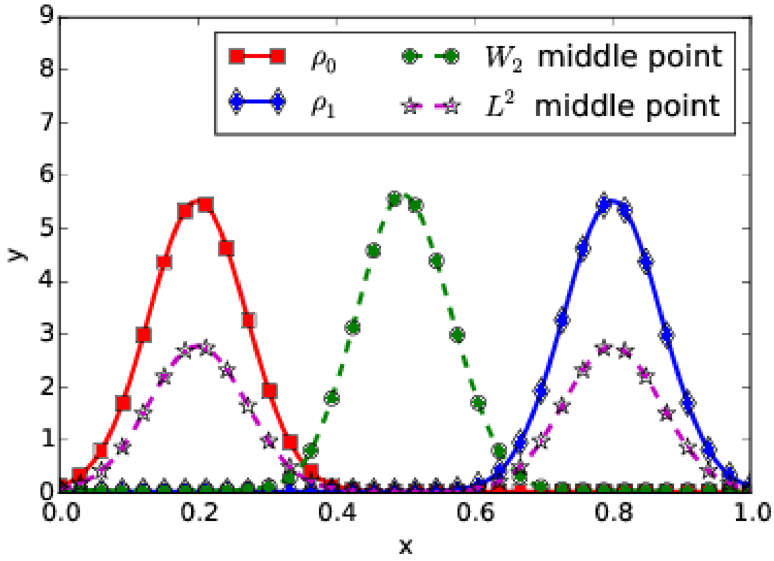

Figure 2. Illustration of the impact of using the Wasserstein distance in Data Assimilation instead of the classical L^2 distance.

conditioned to the previous targets sub-state. Then given the new events the target substate is updated. A simulation study allowed to verify that this approach improves the frequentist approach by Storlie et al. (2009). It has been tested on simulations [69] and investigated in the specific context of real data on West Africa [12]. Using PHD (probability hypothesis density) filters adapted to our problem, generalizing recent developments in particle filtering for spatio-temporal branching processes (e.g. [44]) could be an interesting alternative to explore. The idea of a dynamic, stochastic tracking model should then provide the base for generating rainfall scenarios over a relatively vast area of West Africa in order to identify the main sources of variability in the monsoon phenomenon.

7.6. Land Use and Transport Models Calibration

Participants: Thomas Capelle, Laurent Gilquin, Clémentine Prieur, Arthur Vidard, Peter Sturm, Elise Arnaud.

Given the complexity of modern urban areas, designing sustainable policies calls for more than sheer expert knowledge. This is especially true of transport or land use policies, because of the strong interplay between the land use and the transportation systems. Land use and transport integrated (LUTI) modelling offers invaluable analysis tools for planners working on transportation and urban projects. Yet, very few local authorities in charge of planning make use of these strategic models. The explanation lies first in the difficulty to calibrate these models, second in the lack of confidence in their results, which itself stems from the absence of any well-defined validation procedure. Our expertise in such matters will probably be valuable for improving the reliability of these models. To that purpose we participated to the building up of the ANR project CITiES led by the STEEP EPI. This project started early 2013 and two PhD about sensitivity analysis and calibration were launched late 2013. Laurent Gilquin defended his PhD in October 2016 [2] and Thomas Capelle will defend his in February 2017.

On top of the development on calibration procedure and sensitivity analysis for LUTI models, a study was conducted to understand in what extend modelling is or could be more integrated into urban planning [17].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

A 3-year contract with ARTELIA Group: funding for the PhD thesis of M.P. Daou (CIFRE)

A 3-year contract named ALBATROS with Mercator-Ocean on the topic « Interaction océan, vagues, atmosphère à haute résolution ».

A 1-year contract with NOVELTIS on the thematic "Développement de démonstrateurs avec AGRIF": see 6.1

A 1-year contract with IFREMER on the thematic "Evolution de la librairie de raffinement de maillage en Fortran (AGRIF) : amélioration de la prise en compte du trait de côte et des frontiéres ouvertes en contexte paralléle MPI/OpenMP" : see 6.1

The Chair OQUAIDO – for "Optimisation et QUAntification d'Incertitudes pour les Données Onéreuses" in French – is the chair in applied mathematics held at Mines Saint-Étienne (France). It aims at gathering academical and technological partners to work on problems involving costly-to-evaluate numerical simulators for uncertainty quantification, optimization and inverse problems. This Chair, created in January 2016, is the continuation of the projects DICE and ReDICE which respectively covered the periods 2006-2009 and 2011-2015.

9. Partnerships and Cooperations

9.1. Regional Initiatives

N. Feyeux PhD is sponsored by the action ARC3 Environment of the Region Rhone-Alpes.

Clémentine Prieur obtained a 8kE two-years funding for a local project on risk by the Labex Persyval. Philippe Naveau (from LSCE, Paris) will visit the team during one month in this context.

9.2. National Initiatives

9.2.1. ANR

A 3.5 year ANR contract: ANR CITiES (numerical models project selected in 2012). https://team.inria.fr/steep/projects/.

A 4-year ANR contract: ANR TOMMI (Transport Optimal et Modèles Multiphysiques de l'Image), see paragraphs 7.4.2, 7.4.

A 5 year ANR contract (2011-2016): ANR COMODO (Communauté de Modélisation Océanographique) on the thematic "Numerical Methods in Ocean Modelling". (coordinator L. Debreu), see 7.1.1.

A 4-year contract : ANR HEAT (Highly Efficient ATmospheric modelling) http://www.agence-nationale-recherche.fr/?Project=ANR-14-CE23-0010.

9.2.2. Other Initiatives

A. Vidard leads a group of projects gathering multiple partners in France and UK on the topic "Variational Data Assimilation for the NEMO/OPA9 Ocean Model", see 6.5.

C. Prieur chaired GdR MASCOT NUM 2010-2015, in which are also involved M. Nodet, E. Blayo, C. Helbert, E. Arnaud, L. Viry, S. Nanty, L. Gilquin. She is still strong involved in thie group (co-chair) http://www.gdr-mascotnum.fr/doku.php.

C. Prieur is the leader of the LEFE/MANU project MULTIRISK (2014-2016) on multivariate risk analysis, which gathers experts from Lyon 1 University, CNAM, LSCE and Grenoble University mainly.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. ERA-CLIM2

Type: COOPERATION

Instrument: Specific Targeted Research Project

Program: Collaborative project FP7-SPACE-2013-1

Project acronym: ERA-CLIM2

Project title: European Reanalysis of the Global Climate System

Duration: 01/2014 - 12/2016

Coordinator: Dick Dee (ECMWF, Europe)

Other partners: Met Office (UK), EUMETSAT (Europe), Univ Bern (CH), Univ. Vienne (AT), FFCUL (PT), RIHMI-WDC (RU), Mercator-Océan (FR), Météo-France (FR), DWD (DE), CERFACS (FR), CMCC (IT), FMI (FI), Univ. Pacifico (CL), Univ. Reading (UK), Univ. Versailles St Quentin en Yvelines (FR)

Inria contact: Arthur Vidard

9.3.2. Collaborations with Major European Organizations

Partner: European Centre for Medium Range Weather Forecast. Reading (UK)

World leading Numerical Weather Center, that include an ocean analysis section in order to provide ocean initial condition for the coupled ocean atmosphere forecast. They play a significant role in the NEMOVAR project in which we are also partner.

Partner: Met Office (U.K) National British Numerical Weather and Oceanographic service. Exceter (UK).

We do have a strong collaboration with their ocean initialization team through both our NEMO, NEMO-ASSIM and NEMOVAR activities. They also are our partner in the NEMOVAR consortium.

Partner: University of Reading, Department of Meteorology, Department of Mathematics

Subject: Data assimilation for geophysical systems.

9.4. International Initiatives

9.4.1. Inria International Partners

9.4.1.1. Informal International Partners

F. Lemarié and L. Debreu collaborate with Hans Burchard and Knut Klingbeil from the Leibniz-Institut für Ostseeforschung in Warnemünde.

C. Prieur collaborates with Jose R. Leon (UCV, Central University of Caracas), who is funded by the international Inria chair program.

C. Prieur is collaborating with AC Favre (LTHE, Grenoble) in the framework of a two-years canadian funding from CFQCU (Conseil franco-québécois de coopération universitaire) 2015-2016.

9.4.2. Participation in Other International Programs

9.4.2.1. International Initiatives

SIDRE

Title: Statistical inference for dependent stochastic processes and application in renewable energy

International Partners (Institution - Laboratory - Researcher):

Universidad de Valparaiso (Chile) - Karine Bertin

Universidad Central de Venezuela (Venezuela) - Jose León

Duration: 2016 - 2017

Start year: 2016

C. Prieur is one of the two french coordinators of the MATH AmSud project SIDRE. We want to develop, apply and study the properties of statistical tools in several non-parametric models, segmentation models, time series and random fields models, and to study some classes of long-range dependent processes, for their possible application in renewable energies and other domains. In particular non-parametric statistical procedure in Markov switching non-linear autoregressive models, finite mixture, non-parametric functional test and non-parametric estimators in stochastic damping Hamiltonian systems will be considered. Statistical tools for segmenting dependent multiples series, censoring processes in time series models and a new model interpolation scheme will be studied.

9.5. International Research Visitors

9.5.1. Visits to International Teams

F.-X. Le Dimet has been invited for 2 weeks in October 2016 at Florida State University. He has delivered a seminar.

F.-X. Le Dimet has been invited for 3 weeks at the Harbin Institute of Technology in June 2016 to work with Ma Jianwei and Long Li. He delivered 2 seminars and 2 courses on data assimilation.

F.-X. Le Dimet has been invited for a week at Universidad Complutense in Maddrid in November 2016 to lecture (8 hours) on Variational Data Assimilation. A collaboration has been started on oil pollution on the ocean. The project will include the developments of Assimilation of Images and data assimilation for pollution carried out at the Institute of Mechanics in Hanoi.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific events organisation

E. Blayo, A. Vidard and E. Cosme organized the 6th French national symposium on data assimilation (Grenoble, November 30 - December 2, 2016).

L. Debreu has organized the international workshop "DRAKKAR" on global ocean modelling with the NEMO system (January 2016).

F. Lemarié was the convener of a session « Recent Developments in Numerical Earth System Modeling » during the 2016 European Geosciences Union General Assembly in Vienna (http://meetingorganizer.copernicus.org/EGU2016/session/21050).

C.Prieur was a member of the organizing committee of the Journées MAS 2016, Grenoble http://www.sciencesconf.org/browse/conference/?confid3D2486

10.1.2. Scientific events selection

10.1.2.1. Member of the conference program committees

L. Debreu was a member of the program committee of the International Conference on Computational Science (ICCS 2016), Paris, December 2016.

C.Prieur is a member of the program committee of the International Conference on Sensitivity Analysis of Model Output (SAMO 2016), La Réunion http://samo2016.univ-reunion.fr/

10.1.3. Journal

10.1.3.1. Reviewer - Reviewing activities

E. Blayo: reviewer for Mathematics and Computers in Simulation, Ocean Modelling.

L. Debreu: reviewer for Ocean Modelling, Ocean Dynamics, Geophysical Model Development.

F. Lemarié: reviewer for Ocean Modeling, Dynamics of Atmospheres and Oceans, Geoscientific Model Development, SIAM Journal on Scientific Computing

10.1.4. Leadership within the scientific community

E. Blayo is the chair of the CNRS-INSU research program LEFE-MANU on mathematical and numerical methods for ocean and atmosphere http://www.insu.cnrs.fr/co/lefe.

L. Debreu is the coordinator of the national group COMODO (Numerical Models in Oceanography).

C. Prieur chairs GdR MASCOT NUM, in which are also involved M. Nodet, E. Blayo, C. Helbert, E. Arnaud, L. Viry, S. Nanty, L. Gilquin. http://www.gdr-mascotnum.fr/doku.php.

10.1.5. Scientific expertise

F. Lemarié is a member of the CROCO (https://www.croco-ocean.org/) scientific committee in charge of the « numerical methods » topic.

10.1.6. Research administration

E. Blayo is a deputy director of the Jean Kuntzmann Lab.

L. Debreu is a member of the scientific evaluation committee of the French Research Institute for Development (IRD).

E.Arnaud is a member of the executive committee of IXXI (complex system institute) http://www.ixxi.fr.

C.Prieur is an elected member of the National Council of Universities (CNU).

C.Prieur is a member of the Scientific Council of the Mathematical Society of France (SMF).

C.Prieur is a member of the Committee of Statistical Mathematics Group of the French Statistical Society (SFdS).

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence: E. Blayo, Mathématiques pour l'ingénieur, 52h, L1, University of Grenoble

License : E. Arnaud, Mathématiques pour l'inge´nieur, 57h, L1, University Grenoble Alpes, France.

License : E. Arnaud, Diplôme d'accès à la license, 15h, L1, University Grenoble Alpes, France.

Licence : M. Nodet, outils mathématiques pour l'ingénieur, 100h, L1, Univ. Grenoble Alpes, France

Master : E. Arnaud, Tutorat d'apprentis MIAGE, 28h, M2, University Grenoble Alpes, France.

Master : E. Arnaud, Projet de programmation en traitement d'images, 16h, M1, University Grenoble Alpes, France.

Master : E. Arnaud, Computer Vision, 9h, M2, University Grenoble Alpes, France.

Master : M. Nodet, partial differential equation, 20h, M1, Univ. Grenoble Alpes, France.

Master : M. Nodet, inverse methods and data assimilation, 30h, M2, Univ. Grenoble Alpes, France.

Master: E. Blayo, Méthode des éléments finis, 47h, M1, University of Grenoble.

Master: E. Blayo, Partial Differential Equations and numerical methods, 43h, M1, ENSIMAG and University of Grenoble.

Doctorat: E. Blayo, M. Nodet, A. Vidard, Introduction to data assimilation, 20h, University of Grenoble.

Doctorat : L. Debreu, Formation doctorale nationale Modélisation numérique de l'océan et de l'atmosphère, 21-25 novembre 2016, Paris, France. With T. Dubos (LMD/Ecole Polytechnique, Paris), G. Roullet (Brest University), F. Hourdin (LMD/CNRS, Paris).

E-learning

SPOC : E. Arnaud, M. Nodet, E. Blayo, A. Vidard , 10 weeks, moodle platform http://tinyurl.com/uga-mat207, University Grenoble Alpes , L1 , 150 students

Pedagogical resources : all documents for problem-based learning including videos http://tinyurl.com/youtube-mat207.

10.2.2. Supervision

PhD : Nelson Feyeux, Application du transport optimal pour l'assimilation de données images, December 2016, A. Vidard, M. Nodet.

PhD : Mehdi-Pierre Daou, Développement d'une méthodologie de couplage multimodèles avec changements de dimension - Validation sur un cas-test réaliste, Université Grenoble Alpes, 27 septembre 2016, E. Blayo & A. Rousseau, see [1].

PhD : Laurent Gilquin, Echantillonage Monte Carlo et quasi-Monte Carlo pour l'estimation des indices de Sobol'. Application à un modèle transport-urbanisme, Université Grenoble Alpes, 17 octobre 2016, C. Prieur and E. Arnaud, see [2].

PhD in progress : Thomas Capelle, Calibration of LUTI models, octobre 2013, P. Sturm (EPI STEEP), A.Vidard.

PhD in progress : Rémi Pellrej, Assimilation de données pour les modèles couplés, octobre 2014, A. Vidard, F. Lemarié.

PhD in progress: Charles Pelletier, Etude mathématique et numérique de la formulation du couplage océan-atmosphère dans les modèles de climat. December 2014, E. Blayo, F. Lemarié and P. Braconnot.

PhD in progress : Patricia Tencaliec, Approches stochastiques pour la gestion des risques environnementaux extrêmes, October 2013, Clémentine Prieur, Anne-Catherine Favre (LTHE).

PhD in progress : Reda El Amri, Analyse d'incertitudes et de robustesse pour les modèles à entrées et sorties fonctionnelles, April 2016, Clémentine Prieur, Céline Helbert (Centrale Lyon), funded by IFPEN, int the OQUAIDO chair program.

Internship : Damien Garino, Suivi de formes non rigides dans les images, M2, University Grenoble Alpes, 6 months, E. Arnaud and A. Vidard.

10.2.3. Juries

E. Blayo:

- 1 July 2016 - HDR thesis of Yann Michel, University of Toulouse (referee),
- 5 July 2016 - PhD thesis of François Mercier, University of Versailles-Saint Quentin (examiner),
- 9 November 2016 - PhD thesis of Vladimir Groza, University of Nice (referee),
- 5 December 2016 - PhD thesis of Cyrille Mosbeux, University of Grenoble (president).

L. Debreu – PhD thesis of Charles Colavolpe, University of Toulouse (referee),

L. Debreu – PhD thesis of Amandine Declerck, University of Toulon (referee),

A. Vidard – PhD thesis of Rachida El Ouaranis, Institut national polytechnique de Toulouse / Université Hassan 2 de Casablanca (referee),

F.-X. Le Dimet – HDR thesis of Philippe Moireau, Paris-Saclay,

F. Lemarié: 30 mars 2016 - PhD thesis of Véra Oerder, Université Pierre et Marie Curie, Paris 6 (examiner),

E. Anaud: juries of M2 thesis and M2 Miage apprentices,

Clémentine Prieur took part to recruiting CR2 for Inria Grenoble Alpes (2014,2015,2016).

10.3. Popularization

E. Blayo gave several outreach talks, in particular for middle school and high school students, and for more general audiences.

Ch. Kazantsev and E. Blayo participate in the creation of "La Grange des maths" in Varces (south of Grenoble). See http://www.la-grange-des-maths.fr/.

Since 2010, Ch. Kazantsev is the Director of the IREM of Grenoble http://www-irem.ujf-grenoble.fr/irem/accueil/. The Institute is under rapid development now, joining about 50 teachers of primary and secondary schools of the Grenoble region and 15 university professors. They work together 16 times a year on the development of the teaching strategy for the educational community. In addition to this, IREM is the editor of two journals: "Grand N" destined to primary schools teachers and "Petit x" – to the secondary schools.

M. Nodet and E. Arnaud co-organises a year-round weekly math club in two secondary schools, where pupils research open mathematical problems.

M. Nodet is a member of "les Emulateurs", a group of Grenoble Univ. professors meeting once a month around the subjects of innovative pedagogy and its applications to universities.

M. Nodet takes part in a maths club "Math en Jeans" involving two secondary schools around Grenoble.

M. Nodet takes part in training modelling in mathematics to secondary school maths teachers through the regional "Maison pour la Science" and is also in charge of an IREM group about building interdisciplinary projects for secondary school classes.

Podcast Interstices Clémentine Prieur's interview https://interstices.info/jcms/p_86521/mieux-modeliser-le-climat-grace-aux-statistiques

11. Bibliography

Publications of the year

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[2] L. GILQUIN.*Monte Carlo and quasi-Monte Carlo sampling methods for the estimation of Sobol' indices. Application to a LUTI model*, Université Grenoble Alpes, October 2016, https://hal.inria.fr/tel-01403914.

Articles in International Peer-Reviewed Journal

[3] A. BELJAARS, E. DUTRA, G. BALSAMO, F. LEMARIÉ.*On the numerical stability of surface-atmosphere coupling in weather and climate models*, in "Geoscientific Model Development Discussions", 2016, p. 1 - 19 [*DOI :* 10.5194/GMD-2016-96], https://hal.inria.fr/hal-01406623.

[4] E. BLAYO, D. CHEREL, A. ROUSSEAU.*Towards optimized Schwarz methods for the Navier-Stokes equations*, in "Journal of Scientific Computing", 2016, vol. 66, p. 275–295, https://hal.inria.fr/hal-00982087.

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Project-Team ARIC

Arithmetic and Computing

IN COLLABORATION WITH: Laboratoire de l'Informatique du Parallélisme (LIP)

IN PARTNERSHIP WITH:
CNRS

Ecole normale supérieure de Lyon

Université Claude Bernard (Lyon 1)

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Algorithmics, Computer Algebra and Cryptology

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Project-Team ARIC

Creation of the Team: 2012 January 01, updated into Project-Team: 2013 January 01

Keywords:

Computer Science and Digital Science:

1.1. - Architectures
2.4. - Verification, reliability, certification
4. - Security and privacy
7. - Fundamental Algorithmics

Other Research Topics and Application Domains:

9.4. - Sciences
9.8. - Privacy

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2. Overall Objectives

2.1. Overview

The overall objective of AriC (Arithmetic and Computing) is, through computer arithmetic and computational mathematics, to improve computing at large.

A major challenge in modeling and scientific computing is the simultaneous mastery of hardware capabilities, software design, and mathematical algorithms for the efficiency of the computation. Further, performance relates as much to efficiency as to reliability, requiring progress on automatic proofs, certificates and code generation. In this context, computer arithmetic and mathematical algorithms are the keystones of AriC. Our approach conciliates fundamental studies, practical performance and qualitative aspects, with a shared strategy going from high-level problem specifications and normalization actions, to computer arithmetic and the lowest-level details of implementations.
We focus on the following lines of action:

- Design and integration of new methods and tools for mathematical program specification, certification, security, and guarantees on numerical results. Some main ingredients here are: the interleaving of formal proofs, computer arithmetic and computer algebra; error analysis and computation of certified error bounds; the study of the relationship between performance and numerical quality; and on the cryptology aspects, focus on the practicality of existing protocols and design of more powerful lattice-based primitives.

- Generalization of a hybrid symbolic-numeric trend, and interplay between arithmetics for both improving and controlling numerical approaches (symbolic $\rightarrow$ numeric), and accelerating exact solutions (symbolic $\longleftarrow$ numeric). This trend, especially in the symbolic computation community, has acquired a strategic role for the future of scientific computing. The integration in AriC of computer arithmetic, reliable computing, and algebraic computing is expected to lead to a deeper understanding of the problem and novel solutions.
- Mathematical and algorithmic foundations of computing. We address algorithmic complexity and fundamental aspects of approximation, polynomial and matrix algebra, and lattice-based cryptology. Practical questions concern the design of high performance and reliable computing kernels, thanks to optimized computer arithmetic operators and an improved adequacy between arithmetic bricks and higher level ones.

According to the application domains that we target and our main fields of expertise, these lines of actions are declined in three themes with specific objectives. These themes also correspond to complementary angles for addressing the general computing challenge stated at the beginning of this introduction:

- **Efficient approximation methods** (§3.1). Here lies the question of interleaving formal proofs, computer arithmetic and computer algebra, for significantly extending the range of functions whose reliable evaluation can be optimized.
- **Lattices: algorithms and cryptology** (§3.2). Long term goals are to go beyond the current design paradigm in basis reduction, and to demonstrate the superiority of lattice-based cryptography over contemporary public-key cryptographic approaches.
- **Algebraic computing and high performance kernels** (§3.3). The problem is to keep the algorithm and software designs in line with the scales of computational capabilities and application needs, by simultaneously working on the structural and the computer arithmetic levels.

3. Research Program

3.1. Efficient approximation methods

3.1.1. Computer algebra generation of certified approximations

We plan to focus on the generation of certified and efficient approximations for solutions of linear differential equations. These functions cover many classical mathematical functions and many more can be built by combining them. One classical target area is the numerical evaluation of elementary or special functions. This is currently performed by code specifically handcrafted for each function. The computation of approximations and the error analysis are major steps of this process that we want to automate, in order to reduce the probability of errors, to allow one to implement "rare functions", to quickly adapt a function library to a new context: new processor, new requirements – either in terms of speed or accuracy.

In order to significantly extend the current range of functions under consideration, several methods originating from approximation theory have to be considered (divergent asymptotic expansions; Chebyshev or generalized Fourier expansions; Padé approximants; fixed point iterations for integral operators). We have done preliminary work on some of them. Our plan is to revisit them all from the points of view of effectivity, computational complexity (exploiting linear differential equations to obtain efficient algorithms), as well as in their ability to produce provable error bounds. This work is to constitute a major progress towards the automatic generation of code for moderate or arbitrary precision evaluation with good efficiency. Other useful, if not critical, applications are certified quadrature, the determination of certified trajectories of spatial objects and many more important questions in optimal control theory.

3.1.2. Digital Signal Processing

As computer arithmeticians, a wide and important target for us is the design of efficient and certified linear filters in digital signal processing (DSP). Actually, following the advent of MATLAB as the major tool for filter design, the DSP experts now systematically delegate to MATLAB all the part of the design related to numerical issues. And yet, various key MATLAB routines are neither optimized, nor certified. Therefore, there is a lot of room for enhancing numerous DSP numerical implementations and there exist several promising approaches to do so.

The main challenge that we want to address over the next period is the development and the implementation of optimal methods for rounding the coefficients involved in the design of the filter. If done in a naive way, this rounding may lead to a significant loss of performance. We will study in particular FIR and IIR filters.

3.1.3. Table Maker's Dilemma (TMD)

There is a clear demand for hardest-to-round cases, and several computer manufacturers recently contacted us to obtain new cases. These hardest-to-round cases are a precious help for building libraries of correctly rounded mathematical functions. The current code, based on Lefèvre's algorithm, will be rewritten and formal proofs will be done.

We plan to use uniform polynomial approximation and diophantine techniques in order to tackle the case of the IEEE quad precision, and analytic number theory techniques (exponential sums estimates) for counting the hardest-to-round cases.

3.2. Lattices: algorithms and cryptology

Lattice-based cryptography (LBC) is an utterly promising, attractive (and competitive) research ground in cryptography, thanks to a combination of unmatched properties:

- **Improved performance.** LBC primitives have low asymptotic costs, but remain cumbersome in practice (e.g., for parameters achieving security against computations of up to 2100 bit operations). To address this limitation, a whole branch of LBC has evolved where security relies on the restriction of lattice problems to a family of more structured lattices called *ideal lattices*. Primitives based on such lattices can have quasi-optimal costs (i.e., quasi-constant amortized complexities), outperforming all contemporary primitives. This asymptotic performance sometimes translates into practice, as exemplified by NTRUEncrypt.
- **Improved security.** First, lattice problems seem to remain hard even for quantum computers. Moreover, the security of most of LBC holds under the assumption that standard lattice problems are hard in the worst case. Oppositely, contemporary cryptography assumes that specific problems are hard with high probability, for some precise input distributions. Many of these problems were artificially introduced for serving as a security foundation of new primitives.
- **Improved flexibility.** The master primitives (encryption, signature) can all be realized based on worst-case (ideal) lattice assumptions. More evolved primitives such as ID-based encryption (where the public key of a recipient can be publicly derived from its identity) and group signatures, that were the playing-ground of pairing-based cryptography (a subfield of elliptic curve cryptography), can also be realized in the LBC framework, although less efficiently and with restricted security properties. More intriguingly, lattices have enabled long-wished-for primitives. The most notable example is homomorphic encryption, enabling computations on encrypted data. It is the appropriate tool to securely outsource computations, and will help overcome the privacy concerns that are slowing down the rise of the cloud.

We work on three directions, detailed now.

3.2.1. Lattice algorithms

All known lattice reduction algorithms follow the same design principle: perform a sequence of small elementary steps transforming a current basis of the input lattice, where these steps are driven by the Gram-Schmidt orthogonalisation of the current basis.

In the short term, we will fully exploit this paradigm, and hopefully lower the cost of reduction algorithms with respect to the lattice dimension. We aim at asymptotically fast algorithms with complexity bounds closer to those of basic and normal form problems (matrix multiplication, Hermite normal form). In the same vein, we plan to investigate the parallelism potential of these algorithms.

Our long term goal is to go beyond the current design paradigm, to reach better trade-offs between run-time and shortness of the output bases. To reach this objective, we first plan to strengthen our understanding of the interplay between lattice reduction and numerical linear algebra (how far can we push the idea of working on approximations of a basis?), to assess the necessity of using the Gram-Schmidt orthogonalisation (e.g., to obtain a weakening of LLL-reduction that would work up to some stage, and save computations), and to determine whether working on generating sets can lead to more efficient algorithms than manipulating bases. We will also study algorithms for finding shortest non-zero vectors in lattices, and in particular look for quantum accelerations.

We will implement and distribute all algorithmic improvements, e.g., within the fplll library. We are interested in high performance lattice reduction computations (see application domains below), in particular in connection with/continuation of the HPAC ANR project (algebraic computing and high performance consortium).

3.2.2. Lattice-based cryptography

Our long term goal is to demonstrate the superiority of lattice-based cryptography over contemporary public-key cryptographic approaches. For this, we will 1- Strengthen its security foundations, 2- Drastically improve the performance of its primitives, and 3- Show that lattices allow to devise advanced and elaborate primitives.

The practical security foundations will be strengthened by the improved understanding of the limits of lattice reduction algorithms (see above). On the theoretical side, we plan to attack two major open problems: Are ideal lattices (lattices corresponding to ideals in rings of integers of number fields) computationally as hard to handle as arbitrary lattices? What is the quantum hardness of lattice problems?

Lattice-based primitives involve two types of operations: sampling from discrete Gaussian distributions (with lattice supports), and arithmetic in polynomial rings such as $(\mathbb{Z}/q\mathbb{Z})[x]/(x^n+1)$ with n a power of 2. When such polynomials are used (which is the case in all primitives that have the potential to be practical), then the underlying algorithmic problem that is assumed hard involves ideal lattices. This is why it is crucial to precisely understand the hardness of lattice problems for this family. We will work on improving both types of operations, both in software and in hardware, concentrating on values of q and n providing security. As these problems are very arithmetic in nature, this will naturally be a source of collaboration with the other themes of the AriC team.

Our main objective in terms of cryptographic functionality will be to determine the extent to which lattices can help securing cloud services. For example, is there a way for users to delegate computations on their outsourced dataset while minimizing what the server eventually learns about their data? Can servers compute on encrypted data in an efficiently verifiable manner? Can users retrieve their files and query remote databases anonymously provided they hold appropriate credentials? Lattice-based cryptography is the only approach so far that has allowed to make progress into those directions. We will investigate the practicality of the current constructions, the extension of their properties, and the design of more powerful primitives, such as functional encryption (allowing the recipient to learn only a function of the plaintext message). To achieve these goals, we will in particular focus on cryptographic multilinear maps.

This research axis of AriC is gaining strength thanks to the recruitment of Benoit Libert. We will be particularly interested in the practical and operational impacts, and for this reason we envision a collaboration with an industrial partner.

3.2.3. Application domains

- Diophantine equations. Lattice reduction algorithms can be used to solve diophantine equations, and in particular to find simultaneous rational approximations to real numbers. We plan to investigate the interplay between this algorithmic task, the task of finding integer relations between real numbers, and lattice reduction. A related question is to devise LLL-reduction algorithms that exploit specific shapes of input bases. This will be done within the ANR DynA3S project.

- Communications. We will continue our collaboration with Cong Ling (Imperial College) on the use of lattices in communications. We plan to work on the wiretap channel over a fading channel (modeling cell phone communications in a fast moving environment). The current approaches rely on ideal lattices, and we hope to be able to find new approaches thanks to our expertise on them due to their use in lattice-based cryptography. We will also tackle the problem of sampling vectors from Gaussian distributions with lattice support, for a very small standard deviation parameter. This would significantly improve current schemes for communication schemes based on lattices, as well as several cryptographic primitives.
- Cryptanalysis of variants of RSA. Lattices have been used extensively to break variants of the RSA encryption scheme, via Coppersmith's method to find small roots of polynomials. We plan to work with Nadia Heninger (U. of Pennsylvania) on improving these attacks, to make them more practical. This is an excellent test case for testing the practicality of LLL-type algorithm. Nadia Heninger has a strong experience in large scale cryptanalysis based on Coppersmith's method (http://smartfacts.cr.yp.to/)

3.3. Algebraic computing and high performance kernels

The main theme here is the study of fundamental operations ("kernels") on a hierarchy of symbolic or numeric data types spanning integers, floating-point numbers, polynomials, power series, as well as matrices of all these. Fundamental operations include basic arithmetic (e.g., how to multiply or how to invert) common to all such data, as well as more specific ones (change of representation/conversions, GCDs, determinants, etc.). For such operations, which are ubiquitous and at the very core of computing (be it numerical, symbolic, or hybrid numeric-symbolic), our goal is to ensure both high performance and reliability.

3.3.1. Algorithms

On the symbolic side, we will focus on the design and complexity analysis of algorithms for matrices over various domains (fields, polynomials, integers) and possibly with specific properties (structure). So far, our algorithmic improvements for polynomial matrices and structured matrices have been obtained in a rather independent way. Both types are well known to have much in common, but this is sometimes not reflected by the complexities obtained, especially for applications in cryptology and coding theory. Our goal in this area is thus to explore these connections further, to provide a more unified treatment, and eventually bridge these complexity gaps, A first step towards this goal will be the design of enhanced algorithms for various generalizations of Hermite-Padé approximation; in the context of list decoding, this should in particular make it possible to match or even improve over the structured-matrix approach, which is so far the fastest known.

On the other hand we will focus on the design of algorithms for certified computing. We will study the use of various representations, such as mid-rad for classical interval arithmetic, or affine arithmetic. We will explore the impact of precision tuning in intermediate computations, possibly dynamically, on the accuracy of the results (e.g. for iterative refinement and Newton iterations). We will continue to revisit and improve the classical error bounds of numerical linear algebra in the light of the subtleties of IEEE floating-point arithmetic.

Our goals in linear algebra and lattice basis reduction that have been detailed above in Section 3.2 will be achieved in the light of a hybrid symbolic-numeric approach.

3.3.2. Computer arithmetic

Our work on certified computing and especially on the analysis of algorithms in floating-point arithmetic leads us to manipulate floating-point data in their greatest generality, that is, as symbolic expressions in the base and the precision. Our aim here is thus to develop theorems as well as efficient data structures and algorithms for handling such quantities by computer rather than by hand as we do now. The main outcome would be a "symbolic floating-point toolbox" which provides a way to check automatically the certificates of optimality we have obtained on the error bounds of various numerical algorithms.

We will also work on the interplay between floating-point and integer arithmetics. Currently, small numerical kernels like an exponential or a 2×2 determinant are typically written using exclusively one of these two kinds of arithmetic. However, modern processors now have hardware support for both floating-point and integer arithmetics, often with vector (SIMD) extensions, and an important question is how to make the best use of all such capabilities to optimize for both accuracy and efficiency.

A third direction will be to work on algorithms for performing correctly-rounded arithmetic operations in medium precision as efficiently and reliably as possible. Indeed, many numerical problems require higher precision than the conventional floating-point (single, double) formats. One solution is to use multiple precision libraries, such as GNU MPFR, which allow the manipulation of very high precision numbers, but their generality (they are able to handle numbers with millions of digits) is a quite heavy alternative when high performance is needed. Our objective here is thus to design a multiple precision arithmetic library that would allow to tackle problems where a precision of a few hundred bits is sufficient, but which have strong performance requirements. Applications include the process of long-term iteration of chaotic dynamical systems ranging from the classical Henon map to calculations of planetary orbits. The designed algorithms will be formally proved.

Finally, our work on the IEEE 1788 standard leads naturally to the development of associated reference libraries for interval arithmetic. A first direction will be to implement IEEE 1788 interval arithmetic within MPFI, our library for interval arithmetic using the arbitrary precision floating-point arithmetic provided by MPFR: indeed, MPFI has been originally developed with definitions and handling of exceptions which are not compliant with IEEE 1788. Another one will be to provide efficient support for multiple-precision intervals, in mid-rad representation and by developing MPFR-based code-generation tools aimed at handling families of functions.

3.3.3. High-performance algorithms and software

The algorithmic developments for medium precision floating-point arithmetic discussed above will lead to high performance implementations on GPUs. As a follow-up of the HPAC project (which ended in December 2015) we shall pursue the design and implementation of high performance linear algebra primitives and algorithms.

4. Application Domains

4.1. Floating-point and Validated Numerics

Our expertise on validated numerics is useful to analyze and improve, and guarantee the quality of numerical results in a wide range of applications including:

- scientific simulation;
- global optimization;
- control theory.

Much of our work, in particular the development of correctly rounded elementary functions, is critical to the

- reproducibility of floating-point computations.

4.2. Cryptography, Cryptology, Communication Theory

Lattice reduction algorithms have direct applications in

- public-key cryptography;
- diophantine equations;
- communications theory.

5. New Software and Platforms

5.1. FPLLL

SCIENTIFIC DESCRIPTION

The fplll library is used or has been adapted to be integrated within several mathematical computation systems such as Magma, Sage, and PariGP. It is also used for cryptanalytic purposes, to test the resistance of cryptographic primitives.

FUNCTIONAL DESCRIPTION

fplll contains implementations of several lattice algorithms. The implementation relies on floating-point orthogonalization, and the LLL algorithm is central to the code, hence the name. It includes implementations of floating-point LLL reduction algorithms, offering different speed/guarantees ratios. It further includes an implementation of the BKZ reduction algorithm and variants thereof. It includes an implementation of the Kannan-Fincke-Pohst algorithm that finds a shortest non-zero lattice vector. For the same task, the GaussSieve algorithm is also available. Finally, it contains a variant of the enumeration algorithm that computes a lattice vector closest to a given vector belonging to the real span of the lattice.

- Participants: Martin Albrecht, Shi Bai, Guillaume Bonnoron, Léo Ducas, Damien Stehlé and Marc Stevens
- Contact: Damien Stehlé
- URL: https://github.com/fplll/fplll

5.2. HPLLL

hplll is an experimental C++ library companion to fplll.

FUNCTIONAL DESCRIPTION

hplll provides a specific LLL reduction algorithm using Householder orthogonalization, and HPC preliminary solutions especially for integer relation finding.

- Contact: Gilles Villard
- URL: http://perso.ens-lyon.fr/gilles.villard/hplll

5.3. GNU-MPFR

KEYWORDS: Multiple-Precision - Floating-point - Correct Rounding

FUNCTIONAL DESCRIPTION

GNU MPFR is an efficient multiple-precision floating-point library with well-defined semantics (copying the good ideas from the IEEE-754 standard), in particular correct rounding in 5 rounding modes. GNU MPFR provides about 80 mathematical functions, in addition to utility functions (assignments, conversions...). Special data (Not a Number, infinities, signed zeros) are handled like in the IEEE-754 standard.

There have been two new releases in 2016: 3.1.4 and 3.1.5. An MPFR-MPC developers meeting took place on 23 and 24 May 2016.

- Participants: Vincent Lefèvre and Paul Zimmermann
- Contact: Vincent Lefèvre
- URL: http://www.mpfr.org/

5.4. Gfun

A Maple package for solutions of linear differential or recurrence equations

FUNCTIONAL DESCRIPTION

Gfun is a Maple package for the manipulation of linear recurrence or differential equations. It provides tools for guessing a sequence or a series from its first terms, for manipulating rigorously solutions of linear differential or recurrence equations, using the equation as a data-structure.

- Contact: Bruno Salvy
- URL: http://perso.ens-lyon.fr/bruno.salvy/software/the-gfun-package/

5.5. Sipe

KEYWORDS: Floating-point - Correct Rounding
FUNCTIONAL DESCRIPTION

Sipe is a mini-library in the form of a C header file, to perform radix-2 floating-point computations in very low precisions with correct rounding, either to nearest or toward zero. The goal of such a tool is to do proofs of algorithms/properties or computations of tight error bounds in these precisions by exhaustive tests, in order to try to generalize them to higher precisions. The currently supported operations are addition, subtraction, multiplication (possibly with the error term), fused multiply-add/subtract (FMA/FMS), and miscellaneous comparisons and conversions. Sipe provides two implementations of these operations, with the same API and the same behavior: one based on integer arithmetic, and a new one based on floating-point arithmetic.

- Participant: Vincent Lefèvre
- Contact: Vincent Lefèvre
- URL: https://www.vinc17.net/research/sipe/

5.6. LinBox: a C++ library for exact, high-performance linear algebra computation

LinBox is a C++ template library for exact, high-performance linear algebra computation with dense, sparse, and structured matrices over the integers and over finite fields. LinBox is distributed under the LGPL license. The library is developed by a consortium of researchers in Canada, USA, and France. Clément Pernet is a main contributor, especially with a focus on parallel aspects during the period covered by this report.

- Participants: Clément Pernet, Gilles Villard
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- URL: http://www.linalg.org

6. New Results

6.1. Floating-point arithmetic

6.1.1. Parallel floating-point expansions for extended-precision GPU computations

GPUs are an important hardware development platform for problems where massive parallel computations are needed. Many of these problems require a higher precision than the standard double floating-point (FP) available. One common way of extending the precision is the multiple-component approach, in which real numbers are represented as the unevaluated sum of several standard machine precision FP numbers. This representation is called an FP expansion and it offers the simplicity of using directly available and highly optimized FP operations. In [30] we present new data-parallel algorithms for adding and multiplying FP expansions specially designed for extended precision computations on GPUs. These are generalized algorithms that can manipulate FP expansions of different sizes (from double-double up to a few tens of doubles) and ensure a certain worst case error bound on the results.

6.1.2. Error analysis of the Cornea-Harrison-Tang method

Assuming floating-point arithmetic with a fused multiply-add operation and rounding to nearest, the Cornea-Harrison-Tang method aims to evaluate expressions of the form $ab + cd$ with high relative accuracy. In [12] we provide a rounding error analysis of this method, which unlike previous studies is not restricted to binary floating-point arithmetic but holds for any radix β. We show first that an asymptotically optimal bound on the relative error of this method is $\frac{2\beta u+2u^2}{\beta-2u^2} = 2u + \frac{2}{\beta}u^2 + O(u^3)$, where $u = \frac{1}{2}\beta^{1-p}$ is the unit roundoff in radix β and precision p. Then we show that the possibility of removing the $O(u^2)$ term from this bound is governed by the radix parity and the tie-breaking strategy used for rounding: if β is odd or rounding is *to nearest even*, then the simpler bound $2u$ is obtained, while if β is even and rounding is *to nearest away*, then there exist floating-point inputs a, b, c, d that lead to a relative error larger than $2u + \frac{2}{\beta}u^2 - 4u^3$. All these results hold provided underflows and overflows do not occur and under some mild assumptions on β and p satisfied by IEEE 754-2008 formats.

6.1.3. Sharp error bounds for complex floating-point inversion

In [14] we study the accuracy of the classic algorithm for inverting a complex number given by its real and imaginary parts as floating-point numbers. Our analyses are done in binary floating-point arithmetic, with an unbounded exponent range and in precision p; we also assume that the basic arithmetic operations ($+$, $-$, $\times$, $/$) are rounded to nearest, so that the unit roundoff is $u = 2^{-p}$. We bound the largest relative error in the computed inverse either in the componentwise or in the normwise sense. We prove the componentwise relative error bound $3u$ for the complex inversion algorithm (assuming $p \geq 4$), and we show that this bound is asymptotically optimal (as $p \to \infty$) when p is even, and sharp when using one of the basic IEEE 754 binary formats with an odd precision ($p = 53, 113$). This componentwise bound obviously leads to the same bound $3u$ for the normwise relative error. However, we prove that the smaller bound $2.707131u$ holds (assuming $p \geq 24$) for the normwise relative error, and we illustrate the sharpness of this bound for the basic IEEE 754 binary formats ($p = 24, 53, 113$) using numerical examples.

6.1.4. On relative errors of floating-point operations: optimal bounds and applications

Rounding error analyses of numerical algorithms are most often carried out via repeated applications of the so-called standard models of floating-point arithmetic. Given a round-to-nearest function fl and barring underflow and overflow, such models bound the relative errors $E_1(t) = |t - \text{fl}(t)|/|t|$ and $E_(t) = |t - \text{fl}(t)|/|\text{fl}(t)|$ by the unit roundoff u. With S. M. Rump (Hamburg University of Technology), we investigate in [15] the possibility and the usefulness of refining these bounds, both in the case of an arbitrary real t and in the case where t is the exact result of an arithmetic operation on some floating-point numbers. We show that $E_1(t)$ and $E_2(t)$ are optimally bounded by $u/(1 + u)$ and u, respectively, when t is real or, under mild assumptions on the base and the precision, when $t = x \pm y$ or $t = xy$ with x, y two floating-point numbers. We prove that while this remains true for division in base $\beta > 2$, smaller, attainable bounds can be derived for both division in base $\beta = 2$ and square root. This set of optimal bounds is then applied to the rounding error analysis of various numerical algorithms: in all cases, we obtain significantly shorter proofs of the best-known error bounds for such algorithms, and/or improvements on these bounds themselves.

6.1.5. Computing floating-point logarithms with fixed-point operations

Elementary functions from the mathematical library input and output floating-point numbers. However, it is possible to implement them purely using integer/fixed-point arithmetic. This option was not attractive between 1985 and 2005, because mainstream processor hardware supported 64-bit floating-point, but only 32-bit integers. Besides, conversions between floating-point and integer were costly. This has changed in recent years, in particular with the generalization of native 64-bit integer support. The purpose of this article is therefore to reevaluate the relevance of computing floating-point functions in fixed-point. For this, several variants of the double-precision logarithm function are implemented and evaluated. Formulating the problem as a fixed-point one is easy after the range has been (classically) reduced. Then, 64-bit integers provide slightly more accuracy than 53-bit mantissa, which helps speed up the evaluation. Finally, multi-word arithmetic, critical for accurate implementations, is much faster in fixed-point, and natively supported by recent compilers. Novel techniques of argument reduction and rounding test are introduced in this context. Thanks to all this, a purely integer implementation of the correctly rounded double-precision logarithm outperforms the previous state of the art, with the worst-case execution time reduced by a factor 5. This work also introduces variants of the logarithm that input a floating-point number and output the result in fixed-point. These are shown to be both more accurate and more efficient than the traditional floating-point functions for some applications [35].

6.1.6. A library for symbolic floating-point arithmetic

To analyze a priori the accuracy of an algorithm in floating-point arithmetic, one usually derives a uniform error bound on the output, valid for most inputs and parametrized by the precision p. To show further that this bound is sharp, a common way is to build an input example for which the error committed by the algorithm comes close to that bound, or even attains it. Such inputs may be given as floating-point numbers in one of the IEEE standard formats (say, for $p = 53$) or, more generally, as expressions parametrized by p, that can be viewed as symbolic floating-point numbers. With such inputs, a sharpness result can thus be established for virtually all reasonable formats instead of just one of them. This, however, requires the ability to run the algorithm on those inputs and, in particular, to compute the correctly-rounded sum, product, or ratio of two symbolic floating-point numbers. We show in [61] how these basic arithmetic operations can be performed automatically. We introduce a way to model symbolic floating-point data, and present algorithms for round-to-nearest addition, multiplication, fused multiply-add, and division. An implementation as a Maple library is also described, and experiments using examples from the literature are provided to illustrate its interest in practice.

6.1.7. On the robustness of the 2Sum and Fast2Sum algorithms

The 2Sum and Fast2Sum algorithms are important building blocks in numerical computing. They are used (implicitly or explicitly) in many *compensated* algorithms (such as compensated summation or compensated polynomial evaluation). They are also used for manipulating floating-point *expansions*. We show in [56] that these algorithms are much more robust than it is usually believed: the returned result makes sense even when the rounding function is not round-to-nearest, and they are almost immune to overflow.

6.1.8. Tight and rigourous error bounds for basic building blocks of double-word arithmetic

In [63] we analyze several classical basic building blocks of double-word arithmetic (frequently called "double-double arithmetic" in the literature): the addition of a double-word number and a floating-point number, the addition of two double-word numbers, the multiplication of a double-word number by a floating-point number, the multiplication of two double-word numbers, the division of a double-word number by a floating-point number, and the division of two double-word numbers. For multiplication and division we get better relative error bounds than the ones previously published. For addition of two double-word numbers, we show that the previously published bound was wrong, and we provide a relative error bound. We introduce new algorithms for division. We also give examples that illustrate the tightness of our bounds.

6.1.9. A new multiplication algorithm for extended precision using floating-point expansions

Some important computational problems must use a floating-point (FP) precision several times higher than the hardware-implemented available one. These computations critically rely on software libraries for high-precision FP arithmetic. The representation of a high-precision data type crucially influences the corresponding arithmetic algorithms. Recent work showed that algorithms for FP expansions, that is, a representation based on unevaluated sum of standard FP types, benefit from various high-performance support for native FP, such as low latency, high throughput, vectorization, threading, etc. Bailey's QD library and its corresponding Graphics Processing Unit (GPU) version, GQD, are such examples. Despite using native FP arithmetic as the key operations, QD and GQD algorithms are focused on double-double or quad-double representations and do not generalize efficiently or naturally to a flexible number of components in the FP expansion. In [45] we introduce a new multiplication algorithm for FP expansion with flexible precision, up to the order of tens of FP elements in mind. The main feature consists in the partial products being accumulated in a special designed data structure that has the regularity of a fixed-point representation while allowing the computation to be naturally carried out using native FP types. This allows us to easily avoid unnecessary computation and to present rigorous accuracy analysis transparently. The algorithm, its correctness and accuracy proofs and some performance comparisons with existing libraries are all contributions of this paper.

6.1.10. CAMPARY: Cuda Multiple Precision Arithmetic Library and Applications

Many scientific computing applications demand massive numerical computations on parallel architectures such as Graphics Processing Units (GPUs). Usually, either floating-point single or double precision arithmetic is used. Higher precision is generally not available in hardware, and software extended precision libraries are much slower and rarely supported on GPUs. We develop CAMPARY: a multiple-precision arithmetic library, using the CUDA programming language for the NVidia GPU platform. In our approach, the precision is extended by representing real numbers as the unevaluated sum of several standard machine precision floating-point numbers. We make use of error-free transforms algorithms, which are based only on native precision operations, but keep track of all rounding errors that occur when performing a sequence of additions and multiplications. This offers the simplicity of using hardware highly optimized floating-point operations, while also allowing for rigorously proven rounding error bounds. This also allows for easy implementation of an interval arithmetic. Currently, all basic multiple-precision arithmetic operations are supported. Our target applications are in chaotic dynamical systems or automatic control [34].

6.1.11. Arithmetic algorithms for extended precision using floating-point expansions

Many numerical problems require a higher computing precision than the one offered by standard floating-point (FP) formats. One common way of extending the precision is to represent numbers in a *multiple component* format. By using the so-called *floating-point expansions*, real numbers are represented as the unevaluated sum of standard machine precision FP numbers. This representation offers the simplicity of using directly available, hardware implemented and highly optimized, FP operations. It is used by multiple-precision libraries such as Bailey's QD or the analogue Graphics Processing Units (GPU) tuned version, GQD. In this article we briefly revisit algorithms for adding and multiplying FP expansions, then we introduce and prove new algorithms for normalizing, dividing and square rooting of FP expansions. The new method used for computing the reciprocal a^{-1} and the square root $\sqrt{a}$ of an FP expansion a is based on an adapted Newton-Raphson iteration where the intermediate calculations are done using "truncated" operations (additions, multiplications) involving FP expansions. We give here a thorough error analysis showing that it allows very accurate computations. More precisely, after q iterations, the computed FP expansion $x = x_0 + \cdots + x_{2^q-1}$ satisfies, for the reciprocal algorithm, the relative error bound: $|(x - a^{-1})/a^{-1}| \leq 2^{-2^q(p-3)-1}$ and, respectively, for the square root one: $|x - 1/\sqrt{a}| \leq 2^{-2^q(p-3)-1}/\sqrt{a}$, where $p > 2$ is the precision of the FP representation used ($p = 24$ for single precision and $p = 53$ for double precision) [16].

6.1.12. Comparison between binary and decimal floating-point numbers

We introduce an algorithm to compare a binary floating-point (FP) number and a decimal FP number, assuming the "binary encoding" of the decimal formats is used, and with a special emphasis on the basic interchange formats specified by the IEEE 754-2008 standard for FP arithmetic. It is a two-step algorithm: a first pass, based on the exponents only, quickly eliminates most cases, then, when the first pass does not suffice, a more accurate second pass is performed. We provide an implementation of several variants of our algorithm, and compare them [8].

6.1.13. Automatic source-to-source error compensation of floating-point programs: code synthesis to optimize accuracy and time

Numerical programs with IEEE 754 floating-point computations may suffer from inaccuracies, since finite precision arithmetic is an approximation of real arithmetic. Solutions that reduce the loss of accuracy are available, such as compensated algorithms or double-double precision floating-point arithmetic. With Ph. Langlois and M. Martel (LIRMM and Université de Perpignan), we show in [21] how to automatically improve the numerical quality of a numerical program with the smallest impact on its performance. We define and implement source code transformations in order to derive automatically compensated programs. We present several experimental results to compare the transformed programs and existing solutions. The transformed programs are as accurate and efficient as the implementations of compensated algorithms when the latter exist. Furthermore, we propose some transformation strategies allowing us to improve partially the accuracy of programs and to tune the impact on execution time. Trade-offs between accuracy and performance are assured by code synthesis. Experimental results show that user-defined trade-offs are achievable in a reasonable amount of time, with the help of the tools we present here.

6.1.14. Correctly rounded arbitrary-precision floating-point summation

We have designed a fast, low-level algorithm to compute the correctly rounded summation of several floating-point numbers in arbitrary precision in radix 2, each number (each input and the output) having its own precision. We have implemented it in GNU MPFR; it will be part of the next MPFR major release (GNU MPFR 4.0). In addition to a pen-and-paper proof, various kinds of tests are provided. Timings show that this new algorithm/implementation is globally much faster and takes less memory than the previous one (from MPFR 3.1.5): the worst-case time and memory complexity was exponential and it is now polynomial. Timings on pseudo-random inputs with various sets of parameters also show that this new implementation is even much faster than the (inaccurate) basic sum implementation in some cases. [36], [65]

6.2. Lattices: algorithms and cryptology

6.2.1. Zero-Knowledge Arguments for Lattice-Based Accumulators: Logarithmic-Size Ring Signatures and Group Signatures Without Trapdoors

An accumulator is a function that hashes a set of inputs into a short, constant-size string while preserving the ability to efficiently prove the inclusion of a specific input element in the hashed set. It has proved useful in the design of numerous privacy-enhancing protocols, in order to handle revocation or simply prove set membership. In the lattice setting, currently known instantiations of the primitive are based on Merkle trees, which do not interact well with zero-knowledge proofs. In order to efficiently prove the membership of some element in a zero-knowledge manner, the prover has to demonstrate knowledge of a hash chain without revealing it, which is not known to be efficiently possible under well-studied hardness assumptions. In [39], we provide an efficient method of proving such statements using involved extensions of Stern's protocol. Under the Small Integer Solution assumption, we provide zero-knowledge arguments showing possession of a hash chain. As an application, [39] describes new lattice-based group and ring signatures in the random oracle model. In particular, the paper obtains: (i) The first lattice-based ring signatures with logarithmic size in the cardinality of the ring; (ii) The first lattice-based group signature that does not require any GPV trapdoor and thus allows for a much more efficient choice of parameters.

6.2.2. A Lattice-Based Group Signature Scheme with Message-Dependent Opening

Group signatures are an important anonymity primitive allowing users to sign messages while hiding in a crowd. At the same time, signers remain accountable since an authority is capable of de-anonymizing signatures via a process called opening. In many situations, this authority is granted too much power as it can identify the author of any signature. Sakai et al. proposed a flavor of the primitive, called Group Signature with Message-Dependent Opening (GS-MDO), where opening operations are only possible when a separate authority (called "admitter") has revealed a trapdoor for the corresponding message. So far, all existing GS-MDO constructions rely on bilinear maps, partially because the message-dependent opening functionality inherently implies identity-based encryption. In [40], the team proposes the first GS-MDO candidate based on lattice assumptions. The construction combines the group signature of Ling, Nguyen and Wang (PKC'15) with two layers of identity-based encryption. These components are tied together using suitable zero-knowledge argument systems.

6.2.3. Practical "Signatures with Efficient Protocols" from Simple Assumptions

Digital signatures are perhaps the most important base for authentication and trust relationships in large scale systems. More specifically, various applications of signatures provide privacy and anonymity preserving mechanisms and protocols, and these, in turn, are becoming critical (due to the recently recognized need to protect individuals according to national rules and regulations). A specific type of signatures called "signatures with efficient protocols", as introduced by Camenisch and Lysyanskaya (CL), efficiently accommodates various basic protocols and extensions like zero-knowledge proofs, signing committed messages, or re-randomizability. These are, in fact, typical operations associated with signatures used in typical anonymity and privacy-preserving scenarios. To date there are no "signatures with efficient protocols" which are based on simple assumptions and truly practical. These two properties assure us a robust primitive: First, simple assumptions are needed for ensuring that this basic primitive is mathematically robust and does not require special ad hoc assumptions that are more risky, imply less efficiency, are more tuned to the protocol itself, and are perhaps less trusted. In the other dimension, efficiency is a must given the anonymity applications of the protocol, since without proper level of efficiency the future adoption of the primitives is always questionable (in spite of their need). In [41], the team presents a new CL-type signature scheme that is re-randomizable under a simple, well-studied, and by now standard, assumption (SXDH). The signature is efficient (built on the recent QA-NIZK constructions), and is, by design, suitable to work in extended contexts that typify privacy settings (like anonymous credentials, group signature, and offline e-cash). The paper demonstrates its power by presenting practical protocols based on it.

6.2.4. Functional Commitment Schemes: From Polynomial Commitments to Pairing-Based Accumulators from Simple Assumptions

In [42], the team formalizes a cryptographic primitive called functional commitment (FC) which can be viewed as a generalization of vector commitments (VCs), polynomial commitments and many other special kinds of commitment schemes. A non-interactive functional commitment allows committing to a message in such a way that the committer has the flexibility of only revealing a function $F(M)$ of the committed message during the opening phase. We provide constructions for the functionality of linear functions, where messages consist of a vectors of n elements over some domain D (e.g., $m = (m_1, ..., m_n) \in D_n$) and commitments can later be opened to a specific linear function of the vector coordinates. An opening for a function $F : D_n \to R$ thus generates a witness for the fact that $F(m)$ indeed evaluates to $y \in R$. One security requirement is called function binding and requires that no adversary be able to open a commitment to two different evaluations y, y' for the same function F. The paper [42] proposes a construction of functional commitment for linear functions based on constant-size assumptions in composite order groups endowed with a bilinear map. The construction has commitments and openings of constant size (i.e., independent of n or function description) and is perfectly hiding – the underlying message is information theoretically hidden. Our security proofs builds on the Déjà Q framework of Chase and Meiklejohn (Eurocrypt 2014) and its extension by Wee (TCC 2016) to encryption primitives, thus relying on constant-size subgroup decisional assumptions. The paper shows that the FC for linear functions are sufficiently powerful to solve four open problems. They, first, imply polynomial commitments, and, then, give cryptographic accumulators (i.e., an algebraic hash function which makes it possible to efficiently prove that some input belongs to a hashed set). In particular, specializing the new FC construction leads to the first pairing-based polynomial commitments and accumulators for large universes known to achieve security under simple assumptions. We also substantially extend our pairing-based accumulator to handle subset queries which requires a non-trivial extension of the Déjà Q framework.

6.2.5. Fully Secure Functional Encryption for Inner Products, from Standard Assumptions

Functional encryption is a modern public-key paradigm where a master secret key can be used to derive sub-keys SKF associated with certain functions F in such a way that the decryption operation reveals $F(M)$, if M is the encrypted message, and nothing else. Recently, Abdalla *et al.* gave simple and efficient realizations of the primitive for the computation of linear functions on encrypted data: given an encryption of a vector y over some specified base ring, a secret key SK_x for the vector x allows computing $\langle x, y \rangle$. Their technique surprisingly allows for instantiations under standard assumptions, like the hardness of the Decision Diffie-Hellman (DDH) and Learning-with-Errors (LWE) problems. Their constructions, however, are only proved secure against selective adversaries, which have to declare the challenge messages M_0 and M_1 at the outset of the game. In [22], we provide constructions that provably achieve security against more realistic adaptive attacks (where the messages M_0 and M_1 may be chosen in the challenge phase, based on the previously collected information) for the same inner product functionality. The constructions of [22] are obtained from hash proof systems endowed with homomorphic properties over the key space. They are (almost) as efficient as those of Abdalla *et al.* and rely on the same hardness assumptions. In addition, the paper [22] obtains a solution based on Paillier's composite residuosity assumption, which was an open problem even in the case of selective adversaries. We also propose LWE-based schemes that allow evaluation of inner products modulo a prime p, as opposed to the schemes of Abdalla et al. that are restricted to evaluations of integer inner products of short integer vectors. The paper [22] finally proposes a solution based on Paillier's composite residuosity assumption that enables evaluation of inner products modulo an RSA integer $N = pq$. The paper [22] demonstrates that the functionality of inner products over a prime field is powerful and can be used to construct bounded collusion FE for all circuits.

6.2.6. Signature Schemes with Efficient Protocols and Dynamic Group Signatures from Lattice Assumptions

A recent line of works – initiated by Gordon, Katz and Vaikuntanathan (Asiacrypt 2010) – gave lattice-based realizations of privacy-preserving protocols allowing users to authenticate while remaining hidden in a crowd. Despite five years of efforts, known constructions remain limited to static populations of users, which cannot be dynamically updated. For example, none of the existing lattice-based group signatures seems easily extendable to the more realistic setting of dynamic groups. In [37], the team provides new tools enabling the design of anonymous authen-tication systems whereby new users can register and obtain credentials at any time. The first contribution of [37] is a signature scheme with efficient protocols, which allows users to obtain a signature on a committed value and subsequently prove knowledge of a signature on a committed message. This construction, which builds on the lattice-based signature of Böhl *et al.* (Eurocrypt'13), is well-suited to the design of anonymous credentials and dynamic group signatures. As a second technical contribution, [37] provides a simple, round-optimal joining mechanism for introducing new members in a group. This mechanism consists of zero-knowledge arguments allowing registered group members to prove knowledge of a secret short vector of which the corresponding public syndrome was certified by the group manager. This method provides similar advantages to those of structure-preserving signatures in the realm of bilinear groups. Namely, it allows group members to generate their public key on their own without having to prove knowledge of the underlying secret key. This results in a two-round join protocol supporting concurrent enrollments, which can be used in other settings such as group encryption.

6.2.7. Zero-Knowledge Arguments for Matrix-Vector Relations and Lattice-Based Group Encryption

Group encryption (GE) is the natural encryption analogue of group signatures in that it allows verifiably encrypting messages for some anonymous member of a group while providing evidence that the receiver is a properly certified group member. Should the need arise, an opening authority is capable of identifying the receiver of any ciphertext. As introduced by Kiayias, Tsiounis and Yung (Asiacrypt'07), GE is motivated by applications in the context of oblivious retriever storage systems, anonymous third parties and hierarchical group signatures. In [38], we provide the first realization of group encryption under lattice assumptions. The construction of [38] is proved secure in the standard model (assuming interaction in the proving phase) under the Learning-With-Errors (LWE) and Short-Integer-Solution (SIS) assumptions. As a crucial component of our system, [38] describes a new zero-knowledge argument system allowing to demonstrate that a given ciphertext is a valid encryption under some hidden but certified public key, which incurs to prove quadratic statements about LWE relations. Specifically, the protocol of [38] allows arguing knowledge of witnesses consisting of $X \in \mathbb{Z}_q^{m\times}$, $s \in \mathbb{Z}_q^n$ and a small-norm $e \in \mathbb{Z}^m$ which underlie a public vector $b = X{\cdot}s + e \in \mathbb{Z}_q^m$ while simultaneously proving that the matrix $X \in \mathbb{Z}_q^{m\times n}$ has been correctly certified.

6.2.8. Efficient Cryptosystems From 2^k-th Power Residue Symbols

Goldwasser and Micali (1984) highlighted the importance of randomizing the plaintext for public-key encryption and introduced the notion of semantic security. They also realized a cryptosystem meeting this security notion under the standard complexity assumption of deciding quadratic residuosity modulo a composite number. The Goldwasser-Micali cryptosystem is simple and elegant but is quite wasteful in bandwidth when encrypting large messages. A number of works followed to address this issue and proposed various modifications. In [4], we revisit the original Goldwasser-Micali cryptosystem using 2^k-th power residue symbols. The so-obtained cryptosystems appear as a very natural generalization for $k \geq 2$ (the case $k = 1$ corresponds exactly to the Goldwasser-Micali cryptosystem). Advantageously, they are efficient in both bandwidth and speed; in particular, they allow for fast decryption. Further, the cryptosystems described in this paper inherit the useful features of the original cryptosystem (like its homomorphic property) and are shown to be secure under a similar complexity assumption. As a prominent application, the paper [4] describes an efficient lossy trapdoor function based thereon.

6.2.9. Born and raised distributively: Fully distributed non-interactive adaptively-secure threshold signatures with short shares

Threshold cryptography is a fundamental distributed computational paradigm for enhancing the availability and the security of cryptographic public-key schemes. It does it by dividing private keys into n shares handed out to distinct servers. In threshold signature schemes, a set of at least $t + 1 \leq n$ servers is needed to produce a valid digital signature. Availability is assured by the fact that any subset of $t + 1$ servers can produce a signature when authorized. At the same time, the scheme should remain robust (in the fault tolerance sense) and unforgeable (cryptographically) against up to t corrupted servers; i.e., it adds quorum control to traditional cryptographic services and introduces redundancy. Originally, most practical threshold signatures have a number of demerits: They have been analyzed in a static corruption model (where the set of corrupted servers is fixed at the very beginning of the attack); they require interaction; they assume a trusted dealer in the key generation phase (so that the system is not fully distributed); or they suffer from certain overheads in terms of storage (large share sizes). In [17], we construct practical fully distributed (the private key is born distributed), non-interactive schemes – where the servers can compute their partial signatures without communication with other servers – with adaptive security (i.e., the adversary corrupts servers dynamically based on its full view of the history of the system). The schemes of [17] are very efficient in terms of computation, communication, and scalable storage (with private key shares of size $O(1)$, where certain solutions incur $O(n)$ storage costs at each server). Unlike other adaptively secure schemes, the new schemes [17] are erasure-free (reliable erasure is hard to assure and hard to administer properly in actual systems). To the best of our knowledge, such a fully distributed highly constrained scheme has been an open problem in the area. In particular, and of special interest, is the fact that Pedersen's traditional distributed key generation (DKG) protocol can be safely employed in the initial key generation phase when the system is born although it is well-known not to ensure uniformly distributed public keys. An advantage of this is that this protocol only takes one round optimistically (in the absence of faulty player).

6.2.10. Non-Zero Inner Product Encryption with Short Ciphertexts and Private Keys

In [28], the team describes two constructions of non-zero inner product encryption (NIPE) systems in the public index setting, both having ciphertexts and secret keys of constant size. Both schemes are obtained by tweaking the Boneh-Gentry-Waters broadcast encryption system (Crypto 2005) and are proved selectively secure without random oracles under previously considered assumptions in groups with a bilinear map. Our first realization builds on prime-order bilinear groups and is proved secure under the Decisional Bilinear Diffie-Hellman Exponent assumption, which is parameterized by the length n of vectors over which the inner product is defined. By moving to composite order bilinear groups, the paper [28] obtains security under static subgroup decision assumptions following the Déjà Q framework of Chase and Meiklejohn (Eurocrypt 2014) and its extension by Wee (TCC 2016). The schemes of [28] are the first NIPE systems to achieve such parameters, even in the selective security setting. Moreover, they are the first proposals to feature optimally short private keys, which only consist of one group element. The prime-order-group realization of [28] is also the first one with a deterministic key generation mechanism.

6.2.11. More Efficient Constructions for Inner-Product Encryptions

In [48], the team describes new constructions for inner product encryption (called IPE1 and IPE2), which are both secure under the eXternal Diffie-Hellman assumption (SXDH) in asymmetric pairing groups. The IPE1 scheme of [48] has constant-size ciphertexts whereas the second one is weakly attribute hiding. The second scheme is derived from the identity-based encryption scheme of Jutla and Roy (Asiacrypt 2013), that was extended from tag-based quasi-adaptive non-interactive zero-knowledge (QA-NIZK) proofs for linear subspaces of vector spaces over bilinear groups. The verifier common reference string (CRS) in these tag-based systems are split into two parts, that are combined during verification. The paper [48] considers an alternate form of the tag-based QA-NIZK proof with a single verifier CRS that already includes a tag, different from the one defining the language. The verification succeeds as long as the two tags are unequal. Essentially, we embed a two-equation revocation mechanism in the verification. The new QA-NIZK proof system leads to IPE1, a constant-sized ciphertext IPE scheme with very short ciphertexts. Both the IPE schemes are obtained by applying the n-equation revocation technique of Attrapadung and Libert (PKC 2010) to the corresponding identity based encryption schemes and proved secure under SXDH assumption. As an application, the paper [48] shows how the new schemes can be specialized to obtain the first fully secure identity-based broadcast encryption based on SXDH with a trade-off among the public parameters, ciphertext and key sizes, all of them being sub-linear in the maximum number of recipients of a broadcast.

6.2.12. Verifiable Message-Locked Encryption

One of today's main challenge related to cloud storage is to maintain the functionalities and the efficiency of customers' and service providers' usual environments, while protecting the confidentiality of sensitive data. Deduplication is one of those functionalities: it enables cloud storage providers to save a lot of memory by storing only once a file uploaded several times. But classical encryption blocks deduplication. One needs to use a "message-locked encryption" (MLE), which allows the detection of duplicates and the storage of only one encrypted file on the server, which can be decrypted by any owner of the file. However, in most existing scheme, a user can bypass this deduplication protocol. In [27], we provide servers verifiability for MLE schemes: the servers can verify that the ciphertexts are well-formed. This property that we formally define forces a customer to prove that she complied to the deduplication protocol, thus preventing her to deviate from *the prescribed functionality* of MLE. We call it *deduplication consistency*. To achieve this deduplication consistency, we provide (i) a generic transformation that applies to any MLE scheme and (ii) an ElGamal-based deduplication-consistent MLE, which is secure in the random oracle model.

6.2.13. Privately Outsourcing Exponentiation to a Single Server: Cryptanalysis and Optimal Constructions

In [29], we address the problem of speeding up group computations in cryptography using a single untrusted computational resource. We analyze the security of an efficient protocol for securely outsourcing multi-exponentiations proposed at ESORICS 2014. We show that this scheme does not achieve the claimed security guarantees and we present several practical polynomial-time attacks on the delegation protocol which allows the untrusted helper to recover part (or the whole) of the device secret inputs. We then provide simple constructions for outsourcing group exponentiations in different settings (e.g. public/secret, fixed/variable bases and public/secret exponents). Finally, we prove that our attacks on the ESORICS 2014 protocol are unavoidable if one wants to use a single untrusted computational resource and to limit the computational cost of the limited device to a constant number of (generic) group operations. In particular, we show that our constructions are actually optimal.

6.3. Algebraic computing and high-performance kernels

6.3.1. Algebraic Diagonals and Walks: Algorithms, Bounds, Complexity

The diagonal of a multivariate power series F is the univariate power series $\mathrm{Diag}(F)$ generated by the diagonal terms of F. Diagonals form an important class of power series; they occur frequently in number theory, theoretical physics and enumerative combinatorics. We study algorithmic questions related to diagonals in the case where F is the Taylor expansion of a bivariate rational function. It is classical that in this case $\mathrm{Diag}(F)$ is an algebraic function. We propose an algorithm that computes an annihilating polynomial for $\mathrm{Diag}(F)$. We give a precise bound on the size of this polynomial and show that generically, this polynomial is the minimal polynomial and that its size reaches the bound. The algorithm runs in time quasi-linear in this bound, which grows exponentially with the degree of the input rational function. We then address the related problem of enumerating directed lattice walks. The insight given by our study leads to a new method for expanding the generating power series of bridges, excursions and meanders. We show that their first N terms can be computed in quasi-linear complexity in N, without first computing a very large polynomial equation [6].

6.3.2. Multiple Binomial Sums

Multiple binomial sums form a large class of multi-indexed sequences, closed under partial summation, which contains most of the sequences obtained by multiple summation of products of binomial coefficients and also all the sequences with algebraic generating function. We study the representation of the generating functions of binomial sums by integrals of rational functions. The outcome is twofold. Firstly, we show that a univariate sequence is a multiple binomial sum if and only if its generating function is the diagonal of a rational function. Secondly, we propose algorithms that decide the equality of multiple binomial sums and that compute recurrence relations for them. In conjunction with geometric simplifications of the integral representations, this approach behaves well in practice. The process avoids the computation of certificates and the problem of the appearance of spurious singularities that afflicts discrete creative telescoping, both in theory and in practice [7].

6.3.3. Fast and Accurate Computation of Orbital Collision Probability for Short-Term Encounters

We provide a new method for computing the probability of collision between two spherical space objects involved in a short-term encounter under Gaussian-distributed uncertainty. In this model of conjunction, classical assumptions reduce the probability of collision to the integral of a two-dimensional Gaussian probability density function over a disk. The computational method is based on an analytic expression for the integral, derived by use of Laplace transform and D-finite functions properties. The formula has the form of a product between an exponential term and a convergent power series with positive coefficients. Analytic bounds on the truncation error are also derived and are used to obtain a very accurate algorithm. Another contribution is the derivation of analytic bounds on the probability of collision itself, allowing for a very fast and — in most cases — very precise evaluation of the risk. The only other analytical method of the literature — based on an approximation — is shown to be a special case of the new formula. A numerical study illustrates the efficiency of the proposed algorithms on a broad variety of examples and favorably compares the approach to the other methods of the literature [20].

6.3.4. Efficient Algorihtms for Mixed Creative Telescoping

Creative telescoping is a powerful computer algebra paradigm — initiated by Doron Zeilberger in the 90's — for dealing with definite integrals and sums with parameters. We address the mixed continuous-discrete case, and focus on the integration of bivariate hypergeometric-hyperexponential terms. We design a new creative telescoping algorithm operating on this class of inputs, based on a Hermite-like reduction procedure. The new algorithm has two nice features: it is efficient and it delivers, for a suitable representation of the input, a minimal-order telescoper. Its analysis reveals tight bounds on the sizes of the telescoper it produces [26].

6.3.5. Symbolic-Numeric Tools for Analytic Combinatorics in Several Variables

Analytic combinatorics studies the asymptotic behaviour of sequences through the analytic properties of their generating functions. This article provides effective algorithms required for the study of analytic combinatorics in several variables, together with their complexity analyses. Given a multivariate rational function we show how to compute its smooth isolated critical points, with respect to a polynomial map encoding asymptotic behaviour, in complexity singly exponential in the degree of its denominator. We introduce a numerical Kronecker representation for solutions of polynomial systems with rational coefficients and show that it can be used to decide several properties (0 coordinate, equal coordinates, sign conditions for real solutions, and vanishing of a polynomial) in good bit complexity. Among the critical points, those that are minimal—a property governed by inequalities on the moduli of the coordinates—typically determine the dominant asymptotics of the diagonal coefficient sequence. When the Taylor expansion at the origin has all non-negative coefficients (known as the 'combinatorial case') and under regularity conditions, we utilize this Kronecker representation to determine probabilistically the minimal critical points in complexity singly exponential in the degree of the denominator, with good control over the exponent in the bit complexity estimate. Generically in the combinatorial case, this allows one to automatically and rigorously determine asymptotics for the diagonal coefficient sequence. Examples obtained with a preliminary implementation show the wide applicability of this approach [43].

6.3.6. Tableau sequences, open diagrams, and Baxter families

Walks on Young's lattice of integer partitions encode many objects of algebraic and combinatorial interest. Chen *et al.* established connections between such walks and arc diagrams. We show that walks that start at $\varnothing$, end at a row shape, and only visit partitions of bounded height are in bijection with a new type of arc diagram — open diagrams. Remarkably, two subclasses of open diagrams are equinumerous with well known objects: standard Young tableaux of bounded height, and Baxter permutations. We give an explicit combinatorial bijection in the former case, and a generating function proof and new conjecture in the second case [9].

6.3.7. On 3-dimensional lattice walks confined to the positive octant

Many recent papers deal with the enumeration of 2-dimensional walks with prescribed steps confined to the positive quadrant. The classification is now complete for walks with steps in $\{0, \pm 1\}^2$: the generating function is differentially finite if and only if a certain group associated with the step set is finite. We explore in this paper the analogous problem for 3-dimensional walks confined to the positive octant. The first difficulty is their number: we have to examine no less than 11074225 step sets in $\{0, \pm 1\}^3$ (instead of 79 in the quadrant case). We focus on the 35548 that have at most six steps. We apply to them a combined approach, first experimental and then rigorous. On the experimental side, we try to guess differential equations. We also try to determine if the associated group is finite. The largest finite groups that we find have order 48 — the larger ones have order at least 200 and we believe them to be infinite. No differential equation has been detected in those cases. On the rigorous side, we apply three main techniques to prove D-finiteness. The algebraic kernel method, applied earlier to quadrant walks, works in many cases. Certain, more challenging, cases turn out to have a special Hadamard structure, which allows us to solve them via a reduction to problems of smaller dimension. Finally, for two special cases, we had to resort to computer algebra proofs. We prove with these techniques all the guessed differential equations. This leaves us with exactly 19 very intriguing step sets for which the group is finite, but the nature of the generating function still unclear [5].

6.3.8. Asymptotic Lattice Path Enumeration Using Diagonals

We consider d-dimensional lattice path models restricted to the first orthant whose defining step sets exhibit reflective symmetry across every axis. Given such a model, we provide explicit asymptotic enumerative formulas for the number of walks of a fixed length: the exponential growth is given by the number of distinct steps a model can take, while the sub-exponential growth depends only on the dimension of the underlying lattice and the number of steps moving forward in each coordinate. The generating function of each model is first expressed as the diagonal of a multivariate rational function, then asymptotic expressions are derived by analyzing the singular variety of this rational function. Additionally, we show how to compute subdominant growth, reflect on the difference between rational diagonals and differential equations as data structures for D-finite functions, and show how to determine first order asymptotics for the subset of walks that start and end at the origin [18].

6.3.9. Asymptotics of lattice walks via analytic combinatorics in several variables

We consider the enumeration of walks on the two-dimensional non-negative integer lattice with steps defined by a finite set $S \subset \{0, \pm 1\}^2$. Up to isomorphism there are 79 unique two-dimensional models to consider, and previous work in this area has used the kernel method, along with a rigorous computer algebra approach, to show that 23 of the 79 models admit D-finite generating functions. In 2009, Bostan and Kauers used Padé-Hermite approximants to guess differential equations which these 23 generating functions satisfy, in the process guessing asymptotics of their coefficient sequences. In this article we provide, for the first time, a complete rigorous verification of these guesses. Our technique is to use the kernel method to express 19 of the 23 generating functions as diagonals of tri-variate rational functions and apply the methods of analytic combinatorics in several variables (the remaining 4 models have algebraic generating functions and can thus be handled by univariate techniques). This approach also shows the link between combinatorial properties of the models and features of its asymptotics such as asymptotic and polynomial growth factors. In addition, we give expressions for the number of walks returning to the x-axis, the y-axis, and the origin, proving recently conjectured asymptotics of Bostan, Chyzak, van Hoeij, Kauers, and Pech [44].

6.3.10. Linear Time Interactive Certificates

With J.G. Dumas (LJK, Grenoble), E. Kaltofen (NCSU, USA), and E. Thomé (Inria Nancy) we work on interactive certificates. Computational problem certificates are additional data structures for each output, which can be used by a (possibly randomized) verification algorithm that proves the correctness of each output. In [32] we give a new certificate for the minimal polynomial of sparse or structured matrices whose Monte Carlo verification complexity requires a single matrix-vector multiplication and a linear number of extra field operations (sufficiently large cardinality field). We also propose a novel preconditioner that ensures irreducibility of the characteristic polynomial of the generically preconditioned matrix. This preconditioner takes linear time to be applied and uses only two random entries. We combine these two techniques to give algorithms that compute certificates for the determinant, and thus for the characteristic polynomial, whose Monte Carlo verification complexity is therefore also linear.

6.3.11. Computing minimal interpolation bases

With É. Schost (U. Waterloo, Canada), we consider the problem of computing minimal bases of solutions for a general interpolation problem, which encompasses Hermite-Padé approximation and constrained multivariate interpolation, and has applications in coding theory and security. The problem is classically solved using iterative algorithms based on recurrence relations. First, we discuss in [62] a fast, divide-and-conquer version of this recurrence, taking advantage of fast matrix computations over the scalars and over the polynomials. This new algorithm is deterministic, and for computing shifted minimal bases of relations between m vectors of size σ it uses $\widetilde{O}(m^{\omega-1}(\sigma+|s|))$ field operations, where the notation $\widetilde{O}(\cdot)$ indicates that logarithmic terms are omitted, $\omega \in [2, 2.38]$ is the exponent of matrix multiplication, and $|s|$ is the sum of the entries of the input shift s, with $\min(s) = 0$. This complexity bound improves in particular on earlier algorithms in the case of bivariate interpolation for soft decoding, while matching fastest existing algorithms for simultaneous Hermite-Padé approximation. Then we propose in [33] an algorithm for the computation of an interpolation basis in shifted-Popov normal form with a cost of $\widetilde{O}(m^{\omega-1}\sigma)$ field operations. Previous works, in the case of Hermite-Padé approximation and in the general interpolation case, compute non-normalized bases. Since for arbitrary shifts such bases may have size $\Theta(m^2\sigma)$, the cost bound $\widetilde{O}(m^{\omega-1}\sigma)$ was feasible only with restrictive assumptions on the shift that ensure small output sizes. The question of handling arbitrary shifts with the same complexity bound was left open. To obtain the target cost for any shift, we strengthen the properties of the output bases, and of those obtained during the course of the algorithm: all the bases are computed in shifted Popov form, whose size is always $O(m\sigma)$. Then, we design a divide-and-conquer scheme. We recursively reduce the initial interpolation problem to sub-problems with more convenient shifts by first computing information on the degrees of the intermediate bases.

6.3.12. Fast computation of shifted Popov forms of polynomial matrices via systems of modular polynomial equations

In [46] we give a Las Vegas algorithm which computes the shifted Popov form of an $m \times m$ nonsingular polynomial matrix of degree d in expected $\widetilde{O}(m^{\omega}d)$ field operations, where ω is the exponent of matrix multiplication and $\widetilde{O}(\cdot)$ indicates that logarithmic factors are omitted. This is the first algorithm in $\widetilde{O}(m^{\omega}d)$ for shifted row reduction with arbitrary shifts. Using partial linearization, we reduce the problem to the case $d \le \lceil \sigma/m \rceil$ where σ is the generic determinant bound, with σ/m bounded from above by both the average row degree and the average column degree of the matrix. The cost above becomes $\widetilde{O}(m^{\omega}\lceil \sigma/m \rceil)$, improving upon the cost of the fastest previously known algorithm for row reduction, which is deterministic. Our algorithm first builds a system of modular equations whose solution set is the row space of the input matrix, and then finds the basis in shifted Popov form of this set. We give a deterministic algorithm for this second step supporting arbitrary moduli in $\widetilde{O}(m^{\omega-1}\sigma)$ field operations, where m is the number of unknowns and σ is the sum of the degrees of the moduli. This extends previous results with the same cost bound in the specific cases of order basis computation and M-Padé approximation, in which the moduli are products of known linear factors.

6.3.13. Fast, deterministic computation of the Hermite normal form and determinant of a polynomial matrix

With G. Labahn and W. Zhou (U. Waterloo, Canada) we give in [64] fast and deterministic algorithms to compute the determinant and Hermite normal form of a nonsingular $n \times n$ matrix of univariate polynomials over a field $\mathbb{K}$. Our algorithms use $\widetilde{O}(n^{\omega}\lceil s \rceil)$ operations in $\mathbb{K}$, where s is bounded from above by both the average of the degrees of the rows and that of the columns of the matrix and ω is the exponent of matrix multiplication. The soft-O notation indicates that logarithmic factors in the big-O are omitted while the ceiling function indicates that the cost is $\widetilde{O}(n^{\omega})$ when $s = o(1)$. Our algorithms are based on a fast and deterministic triangularization method for computing the diagonal entries of the Hermite form of a nonsingular matrix.

6.3.14. Fast Computation of the Rank Profile Matrix and the Generalized Bruhat Decomposition

The row (resp. column) rank profile of a matrix describes the stair-case shape of its row (resp. column) echelon form. With J. G. Dumas and Z. Sultan (LJK, Grenoble), we propose in [11] a new matrix invariant, the rank profile matrix, summarizing all information on the row and column rank profiles of all the leading sub-matrices. We show that this normal form exists and is unique over any ring, provided that the notion of McCoy's rank is used, in the presence of zero divisors. We then explore the conditions for a Gaussian elimination algorithm to compute all or part of this invariant, through the corresponding PLUQ decomposition. This enlarges the set of known Elimination variants that compute row or column rank profiles. As a consequence a new Crout base case variant significantly improves the practical efficiency of previously known implementations over a finite field. With matrices of very small rank, we also generalize the techniques of Storjohann and Yang to the computation of the rank profile matrix, achieving an $(r^{\omega} + mn)^{1+o(1)}$ time complexity for an $m \times n$ matrix of rank r, where ω is the exponent of matrix multiplication. Finally, by give connections to the Bruhat decomposition, and several of its variants and generalizations. Thus, our algorithmic improvements for the PLUQ factorization, and their implementations, directly apply to these decompositions. In particular, we show how a PLUQ decomposition revealing the rank profile matrix also reveals both a row and a column echelon form of the input matrix or of any of its leading sub-matrices, by a simple post-processing made of row and column permutations.

6.3.15. Computing with quasiseparable matrices

The class of quasiseparable matrices is defined by a pair of bounds, called the quasiseparable orders, on the ranks of the sub-matrices entirely located in their strictly lower and upper triangular parts. These arise naturally in applications, as e.g. the inverse of band matrices, and are widely used for they admit structured representations allowing to compute with them in time linear in the dimension. In [47] we show the connection between the notion of quasiseparability and the rank profile matrix invariant of Dumas et al. This allows us to propose an algorithm computing the quasiseparable orders (r_L, r_U) in time $O(n^2 s^{\omega-2})$, where $s = \max(r_L, r_U)$ and ω is the exponent of matrix multiplication. We then present two new structured representations, a binary tree of PLUQ decompositions, and the Bruhat generator, using respectively $O(ns\log(n/s))$ and $O(ns)$ field elements instead of $O(ns^2)$ for the classical generator and $O(nslogn)$ for the hierarchically semiseparable representations. We present algorithms computing these representations in time $O(n^2 s^{\omega-2})$. These representations allow a matrix-vector product in time linear in the size of their representation. Lastly we show how to multiply two such structured matrices in time $O(n^2 s^{\omega-2})$.

6.3.16. A Real QZ Algorithm for Structured Companion Pencils

With Y. Eidelman (U. Tel Aviv) and L. Gemignani (U. Pisa), we design in [54] a fast implicit real QZ algorithm for eigenvalue computation of structured companion pencils arising from linearizations of polynomial rootfind-ing problems. The modified QZ algorithm computes the generalized eigenvalues of an $N \times N$ structured matrix pencil using $O(N^2)$ flops and $O(N)$ memory storage. Numerical experiments and comparisons confirm the effectiveness and the stability of the proposed method.

6.3.17. *Efficient Solution of Parameter Dependent Quasiseparable Systems and Computation of Meromorphic Matrix Functions*

In [55], with Y. Eidelman (U. Tel Aviv) and L. Gemignani (U. Pisa), we focus on the solution of shifted quasiseparable systems and of more general parameter dependent matrix equations with quasiseparable representations. We propose an efficient algorithm exploiting the invariance of the quasiseparable structure under diagonal shifting and inversion. This algorithm is applied to compute various functions of matrices. Numerical experiments show the effectiveness of the approach.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

Bosch (Germany) ordered us some support for implementing complex numerical algorithms.

7.2. Bilateral Grants with Industry

- Marie Paindavoine is supported by an Orange Labs PhD Grant (from October 2013 to November 2016). She works on privacy-preserving encryption mechanisms.
- Miruna Rosca and Radu Titiu are employees of BitDefender. Their research internships (from October to December 2016) are supervised by Damien Stehlé and Benoît Libert, respectively. Miruna Rosca works on the foundations of lattice-based cryptography, and Radu Titiu works on functional encryption.
- Within the program Nano 2017, we collaborate with the Compilation Expertise Center of STMicroelectronics on the theme of floating-point arithmetic for embedded processors.

8. Partnerships and Cooperations

8.1. Regional Initiatives

ARC6 PHD PROGRAMME. The PhD grant of Valentina Popescu is funded since September 2014 by Région Rhône-Alpes through the "ARC6" programme.

PALSE PROJECT. Benoît Libert was awarded a 500keur grant (from July 2014 to November 2016) for his PALSE (Programme d'Avenir Lyon Saint-Etienne) project *Towards practical enhanced asymmetric encryption schemes*.

8.2. National Initiatives

8.2.1. *ANR HPAC Project*

Participants: Claude-Pierre Jeannerod, Nicolas Louvet, Clément Pernet, Nathalie Revol, Gilles Villard.

"High-performance Algebraic Computing" (HPAC) was a four year ANR project that started in January 2012 and was extended till mid-2016. The final report has been sent in July 2016. The Web page of the project is http://hpac.gforge.inria.fr/. HPAC has been headed by Jean-Guillaume Dumas (CASYS team, LJK laboratory, Grenoble); it was involving AriC as well as the Inria project-team MOAIS (LIG, Grenoble), the Inria project-team PolSys (LIP6 lab., Paris), the ARITH group (LIRMM laboratory, Montpellier), and the HPC Project company.

The overall ambition of HPAC was to provide international reference high-performance libraries for exact linear algebra and algebraic systems on multi-processor architecture and to influence parallel programming approaches for algebraic computing. The central goal has been to extend the efficiency of the LinBox and FGb libraries to new trend parallel architectures such as clusters of multi-processor systems and graphics processing units in order to tackle a broader class of problems in lattice-based cryptography and algebraic cryptanalysis. HPAC has conducted researches along three axes:

- A domain specific parallel language (DSL) adapted to high-performance algebraic computations;
- Parallel linear algebra kernels and higher-level mathematical algorithms and library modules;
- Library composition, their integration into state-of-the-art software, and innovative high-performance solutions for cryptology challenges.

8.2.2. ANR DYNA3S Project

Participants: Guillaume Hanrot, Gilles Villard.

Dyna3s is a four year ANR project that started in October 2013. The Web page of the project is https://www.irif.fr/~dyna3s. It is headed by Valérie Berthé (U. Paris 7) and involves also the University of Caen.

The aim is to study algorithms that compute the greatest common divisor (gcd) from the point of view of dynamical systems. A gcd algorithm is considered as a discrete dynamical system by focusing on integer input. We are mainly interested in the computation of the gcd of several integers. Another motivation comes from discrete geometry, a framework where the understanding of basic primitives, discrete lines and planes, relies on algorithm of the Euclidean type.

8.2.3. ANR FastRelax Project

Participants: Nicolas Brisebarre, Guillaume Hanrot, Vincent Lefèvre, Jean-Michel Muller, Bruno Salvy, Serge Torres, Silviu Filip.

FastRelax stands for “Fast and Reliable Approximation”. It is a four year ANR project started in October 2014. The web page of the project is http://fastrelax.gforge.inria.fr/. It is headed by B. Salvy and involves AriC as well as members of the Marelle Team (Sophia), of the Mac group (LAAS, Toulouse), of the Specfun and Toccata Teams (Saclay), as well as of the Pequan group in UVSQ and a colleague in the Plume group of LIP.

The aim of this project is to develop computer-aided proofs of numerical values, with certified and reasonably tight error bounds, without sacrificing efficiency. Applications to zero-finding, numerical quadrature or global optimization can all benefit from using our results as building blocks. We expect our work to initiate a “fast and reliable” trend in the symbolic-numeric community. This will be achieved by developing interactions between our fields, designing and implementing prototype libraries and applying our results to concrete problems originating in optimal control theory.

8.2.4. ANR MetaLibm Project

Participants: Claude-Pierre Jeannerod, Jean-Michel Muller.

MetaLibm is a four-year project (started in October 2013) focused on the design and implementation of code generators for mathematical functions and filters. The web page of the project is http://www.metalibm.org/ANRMetaLibm/. It is headed by Florent de Dinechin (INSA Lyon and Socrate team) and, besides Socrate and AriC, also involves teams from LIRMM (Perpignan), LIP6 (Paris), CERN (Geneva), and Kalray (Grenoble). The main goals of the project are to automate the development of mathematical libraries (libm), to extend it beyond standard functions, and to make it unified with similar approaches developed in or useful for signal processing (filter design). Within AriC, we are especially interested in studying the properties of fixed-point arithmetic and floating-point arithmetic that can help develop such a framework.

8.2.5. ANR ALAMBIC Project

Participants: Benoît Libert, Fabien Laguillaumie.

ALAMBIC is a four-year project (started in October 2016) focused on the applications of cryptographic primitives with homomorphic or malleability properties. The web page of the project is https://crypto.di.ens.fr/projects:alambic:description. It is headed by Damien Vergnaud (ENS Paris and CASCADE team) and, besides AriC, also involves teams from the XLIM laboratory (Université de Limoges) and the CASCADE team (ENS Paris). The main goals of the project are: (i) Leveraging the applications of malleable cryptographic primitives in the design of advanced cryptographic protocols which require computations on encrypted data; (ii) Enabling the secure delegation of expensive computations to remote servers in the cloud by using malleable cryptographic primitives; (iii) Designing more powerful zero-knowledge proof systems based on malleable cryptography.

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

LATTAC ERC GRANT. Damien Stehlé was awarded an ERC Starting Grant for his project *Euclidean lattices: algorithms and cryptography* (LattAC) in 2013 (1.4Meur for 5 years from January 2014). The LattAC project aims at studying all computational aspects of lattices, from algorithms for manipulating them to applications. The main objective is to enable the rise of lattice-based cryptography.

OPENDREAMKIT is a H2020 Infrastructure project providing substantial funding to the open source computational mathematics ecosystem. It will run for four years, starting from September 2015. Clément Pernet is a participant.

8.4. International Research Visitors

8.4.1. Visiting Scientists

- George Labahn, Professor at U. Waterloo, Ontario, Canada spent the month of April with our team.
- Elena Kirshanova, PhD student at Ruhr-U. Bochum, Germany spent one month with our team, from mid-February to mid-March.
- Jiantao Li, PhD student at East China Normal U., China spends a year with our team. He arrived in September.

8.4.2. Internships

Willy Quach

Date: February 2016–June 2016

Institution: ENS de Lyon

Supervisor: Damien Stehlé

Balthazar Bauer

Date: March 2016–August 2016

Institution: Paris 7

Supervisor: Benoît Libert

Qian Chen

Date: March 2016–August 2016

Institution: ENS Rennes

Supervisors: Fabien Laguillaumie and Benoît Libert

Thi Xuan Vu

Date: May 2016–July 2016

Institution: ENS de Lyon

Supervisors: Claude-Pierre Jeannerod and Vincent Neiger

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

Nathalie Revol, with Javier Hormigo and Stuart Oberman, were general chairs of the Arith 23 conference, Santa Clara, California, USA.

9.1.1.2. Member of the Organizing Committees

Nathalie Revol was the organizer of the SWIM 2016: Summer Workshop on Interval Methods, gathering above 35 participants in Lyon, June 2016.

Bruno Salvy was a co-organizer of the meeting Alea'16 gathering about 80 participants in Luminy, March 2016.

9.1.2. Scientific Events Selection

9.1.2.1. Chair of Conference Program Committees

Jean-Michel Muller belongs to the 3-member board of the steering committee of the Arith series of conferences.

9.1.2.2. Member of the Conference Program Committees

Nathalie Revol was a member of the program committees of REC'16 and SCAN 2016.

Bruno Salvy was a member of the program committee of AofA'16, Krakow, Poland.

Damien Stehlé was member of the program committees of Asiacrypt'16, Eurocrypt'17, SCN'16, ANTS'16, PKC'16 and PQCrypto'16.

Benoît Libert was member of the program committees of PKC'16, Africacrypt'16, ACM-CCS 2016, Eurocrypt'17.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

Jean-Michel Muller is a member of the editorial board of the *IEEE Transactions on Computers*. He is a member of the board of foundation editors of the *Journal for Universal Computer Science*.

Nathalie Revol is a member of the editorial board of the journal *Reliable Computing*.

Bruno Salvy is a member of the editorial boards of the *Journal of Symbolic Computation*, of the *Journal of Algebra* (section Computational Algebra) and of the collection *Texts and Monographs in Symbolic Computation* (Springer).

Gilles Villard is a member of the editorial board of the *Journal of Symbolic Computation*.

9.1.4. Invited Talks

Damien Stehlé gave an invited talk at the YACC conference (Porquerolles, June), on the Learning With Errors Problem. He gave an invited talk at the HEAT workshop (Paris, July) on lattice reduction.

Jean-Michel Muller gave an invited talk at a minisymposium on reproducible research at the CANUM conference (Obernai, May).

Claude-Pierre Jeannerod and Clément Pernet gave invited talks at RAIM (Rencontres Arithmétique de l'Informatique Mathématique; Banyuls-sur-mer, June).

Nathalie Revol gave an invited talk at a minisymposium on numerical reproducibility for high-performance computing at SIAM Parallel Processing (Paris, April).

9.1.5. Leadership within the Scientific Community

Damien Stehlé is a member of the steering committee of the PQCrypto conference series. He is also a member of the steering committee of the Cryptography and Coding French research grouping (C2).

Paola Boito and Claude-Pierre Jeannerod are members of the scientific committee of JNCF (Journées Nationales de Calcul Formel).

Nathalie Revol is the chair of the IEEE 1788 group for the standardization of interval arithmetic: the work now addresses the set-based model and its implementation using simple IEEE-754 formats (IEEE P1788.1).

9.1.6. Scientific Expertise

Jean-Michel Muller is a member of the Scientific Council of CERFACS (Toulouse). He was a member of the Scientific Council of the "La Recherche" prize for 2015.

Jean-Michel Muller is a member of the steering committee of the "Defi 7" (information sciences) of the French Agence Nationale de la Recherche (ANR).

Bruno Salvy was a member of the recruitment committees for University Professors in Bordeaux (computer science) and in Toulouse (Mathematics).

Damien Stehlé is a member of the 2016 Gilles Kahn PhD award committees for 2016.

Claude-Pierre Jeannerod was a member of the recruitment committee for postdocs and sabbaticals at Inria Grenoble Rhône-Alpes.

9.1.7. Research Administration

Guillaume Hanrot is director of the LIP laboratory (Laboratoire de l'Informatique du Parallélisme).

Jean-Michel Muller is co-director of the Groupement de Recherche (GDR) *Informatique Mathématique* of CNRS.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master: Claude-Pierre Jeannerod, Nathalie Revol, *Algorithmique numérique et fiabilité des calculs en arithmétique flottante* (24h), M2 ISFA (Institut de Science Financière et d'Assurances), Université Claude Bernard Lyon 1.

Master: Vincent Lefèvre, *Arithmétique des ordinateurs* (12h), M2 ISFA (Institut de Science Financière et d'Assurances), Université Claude Bernard Lyon 1.

Master: Fabien Laguillaumie, Cryptography, Error Correcting Codes, 150h, Université Claude Bernard Lyon 1.

Master: Damien Stehlé, Cryptography, 12h, ENS de Lyon.

Master: Benoît Libert, Computer science and privacy, 12h, ENS de Lyon; Cryptography, 12h, ENS de Lyon.

Professional teaching: Nathalie Revol, *Contrôler et améliorer la qualité numérique d'un code de calcul industriel* (2h30), Collège de Polytechnique.

Master: Bruno Salvy, Calcul Formel (9h), MPRI.

Master: Bruno Salvy, Mathématiques expérimentales (44h), École polytechnique.

Master: Bruno Salvy, Logique et complexité (32h), École polytechnique.

9.2.2. Supervision

- PhD: Serge Torres, *Tools for the design of reliable and efficient function evaluation libraries*, École normale supérieure de Lyon; defended on September 22, 2016; co-supervised by Nicolas Brisebarre and Jean-Michel Muller.
- PhD: Vincent Neiger, *Bases of relations in one or several variables: fast algorithms and applications*, École normale supérieure de Lyon; defended on November 30, 2016; co-supervised by Claude-Pierre Jeannerod and Gilles Villard (together with Éric Schost (U. Waterloo, Canada)).
- PhD: Silviu-Ioan Filip, *Robust tools for weighted Chebyshev approximation and applications to digital filter design*, École normale supérieure de Lyon; defended on December 7, 2016; co-supervised by Nicolas Brisebarre and Guillaume Hanrot.
- PhD in progress: Marie Paindavoine, *Méthodes de calculs sur des données chiffrées*, since October 2013 (Orange Labs - UCBL), co-supervised by Fabien Laguillaumie (together with Sébastien Canard).
- PhD in progress : Antoine Plet, *Contribution à l'analyse d'algorithmes en arithmétique virgule flottante*, since September 2014, co-supervised by Nicolas Louvet and Jean-Michel Muller.
- PhD in progress : Valentina Popescu, *Vers des bibliothèques multi-précision certifiées et performantes*, since September 2014, co-supervised by Mioara Joldes (LAAS) and Jean-Michel Muller
- PhD in progress: Louis Dumont, *Algorithmique efficace pour les diagonales, applications en combinatoire, physique et théorie des nombres*, since September 2013, co-supervised by Alin Bostan (SpecFun team) and Bruno Salvy.
- PhD in progress: Stephen Melczer, *Effective analytic combinatorics in one and several variables*, since September 2014, co-supervised by George Labahn (U. Waterloo, Canada) and Bruno Salvy.
- PhD in progress: Fabrice Mouhartem, *Privacy-preserving protocols from lattices and bilinear maps*, since September 2015, supervised by Benoît Libert.
- PhD in progress: Chen Qiang, *Applications of Malleability in Cryptography*, since September 2016, co-supervised by Benoît Libert, Adeline Langlois (IRISA) and Pierre-Alain Fouque (IRISA).
- PhD in progress: Weiqiang Wen, *Hard problems on lattices*, since September 2015, supervised by Damien Stehlé.
- PhD in progress: Alice Pellet–Mary, *Cryptographic obfuscation*, since September 2016, supervised by Damien Stehlé.
- PhD in progress: Florent Bréhard, *Outils pour un calcul certifié. Applications aux systèmes dynamiques et à la théorie du contrôle*, since September 2016, co-supervised by Nicolas Brisebarre, Mioara Joldeş (LAAS, Toulouse) and Damien Pous (LIP).

9.2.3. Juries

Paola Boito was an external reviewer for the PhD thesis of Bahar Arslan (University of Manchester, UK). She was also in the PhD committee of Louis Dumont (LIX, École polytechnique).

Claude-Pierre Jeannerod was in the PhD committee of Alexandre Temperville (CRIStAL, U. Lille 1).

Fabien Laguillaumie was a reviewer for the Habilitation thesis of Abderrahmane Nitaj (LMNO, U. Caen) and for the PhD thesis of Mario Cornejo-Ramirez (LIENS, UPSL).

Jean-Michel Muller was a reviewer for the PhD thesis of Arjun Suresh (U. Rennes). He was in the Habilitation committee of Claude Michel (U. Nice Sophia Antipolis).

Nathalie Revol was in the PhD committee of Rafife Nheili (U. Perpignan Via Domitia).

Bruno Salvy was a reviewer for the PhD thesis of Thibaut Verron (LIP6, UPMC) and for the HdR of Loïck Lhôte (Greyc, U. Caen). He was also in the PhD committees of Wenjie Fang (LIAFA, U. Paris-Diderot) and Louis Dumont (LIX, École polytechnique).

Damien Stehlé was a reviewer for the PhD thesis of Hansol Ryu (SNU, South Korea). He was in the PhD committee of Thijs Laarhoven (TU Eindhoven, The Netherlands) and in the Habilitation committee of Hoeteck Wee (DI, CNRS).

9.3. Popularization

Claude-Pierre Jeannerod gave an invited talk at *Journés Nationales de l'APMEP* (Lyon, October 2016), on the theme of algorithms for computer arithmetic.

Paolo Montuschi (Politecnico di Torino) and Jean-Michel Muller wrote a short paper on Computer Arithmetic for Computer Magazine [51].

Nathalie Revol is a member of the steering committee of the MMI: Maison des Mathématiques et de l'Informatique, and in particular she was involved in the creation of the *Magimatique* exhibition. She presented some magic tricks during *Forum des Associations de Lyon 7e* and during the Science Fair, and she helped a class of high-school pupils (2nd) of Lycée Juliette Récamier (Lyon) to prepare a show for other pupils. She belonged to the selection committee for the MathInfoLy summer school for high-school pupils (around 90 french-speaking pupils). As an incentive for high-school pupils, and especially girls, to choose scientific careers, she gave talks at Lycée Lucie Aubrac (Ceyzériat), Lycée Xavier Bichat (Nantua) and Mondial des Métiers (in January and February 2016). She presented computer science for primary school pupils (CM2, École Guilloux, St-Genis-Laval: 12 lectures and hands-on of 1h30 in 2015-2016, for each of the 2 classes). She presented this work during the *Journées Passeurs de Science Informatique* of SIF in June 2016 and during the workshop *Robots pour l'éducation*. She also presented this work at a TEDxINSA talk and for IESF (Ingénieurs et Scientifiques de France). She took part in a training session for teachers, sponsored by Google, in September 2016. She co-organized two days on "Info Sans Ordinateur" gathering researchers interested in unplugged activities. With Jérôme Germoni and Natacha Portier, she co-organized a day *Filles & Maths* in May 2016 and a day *Filles & Info* in November 2016, each gathering about 100 high-school girls of 1e S. She is one of the editors of Interstices: https://interstices.info. She taught how to disseminate (computer) science for PhD students in a 20h module of *Insertion Professionnelle*.

Damien Stehlé will give a talk at the CNRS 'Colloque Sociétal Sécurité Informatique' (December 2016), on Fully Homomorphic Encryption.

10. Bibliography

Publications of the year

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[2] S. BAI, C. BOUVIER, A. KRUPPA, P. ZIMMERMANN. *Better polynomials for GNFS*, in "Mathematics of Computation / Mathematics of Computation", 2016, vol. 85, 12 [*DOI :* 10.1090/MCOM3048], https://hal.inria.fr/hal-01089507.

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Project-Team AVALON

Algorithms and Software Architectures for Distributed and HPC Platforms

IN COLLABORATION WITH: Laboratoire de l'Informatique du Parallélisme (LIP)

IN PARTNERSHIP WITH:
CNRS

Ecole normale supérieure de Lyon

Université Claude Bernard (Lyon 1)

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Distributed and High Performance Computing

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Creation of the Team: 2012 February 01, updated into Project-Team: 2014 July 01

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1. Members

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2. Overall Objectives

2.1. Presentation

The fast evolution of hardware capabilities in terms of wide area communication, computation and machine virtualization leads to the requirement of another step in the abstraction of resources with respect to parallel and distributed applications. Those large scale platforms based on the aggregation of large clusters (Grids), huge datacenters (Clouds), collections of volunteer PC (Desktop computing platforms), or high performance machines (Supercomputers) are now available to researchers of different fields of science as well as to private companies. This variety of platforms and the way they are accessed also have an important impact on how applications are designed (*i.e.,* the programming model used) as well as how applications are executed (*i.e.,* the runtime/middleware system used). The access to these platforms is driven through the use of different services providing mandatory features such as security, resource discovery, virtualization, load-balancing, monitoring, etc.

The goal of the Avalon team is to execute parallel and/or distributed applications on parallel and/or distributed resources while ensuring user and system objectives with respect to performance, cost, energy, security, etc. Users are not interested in the resources used during the execution. Instead, they are interested in how their application is going to be executed: in which duration, at which cost, what is the environmental footprint involved, etc. This vision of utility computing has been strengthened by the cloud concepts and by the short lifespan of supercomputers (around three years) compared to application lifespan (tens of years). Therefore, a major issue is to design models, systems, and algorithms to execute applications on resources while ensuring user constraints (price, performance, etc.) as well as system administrator constraints (maximizing resource usage, minimizing energy consumption, etc.).

2.2. Objectives

To achieve the vision proposed in Section 2.1, the Avalon project aims at making progress to four complementary research axes: energy, data, component models, and application scheduling.

2.2.1. Energy Application Profiling and Modelization

Avalon will improve the profiling and modeling of scientific applications with respect to energy consumption. In particular, it will require to improve the tools that measure the energy consumption of applications, virtualized or not, at large scale, so as to build energy consumption models of applications.

2.2.2. Data-intensive Application Profiling, Modeling, and Management

Avalon will improve the profiling, modeling, and management of scientific applications with respect to CPU and data intensive applications. The challenges are to improve the performance prediction of parallel regular applications, to model and simulate (complex) intermediate storage components, and data-intensive applications, and last to deal with data management for hybrid computing infrastructures.

2.2.3. Resource-Agnostic Application Description Model

Avalon will design component-based models to capture the different facets of parallel and distributed applications while being resource agnostic, so that they can be optimized for a particular execution. In particular, the proposed component models will integrate energy and data modeling results. Avalon in particular targets OpenMP runtime as a specific use case.

2.2.4. Application Mapping and Scheduling

Avalon will propose multi-criteria mapping and scheduling algorithms to meet the challenge of automatizing the efficient utilization of resources taking into consideration criteria such as performance (CPU, network, and storage), energy consumption, and security. Avalon will in particular focus on application deployment, workflow applications, and security management in clouds.

All our theoretical results will be validated with software prototypes using applications from different fields of science such as bioinformatics, physics, cosmology, etc. The experimental testbed GRID'5000 (cf Section 5.9) will be our platform of choice for experiments.

3. Research Program

3.1. Energy Application Profiling and Modelization

International roadmaps schedule to build exascale systems by the 2018 time frame. According to the Top500 list published in November 2013, the most powerful supercomputer is the Tianhe-2 platform, a machine with more than 3,000,000 cores. It consumes more than 17 MW for a maximum performance of 33 PFlops while the Defense Advanced Research Projects Agency (DARPA) has set to 20 MW the maximum energy consumption of an exascale supercomputer [40].

Energy efficiency is therefore a major challenge for building next generation large scale platforms. The targeted platforms will gather hundreds of million cores, low power servers, or CPUs. Besides being very important, their power consumption will be dynamic and irregular.

Thus, to consume energy efficiently, we aim at investigating two research directions. First, we need to improve the measure, the understanding, and the analysis of the large-scale platform energy consumption. Unlike approaches [41] that mix the usage of internal and external wattmeters on a small set of resources, we target high frequency and precise internal and external energy measurements of each physical and virtual resources on large scale distributed systems.

Secondly, we need to find new mechanisms that consume less and better on such platforms. Combined with hardware optimizations, several works based on shutdown or slowdown approaches aim at reducing energy consumption of distributed platforms and applications. To consume less, we first plan to explore the provision of accurate estimation of the energy consumed by applications without pre-executing and knowing them while most of the works try to do it based on in-depth application knowledge (code instrumentation [44], phase detection for specific HPC applications [49], etc.). As a second step, we aim at designing a framework model that allows interactions, dialogues and decisions taken in cooperation between the user/application, the administrator, the resource manager, and the energy supplier. While smart grid is one of the last killer scenarios for networks, electrical provisioning of next generation large IT infrastructures remains a challenge.

3.2. Data-intensive Application Profiling, Modeling, and Management

Recently, the term “Big Data” has emerged to design data sets or collections so large that they become intractable for classical tools. This term is most of the time implicitly linked to “analytics” to refer to issues such as curation, storage, search, sharing, analysis, and visualization. However, the Big Data challenge is not limited to data-analytics, a field that is well covered by programming languages and run-time systems such as Map-Reduce. It also encompasses data-intensive applications. These applications can be sorted into two categories. In High Performance Computing (HPC), data-intensive applications leverage post-petascale infrastructures to perform highly parallel computations on large amount of data, while in High Throughput Computing (HTC), a large amount of independent and sequential computations are performed on huge data collections.

These two types of data-intensive applications (HTC and HPC) raise challenges related to profiling and modeling that the Avalon team proposes to address. While the characteristics of data-intensive applications are very different, our work will remain coherent and focused. Indeed, a common goal will be to acquire a better understanding of both the applications and the underlying infrastructures running them to propose the best match between application requirements and infrastructure capacities. To achieve this objective, we will extensively rely on logging and profiling in order to design sound, accurate, and validated models. Then, the proposed models will be integrated and consolidated within a single simulation framework (SIMGRID). This will allow us to explore various potential “what-if?” scenarios and offer objective indicators to select interesting infrastructure configurations that match application specificities.

Another challenge is the ability to mix several heterogeneous infrastructures that scientists have at their disposal (*e.g.,* Grids, Clouds, and Desktop Grids) to execute data-intensive applications. Leveraging the aforementioned results, we will design strategies for efficient data management service for hybrid computing infrastructures.

3.3. Resourc-Agnostic Application Description Model

When programming in parallel, users expect to obtain performance improvement, whatever the cost is. For long, parallel machines have been simple enough to let a user program them given a minimal abstraction of their hardware. For example, MPI [43] exposes the number of nodes but hides the complexity of network topology behind a set of collective operations; OpenMP [47] simplifies the management of threads on top of a shared memory machine while OpenACC [46] aims at simplifying the use of GPGPU.

However, machines and applications are getting more and more complex so that the cost of manually handling an application is becoming very high [42]. Hardware complexity also stems from the unclear path towards next generations of hardware coming from the frequency wall: multi-core CPU, many-core CPU, GPGPUs, deep memory hierarchy, etc. have a strong impact on parallel algorithms. Hence, even though an abstract enough parallel language (UPC, Fortress, X10, etc.) succeeds, it will still face the challenge of supporting distinct codes corresponding to different algorithms corresponding to distinct hardware capacities.

Therefore, the challenge we aim to address is to define a model, for describing the structure of parallel and distributed applications that enables code variations but also efficient executions on parallel and distributed infrastructures. Indeed, this issue appears for HPC applications but also for cloud oriented applications. The challenge is to adapt an application to user constraints such as performance, energy, security, etc.

Our approach is to consider component based models [50] as they offer the ability to manipulate the software architecture of an application. To achieve our goal, we consider a “compilation” approach that transforms a resource-agnostic application description into a resource-specific description. The challenge is thus to determine a component based model that enables to efficiently compute application mapping while being tractable. In particular, it has to provide an efficient support with respect to application and resource elasticity, energy consumption and data management. OpenMP runtime is a specific use case that we target.

3.4. Application Mapping and Scheduling

This research axis is at the crossroad of the Avalon team. In particular, it gathers results of the three other research axis. We plan to consider application mapping and scheduling through the following three issues.

3.4.1. Application Mapping and Software Deployment

Application mapping and software deployment consist in the process of assigning distributed pieces of software to a set of resources. Resources can be selected according to different criteria such as performance, cost, energy consumption, security management, etc. A first issue is to select resources at application launch time. With the wide adoption of elastic platforms, *i.e.,* platforms that let the number of resources allocated to an application to be increased or decreased during its execution, the issue is also to handle resource selection at runtime.

The challenge in this context corresponds to the mapping of applications onto distributed resources. It will consist in designing algorithms that in particular take into consideration application profiling, modeling, and description.

A particular facet of this challenge is to propose scheduling algorithms for dynamic and elastic platforms. As the amount of elements can vary, some kind of control of the platforms must be used accordingly to the scheduling.

3.4.2. Non-Deterministic Workflow Scheduling

Many scientific applications are described through workflow structures. Due to the increasing level of parallelism offered by modern computing infrastructures, workflow applications now have to be composed not only of sequential programs, but also of parallel ones. New applications are now built upon workflows with conditionals and loops (also called non-deterministic workflows).

These workflows can not be scheduled beforehand. Moreover cloud platforms bring on-demand resource provisioning and pay-as-you-go billing models. Therefore, there is a problem of resource allocation for non-deterministic workflows under budget constraints and using such an elastic management of resources.

Another important issue is data management. We need to schedule the data movements and replications while taking job scheduling into account. If possible, data management and job scheduling should be done at the same time in a closely coupled interaction.

3.4.3. Security Management in Cloud Infrastructure

Security has been proven to be sometimes difficult to obtain [48] and several issues have been raised in Clouds. Nowadays virtualization is used as the sole mechanism to secure different users sharing resources on Clouds. But, due to improper virtualization of all the components of Clouds (such as micro-architectural components), data leak and modification can occur. Accordingly, next-generation protection mechanisms are required to enforce security on Clouds and provide a way to cope with the current limitation of virtualization mechanisms.

As we are dealing with parallel and distributed applications, security mechanisms must be able to cope with multiple machines. Our approach is to combine a set of existing and novel security mechanisms that are spread in the different layers and components of Clouds in order to provide an in-depth and end-to-end security on Clouds. To do it, our first challenge is to define a generic model to express security policies.

Our second challenge is to work on security-aware resource allocation algorithms. The goal of such algorithms is to find a good trade-off between security and unshared resources. Consequently, they can limit resources sharing to increase security. It leads to complex trade-off between infrastructure consolidation, performance, and security.

4. Application Domains

4.1. Overview

The Avalon team targets applications with large computing and/or data storage needs, which are still difficult to program, maintain, and deploy. Those applications can be parallel and/or distributed applications, such as large scale simulation applications or code coupling applications. Applications can also be workflow-based as commonly found in distributed systems such as grids or clouds.

The team aims at not being restricted to a particular application field, thus avoiding any spotlight. The team targets different HPC and distributed application fields, which bring use cases with different issues. This will be eased by our various collaborations: the team participates to the INRIA-Illinois Joint Laboratory for Petascale Computing, the Physics, Radiobiology, Medical Imaging, and Simulation French laboratory of excellence, the E-Biothon project, the INRIA large scale initiative Computer and Computational Sciences at Exascale (C2S@Exa), and to BioSyL, a federative research structure about Systems Biology of the University of Lyon. Moreover, the team members have a long tradition of cooperation with application developers such as CERFACS and EDF R&D. Last but not least, the team has a privileged connection with CC IN2P3 that opens up collaborations, in particular in the astrophysics field.

In the following, some examples of representative applications we are targeting are presented. In addition to highlighting some application needs, they also constitute some of the use cases we will use to valide our theoretical results.

4.2. Climatology

The world's climate is currently changing due to the increase of the greenhouse gases in the atmosphere. Climate fluctuations are forecasted for the years to come. For a proper study of the incoming changes, numerical simulations are needed, using general circulation models of a climate system. Simulations can be of different types: HPC applications (*e.g.,* the NEMO framework [45] for ocean modelization), code-coupling applications (*e.g.,* the OASIS coupler [51] for global climate modeling), or workflows (long term global climate modeling).

As for most applications the team is targeting, the challenge is to thoroughly analyze climate-forecasting applications to model their needs in terms of programing model, execution model, energy consumption, data access pattern, and computing needs. Once a proper model of an application has been set up, appropriate scheduling heuristics could be designed, tested, and compared. The team has a long tradition of working with CERFACS on this topic, for example in the LEGO (2006-09) and SPADES (2009-12) French ANR projects.

4.3. Astrophysics

Astrophysics is a major field to produce large volume of data. For instance, the Large Synoptic Survey Telescope (http://www.lsst.org/lsst/) will produce 15 TB of data every night, with the goals of discovering thousands of exoplanets and of uncovering the nature of dark matter and dark energy in the universe. The Square Kilometer Array (http://www.skatelescope.org/) produces 9 Tbits/s of raw data. One of the scientific projects related to this instrument called Evolutionary Map of the Universe is working on more than 100 TB of images. The Euclid Imaging Consortium will generate 1 PB data per year.

Avalon collaborates with the *Institut de Physique Nucléaire de Lyon* (IPNL) laboratory on large scale numerical simulations in astronomy and astrophysics. Contributions of the Avalon members have been related to algorithmic skeletons to demonstrate large scale connectivity, the development of procedures for the generation of realistic mock catalogs, and the development of a web interface to launch large cosmological simulations on GRID'5000.

This collaboration, that continues around the topics addressed by the CLUES project (http://www.clues-project.org), has been extended thanks to the tight links with the CC-IN2P3. Major astrophysics projects execute part of their computing, and store part of their data on the resources provided by the CC-IN2P3. Among them, we can mention SNFactory, Euclid, or LSST. These applications constitute typical use cases for the research developed in the Avalon team: they are generally structured as workflows and a huge amount of data (from TB to PB) is involved.

4.4. Bioinformatics

Large-scale data management is certainly one of the most important applications of distributed systems in the future. Bioinformatics is a field producing such kinds of applications. For example, DNA sequencing applications make use of MapReduce skeletons.

The Avalon team is a member of BioSyL (http://www.biosyl.org), a Federative Research Structure attached to University of Lyon. It gathers about 50 local research teams working on systems biology. Moreover, the team cooperated with the French Institute of Biology and Chemistry of Proteins (IBCP http://www.ibcp.fr) in particular through the ANR MapReduce project where the team focuses on a bio-chemistry application dealing with protein structure analysis. Avalon have also starting working with the Inria Beagle team (https://team.inria.fr/beagle/) on artificial evolution and computational biology as the challenges are around high performance computation and data management.

5. New Software and Platforms

5.1. Active Data

Participants: Gilles Fedak [correspondant], Valentin Lorentz, Laurent Lefevre.

FUNCTIONAL DESCRIPTION

Active Data is a free software system that tracks the life cycle of data distributed across heterogeneous software and infrastructures.

As the volume of data grows exponentially, the management of these data becomes more complex in proportion. A key point is to handle the complexity of the Data Life Cycle, *i.e.,* the various operations performed on data: transfer, archiving, replication, deletion, etc. Indeed, data-intensive applications span over a large variety of devices and e-infrastructures which implies that many systems are involved in data management and processing. Active Data is a new approach to automate and improve the expressiveness of data management applications. Active Data consists of a formal model that captures the essential data life cycle stages and properties: creation, deletion, replication, derivation, transient unavailability, uniform naming, and many more. Active Data provides a programming model that simplify the development of data life cycle management applications. Active Data allows code execution at each stage of the data life cycle: routines provided by programmers are executed when a set of events (creation, replication, transfer, deletion) happen to any data.

- URL: http://active-data.gforge.inria.fr

5.2. DIET

Participants: Daniel Balouek-Thomert, Yves Caniou, Eddy Caron, Arnaud Lefray.

FUNCTIONAL DESCRIPTION

DIET (Distributed Interactive Engineering Toolbox) is a middleware designed for high-performance computing in a heterogeneous and distributed environment (workstations, clusters, grids, clouds). Three main developments are done in 2016:

Proxmox support: DIET has a new Cloud extension that can be used to interact with this PVE (Proxmox Virtual Environment) solution. Proxmox is a complete open source server virtualization management software, based on KVM virtualization and container-based virtualization. It manages KVM virtual machines, Linux containers (LXC), storage, virtualized networks, and HA clusters. This extension is a contribution provided by the NewGeneration-SR company.

DaaS support: The goal of this development was to add Data-as-a-Service (DaaS) functionality to the DIET middleware via an optional module. We have added the GDConnect plug-in to the DIET Data manager that provides the capability to deal with Google's Cloud Storage.

Energy Support: We designed, implementation and evaluation of an energy-efficient resource management system that builds upon DIET and NSDE-divisible tasks with precedence constraints.

- Partners: CNRS - ENS Lyon - UCBL Lyon 1
- Contact: Eddy Caron
- URL: http://graal.ens-lyon.fr/diet/

5.3. Execo

Participant: Matthieu Imbert.

FUNCTIONAL DESCRIPTION

Execo offers a Python API for asynchronous control of local or remote, standalone or parallel, unix processes. It is especially well suited for quickly and easily scripting workflows of parallel/distributed operations on local or remote hosts: automate a scientific workflow, conduct computer science experiments, perform automated tests, etc. The core python package is execo. The execo_g5k package provides a set of tools and extensions for the Grid'5000 testbed. The execo_engine package provides tools to ease the development of computer sciences experiments. Execo is used directly by 15 to 30 users, in and out of the Avalon team, and is also used by a few Grid'5000 tools such as kwapi, funk, topo5k, g5k_bench_flops.

- Contact: Matthieu Imbert
- URL: http://execo.gforge.inria.fr

5.4. Kaapi

Participant: Thierry Gautier.

Kaapi is a library for high performance applications running on multi-cores/multi- processors with support for multi-GPUs. Kaapi provides ABI compliant implementations of libGOMP (GCC runtime for OpenMP) and libomp.so (CLANG and Intel compiler). It was one of the target runtime of the K'Star compiler (http://kstar.gforge.inria.fr).

Web site:

- Partners: EPI Corse (Philippe Virouleau, François Broquedis)
- Contact: Thierry Gautier
- URL: http://kaapi.gforge.inria.fr

5.5. Kwapi

Participants: Jean-Patrick Gelas, Laurent Lefevre.

FUNCTIONAL DESCRIPTION

Kwapi is a software framework dealing with energy monitoring of large scale infrastructures through heterogeneous energy sensors. Kwapi has been designed inside the FSN XLCloud project for OpenStack infrastructures. Through the support of Hemera Inria project, kwapi has been extended and deployed in production mode to support easy and large scale energy profiling of the Grid'5000 resources.

- Contact: Laurent Lefevre
- URL: https://launchpad.net/kwapi

5.6. L2C and DirectL2C

Participants: Hélène Coullon, Vincent Lanore, Christian Perez, Jérôme Richard.

FUNCTIONAL DESCRIPTION

L2C (http://hlcm.gforge.inria.fr) is a Low Level Component model implementation targeting at use-cases where overhead matters such as High-Performance Computing. L2C does not offer network transparency neither language transparency. Instead, L2C lets the user choose between various kinds of interactions between components, some with ultra low overhead and others that support network transport. L2C is extensible as additional interaction kinds can be added quite easily. L2C currently supports C++, FORTRAN 2013, MPI and CORBA interactions.

DirectL2C is an extension to L2C that enables efficient and consistent reconfiguration of large scale L2C based assemblies. It provides an assembly model enhanced with domains, tranformations, and transformation adapters.

- Partners: CEA/Maison de la Simulation (Julien Bigot)
- Contact: Christian Perez
- URL: http://hlcm.gforge.inria.fr/l2c:start

5.7. Sam4C

Participants: Eddy Caron, Arnaud Lefray, Marc Pinhede, Mathieu Veyrand.

SCIENTIFIC DESCRIPTION

This editor is generated in Java from an EMF -Eclipse Modeling Framework- metamodel to simplify any modifications or extensions. The application model and the associated security policy are compiled in a single XML file which serves as input for an external Cloud security-aware scheduler. Alongside with this editor, Cloud architecture models and provisioning algorithms are provided for simulation (in the current version) or real deployments (in future versions).

FUNCTIONAL DESCRIPTION

Sam4C (https://gforge.inria.fr/projects/sam4c/) -Security-Aware Models for Clouds- is a graphical and textual editor to model Cloud applications (as virtual machines, processes, files and communications) and describe its security policy. Sam4C is suitable to represent any static application without deadline or execution time such as n-tiers or parallel applications.

- Contact: Eddy Caron
- URL: https://gforge.inria.fr/projects/sam4c/

5.8. SimGrid

Participant: Frédéric Suter.

FUNCTIONAL DESCRIPTION

SimGrid is a toolkit that provides core functionalities for the simulation of distributed applications in heterogeneous distributed environments. The simulation engine uses algorithmic and implementation techniques toward the fast simulation of large systems on a single machine. The models are theoretically grounded and experimentally validated. The results are reproducible, enabling better scientific practices.

Its models of networks, cpus and disks are adapted to (Data)Grids, P2P, Clouds, Clusters and HPC, allowing multi-domain studies. It can be used either to simulate algorithms and prototypes of applications, or to emulate real MPI applications through the virtualization of their communication, or to formally assess algorithms and applications that can run in the framework.

The formal verification module explores all possible message interleavings in the application, searching for states violating the provided properties. We recently added the ability to assess liveness properties over arbitrary and legacy codes, thanks to a system-level introspection tool that provides a finely detailed view of the running application to the model checker. This can for example be leveraged to verify both safety or liveness properties, on arbitrary MPI code written in C/C++/Fortran.

- Partners: CNRS - ENS Rennes
- Contact: Martin Quinson (EPC Myriads)
- URL: http://simgrid.gforge.inria.fr/

5.9. Grid'5000

Participants: Laurent Lefevre, Simon Delamare, David Loup, Christian Perez.

FUNCTIONAL DESCRIPTION

The Grid'5000 experimental platform is a scientific instrument to support computer science research related to distributed systems, including parallel processing, high performance computing, cloud computing, operating systems, peer-to-peer systems and networks. It is distributed on 10 sites in France and Luxembourg, including Lyon. Grid'5000 is a unique platform as it offers to researchers many and varied hardware resources and a complete software stack to conduct complex experiments, ensure reproducibility and ease understanding of results. In 2016, a new cluster financially supported by Inria has been deployed on the Grid5000 Lyon site.

- Contact: Laurent Lefevre
- URL: https://www.grid5000.fr/

6. New Results

6.1. Energy Efficiency of Large Scale Distributed Systems

Participants: Laurent Lefevre, Daniel Balouek-Thomert, Eddy Caron, Radu Carpa, Marcos Dias de Assunção, Jean-Patrick Gelas, Olivier Glück, Jean-Christophe Mignot, Violaine Villebonnet.

6.1.1. Energy Efficient Core Networks with SDN

This work [14], [15] seeks to improve the energy efficiency of backbone networks by providing an intra-domain Software Defined Network (SDN) approach to selectively and dynamically turn off and on a subset of links. We proposed the STREETE framework (SegmenT Routing based Energy Efficient Traffic Engineering) that represents an online method to switch some links off/on dynamically according to the network load. We have implemented a working prototype in the OMNET++ simulator and design a validation platform [15] based on NetFPGA and Raspberry equipment with SDN frameworks (ONOS).

6.1.2. Energy Proportionality in HPC Systems

Energy savings are among the most important topics concerning Cloud and HPC infrastructures nowadays. Servers consume a large amount of energy, even when their computing power is not fully utilized. These static costs represent quite a concern, mostly because many datacenter managers are over-provisioning their infrastructures compared to the actual needs. This results in a high part of wasted power consumption. In this work [25], [24], [23] , we proposed the BML ("Big, Medium, Little") infrastructure, composed of heterogeneous architectures, and a scheduling framework dealing with energy proportionality. We introduce heterogeneous power processors inside datacenters as a way to reduce energy consumption when processing variable workloads. Our framework brings an intelligent utilization of the infrastructure by dynamically executing applications on the architecture that suits their needs, while minimizing energy consumption. Our first validation process focuses on distributed stateless web servers scenario and we analyze the energy savings achieved through energy proportionality. This research activity is performed with the collaboration of Sepia Team (IRIT, Toulouse) through the co-advising of Violaine Villebonnet.

6.1.3. Energy-Aware Server Provisioning

Several approaches to reduce the power consumption of datacenters have been described in the literature, most of which aim to improve energy efficiency by trading off performance for reducing power consumption. However, these approaches do not always provide means for administrators and users to specify how they want to explore such trade-offs. This work [11] provides techniques for assigning jobs to distributed resources, exploring energy efficient resource provisioning. We use middleware-level mechanisms to adapt resource allocation according to energy-related events and user-defined rules. A proposed framework enables developers, users and system administrators to specify and explore energy efficiency and performance trade-offs without detailed knowledge of the underlying hardware platform. Evaluation of the proposed solution under three scheduling policies shows gains of 25% in energy-efficiency with minimal impact on the overall application performance. We also evaluate reactivity in the adaptive resource provisioning This research activity is performed with the collaboration of NewGen SR society through the co-advising of Daniel Balouek-Thomert.

6.1.4. Improving Energy Re-Usage of Large Scale Computing Systems

The heat induced by computing resources is generally a waste of energy in supercomputers. This is especially true in very large scale supercomputers, where the produced heat has to be compensated with expensive and energy consuming cooling systems. Energy is a critical point for future supercomputing trends that currently try to achieve exascale, without having its energy consumption reaching an important fraction of a nuclear power plant. Thus, new ways of generating or recovering energy have to be explored. Energy harvesting consists in recovering wasted energy. ThermoElectric Generators (TEGs) aim to recover energy by converting wasted dissipated energy into usable electricity. By combining computing units (CU) and TEGs at very large scale, we spotted a potential way to recover energy from wasted heat generated by computations on supercomputers. In this work [30], [20], we study the potential gains in combining TEGs with computational units at petascale and exascale. We explored the technology behind TEGs, and finally our results concerning binding TEGs and computational units in a petascale and exascale system. With the available technology, we demonstrate that the use of TEGs in a supercomputer environment could be realistic and quickly profitable, and hence have a positive environmental impact.

6.2. MPI Application Simulation

Participant: Frédéric Suter.

6.2.1. The SMPI approach

In [37], we summarized our recent work and developments on SMPI, a flexible simulator of MPI applications. In this tool, we took a particular care to ensure our simulator could be used to produce fast and accurate predictions in a wide variety of situations. Although we did build SMPI on SimGrid whose speed and accuracy had already been assessed in other contexts, moving such techniques to a HPC workload required significant additional effort. Obviously, an accurate modeling of communications and network topology was one of the key to such achievements. Another less obvious key was the choice to combine in a single tool the possibility to do both offline and online simulation.

6.3. MapReduce Computations on Hybrid Distributed Computations Infrastructures

Participant: Gilles Fedak.

6.3.1. Availability and Network-Aware MapReduce Task Scheduling over the Internet

MapReduce offers an easy-to-use programming paradigm for processing large datasets. In our previous work, we have designed a MapReduce framework called BitDew-MapReduce for desktop grid and volunteer computing environment, that allows non-expert users to run data-intensive MapReduce jobs on top of volunteer resources over the Internet. However, network distance and resource availability have great impact on MapReduce applications running over the Internet. To address this, an availability and network-aware MapReduce framework over the Internet is proposed in [9]. Simulation results show that the MapReduce job response time could be decreased by 27.15%, thanks to Naive Bayes Classifier-based availability prediction and landmark-based network estimation.

6.4. Managing Big Data Life Cycle

Participants: Gilles Fedak, Valentin Lorentz, Laurent Lefevre.

6.4.1. Data Energy Traceability

In this work, we have opened a new research topic around the energy traceability of data. The objective is to answer the question of how many energy has been consumed to produce a particular data. This work is partially based on the concept of data life cycle, that is extended to record each step of the data life cycle.

6.5. Desktop Grid Computing

Participant: Gilles Fedak.

6.5.1. Multi-Criteria and Satisfaction Oriented Scheduling for Hybrid Distributed Computing Infrastructures

Assembling and simultaneously using different types of distributed computing infrastructures (DCI) like Grids and Clouds is an increasingly common situation. Because infrastructures are characterized by different attributes such as price, performance, trust, greenness, the task scheduling problem becomes more complex and challenging. In [7], we presented the design for a fault-tolerant and trust-aware scheduler, which allows to execute Bag-of-Tasks applications on elastic and hybrid DCI, following user-defined scheduling strategies. Our approach, named Promethee scheduler, combines a pull-based scheduler with multi-criteria Promethee decision making algorithm. Because multi-criteria scheduling leads to the multiplication of the possible scheduling strategies, we proposed SOFT, a methodology that allows to find the optimal scheduling strategies given a set of application requirements. The validation of this method is performed with a simulator that fully implements the Promethee scheduler and recreates an hybrid DCI environment including Internet Desktop Grid, Cloud and Best Effort Grid based on real failure traces. A set of experiments shows that the Promethee scheduler is able to maximize user satisfaction expressed accordingly to three distinct criteria: price, expected completion time and trust, while maximizing the infrastructure useful employment from the resources owner point of view. Finally, we present an optimization which bounds the computation time of the Promethee algorithm, making realistic the possible integration of the scheduler to a wide range of resource management software.

6.6. HPC Component Models and OpenMP

Participants: Hélène Coullon, Vincent Lanore, Christian Perez, Jérôme Richard, Thierry Gautier.

6.6.1. Combining Both a Component Model and a Task-based Model

We have studied the feasibility of efficiently combining both a software component model and a task-based model. Task based models are known to enable efficient executions on recent HPC computing nodes while component models ease the separation of concerns of application and thus improve their modularity and adaptability. We have designed a prototype version of the COMET programming model combining concepts of task-based and component models, and a preliminary version of the COMET runtime built on top of StarPU and L2C. Evaluations of the approach have been conducted on a real-world use-case analysis of a sub-part of the production application GYSELA. Results show that the approach is feasible and that it enables easy composition of independent software codes without introducing overheads. Performance results are equivalent to those obtained with a plain OpenMP based implementation. Part of this work is described in [38].

6.6.2. OpenMP Scheduling Heuristic for NUMA Architecture

The recent addition of data dependencies to the OpenMP 4.0 standard provides the application programmer with a more flexible way of synchronizing tasks. Using such an approach allows both the compiler and the runtime system to know exactly which data are read or written by a given task, and how these data will be used through the program lifetime. Data placement and task scheduling strategies have a significant impact on performances when considering NUMA architectures. While numerous papers focus on these topics, none of them has made extensive use of the information available through dependencies. One can use this information to modify the behavior of the application at several levels: during initialization to control data placement and during the application execution to dynamically control both the task placement and the tasks stealing strategy, depending on the topology. This paper [26] introduces several heuristics for these strategies and their implementations in our OpenMP runtime XKAAPI. We also evaluate their performances on linear algebra applications executed on a 192-core NUMA machine, reporting noticeable performance improvement when considering both the architecture topology and the tasks data dependencies. We finally compare them to strategies presented previously by related works.

6.6.3. Extending OpenMP with Affinity Clause: Design and Implementation

OpenMP 4.0 introduced dependent tasks, which give the programmer a way to express fine grain parallelism. Using appropriate OS support (such as NUMA libraries), the runtime can rely on the information in the depend clause to dynamically map the tasks to the architecture topology. Controlling data locality is one of the key factors to reach a high level of performance when targeting NUMA architectures. On this topic, OpenMP does not provide a lot of flexibility to the programmer yet, which lets the runtime decide where a task should be executed. In [27], we present a class of applications which would benefit from having such a control and flexibility over tasks and data placement. We also propose our own interpretation of the new affinity clause for the task directive, which is being discussed by the OpenMP Architecture Review Board. This clause enables the programmer to give hints to the runtime about tasks placement during the program execution, which can be used to control the data mapping on the architecture. In our proposal, the programmer can express affinity between a task and the following resources: a thread, a NUMA node, and a data. We then present an implementation of this proposal in the Clang-3.8 compiler, and an implementation of the corresponding extensions in our OpenMP runtime LIBKOMP. Finally , we present a preliminary evaluation of this work running two task-based OpenMP kernels on a 192-core NUMA architecture, that shows noticeable improvements both in terms of performance and scalability.

6.6.4. Support of High Task Throughput for Complex OpenMP Application

In [4], we present block algorithms and their implementation for the parallelization of sub-cubic Gaussian elimination on shared memory architectures using OpenMP standard. Contrarily to the classical cubic algorithms in parallel numerical linear algebra, we focus here on recursive algorithms and coarse grain parallelization. Indeed, sub-cubic matrix arithmetic can only be achieved through recursive algorithms making coarse grain block algorithms perform more efficiently than fine grain ones. This work is motivated by the design and implementation of dense linear algebra over a finite field, where fast matrix multiplication is used extensively and where costly modular reductions also advocate for coarse grain block decomposition. We incrementally build efficient kernels, for matrix multiplication first, then triangular system solving, on top of which a recursive PLUQ decomposition algorithm is built. We study the parallelization of these kernels using several algorithmic variants: either iterative or recursive and using different splitting strategies. Experiments show that recursive adaptive methods for matrix multiplication, hybrid recursive-iterative methods for triangular system solve and tile recursive versions of the PLUQ decomposition, together with various data mapping policies, provide the best performance on a 32 cores NUMA architecture. Overall, we show that the overhead of modular reductions is more than compensated by the fast linear algebra algorithms and that exact dense linear algebra matches the performance of full rank reference numerical software even in the presence of rank deficiencies.

6.7. Security for Virtualization and Clouds

Participants: Eddy Caron, Arnaud Lefray.

6.7.1. Secured Systems in Clouds with Model-Driven Orchestration

As its complexity grows, securing a system is harder than it looks. Even with efficient security mechanisms, their configuration remains a complex task. Indeed, the current practice is the hand-made configuration of these mechanisms to protect systems about which we generally lack information. Cloud computing brings its share of new security concerns but it may also be considered as leverage to overcome these issues. In [13] we adressed the key challenge of achieving global security of Cloud systems and advocate for a new approach: Model-Driven Orchestration. We have designed an implementation of this new approach called Security-Aware Models for Clouds. With this approach an industrial use-case has been deployed and secured using the Sam4C software.

6.8. Large Scale Cloud Deployment

Participants: Eddy Caron, Marcos Dias de Assunção, Christian Perez, Pedro de Souza Bento Da Silva.

6.8.1. Efficient Heuristics for Placing Large-Scale Distributed Applications on Multiple Clouds

With the fast growth of the demand for Cloud computing services, the Cloud has become a very popular platform to develop distributed applications. Features that in the past were available only to big corporations, like fast scalability, availability, and reliability, are now accessible to any customer, including individuals and small companies, thanks to Cloud computing. In order to place an application, a designer must choose among VM types, from private and public cloud providers, those that are capable of hosting her application or its parts using as criteria application requirements, VM prices, and VM resources. This procedure becomes more complicated when the objective is to place large component based applications on multiple clouds. In this case, the number of possible configurations explodes making necessary the automation of the placement. In this context, scalability has a central role since the placement problem is a generalization of the NP-Hard multi-dimensional bin packing problem.

In this work [22], we propose efficient greedy heuristics based on first fit decreasing and best fit algorithms, which are capable of computing near optimal solutions for very large applications, with the objective of minimizing costs and meeting application performance requirements. Through a meticulous evaluation, we show that the greedy heuristics took a few seconds to calculate near optimal solutions to placements that would require hours or even days when calculated using state of the art solutions, namely exact algorithms or meta-heuristics.

6.8.2. Multi-Criteria Malleable Task Management for Hybrid-Cloud Platforms

The use of large distributed computing infrastructure is a mean to address the ever increasing resource demands of scientific and commercial applications. The scale of current large-scale computing infrastructures and their heterogeneity make scheduling applications an increasingly complex task. Cloud computing minimises the heterogeneity by using virtualization mechanisms, but poses new challenges to middleware developers, such as the management of virtualization, elasticity and economic models. In this context, we proposed algorithms for efficient scheduling and execution of malleable computing tasks with high granularity while taking into account multiple optimisation criteria such as resource cost and computation time. We focused on hybrid platforms that comprise both clusters and cloud providers. In [12] we defined and formalized the main aspects of the problem, introduced the difference between local and global scheduling algorithms and evaluate their efficiency using discrete-event simulation.

6.9. Workflow management on Cloud environment

Participants: Daniel Balouek-Thomert, Eddy Caron, Laurent Lefevre.

6.9.1. Multi-objective workflow placements in Clouds

The recent rapid expansion of Cloud computing facilities triggers an attendant challenge to facility providers and users for methods for optimal placement of workflows on distributed resources, under the often-contradictory impulses of minimizing makespan, energy consumption, and other metrics. Evolutionary Optimization techniques that from theoretical principles are guaranteed to provide globally optimum solutions, are among the most powerful tools to achieve such optimal placements. Multi-Objective Evolutionary algorithms by design work upon contradictory objectives, gradually evolving across generations towards a converged Pareto front representing optimal decision variables – in this case the mapping of tasks to resources on clusters. However the computation time taken by such algorithms for convergence makes them prohibitive for real time placements because of the adverse impact on makespan. In [11], we described parallelization, on the same cluster, of a Multi-objective Differential Evolution method (NSDE-2) for optimization of workflow placement, and the attendant speedups that bring the implicit accuracy of the method into the realm of practical utility. We did experimental validation on a reallife testbed using diverse Cloud traces. The solutions under different scheduling policies demonstrate significant reduction in energy consumption with some improvement in makespan. We designed, implementation and evaluation of an energy-efficient resource management system that builds upon DIET, an open source middleware and NSDE-divisible tasks with precedence constraints. Real-life experiment of this approach on the Grid'5000 testbed demonstrates its effectiveness in a dynamic environment.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Grants with Industry

7.1.1. NewGeneration-SR

We have a collaboration with the company NewGeneration-SR (http://newgeneration-sr.com/). The aim of this company is to reduce the energy impact through solutions at each layer of the energy consumption (from datacenter design and the production to usage). NewGeneration-SR improves the life cycle (design, production, recycling) in order to reduce the environmental impact of it. NewGeneration-SR was member of the Nu@ge consortium: one of five national Cloud Computing projects with "emprunts d'avenir" funding. With a CIFRE PhD student (Daniel Balouek-Thomert), we are developing models to reduce the energy consumption for the benefit of data-center.

7.1.2. IFPEN

We also have a collaboration with IFPEN (http://ifpenergiesnouvelles.com/). IFPEN develops numerical codes to solve PDE with specific adaption of the preconditioning step to fit the requirement of their problems. With a PhD student (Adrien Roussel) we are studying the parallel implementation of multi-level decomposition domains on many-core architecture and GPGPU.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. PIA

8.1.1.1. PIA ELCI, Environnement Logiciel pour le Calcul Intensif, 2014-2017

Participants: Hélène Coullon, Thierry Gautier, Laurent Lefevre, Christian Perez, Issam Rais, Jérôme Richard.

The ELCI PIA project is coordinated by BULL with several partners: CEA, Inria, SAFRAB, UVSQ.

This project aims to improve the support for numerical simulations and High Performance Computing (HPC) by providing a new generation software stack to control supercomputers, to improve numerical solvers, and pre- and post computing software, as well as programming and execution environment. It also aims to validate the relevance of these developments by demonstrating their capacity to deliver better scalability, resilience, modularity, abstraction, and interaction on some application use-cases. Avalon is involved in WP1 and WP3 ELCI Work Packages through the PhD of Issam Rais and the postdoc of Hélène Coullon. Laurent Lefevre is the Inria representative in the ELCI technical committee.

8.1.2. French National Research Agency Projects (ANR)

8.1.2.1. ANR INFRA MOEBUS, Multi-objective scheduling for large computing platforms, 4 years, ANR-13-INFR-000, 2013-2016

Participants: Laurent Lefevre, Salem Harrache, Olivier Mornard, Christian Perez, Frédéric Suter.

The ever growing evolution of computing platforms leads to a highly diversified and dynamic landscape. The most significant classes of parallel and distributed systems are supercomputers, grids, clouds and large hierarchical multi-core machines. They are all characterized by an increasing complexity for managing the jobs and the resources. Such complexity stems from the various hardware characteristics and from the applications characteristics. The MOEBUS project focuses on the efficient execution of parallel applications submitted by various users and sharing resources in large-scale high-performance computing environments.

We propose to investigate new functionalities to add at low cost in actual large scale schedulers and programming standards, for a better use of the resources according to various objectives and criteria. We propose to revisit the principles of existing schedulers after studying the main factors impacted by job submissions. Then, we will propose novel efficient algorithms for optimizing the schedule for unconventional objectives like energy consumption and to design provable approximation multi-objective optimization algorithms for some relevant combinations of objectives. An important characteristic of the project is its right balance between theoretical analysis and practical implementation. The most promising ideas will lead to integration in reference systems such as SLURM and OAR as well as new features in programming standards implementations such as MPI or OpenMP.

8.1.2.2. ANR INFRA SONGS, Simulation Of Next Generation Systems, 4 years, ANR-12-INFRA-11, 2012-2016

Participant: Frédéric Suter.

The last decade has brought tremendous changes to the characteristics of large scale distributed computing platforms. Large grids processing terabytes of information a day and the peer-to-peer technology have become common even though understanding how to efficiently manage such platforms still raises many challenges. As demonstrated by the USS SIMGRID project, simulation has proved to be a very effective approach for studying such platforms. Although even more challenging, we think the issues raised by petaflop/exaflop computers and emerging cloud infrastructures can be addressed using similar simulation methodology.

The goal of the SONGS project is to extend the applicability of the SIMGRID simulation framework from Grids and Peer-to-Peer systems to Clouds and High Performance Computation systems. Each type of large-scale computing system will be addressed through a set of use cases and lead by researchers recognized as experts in this area.

Any sound study of such systems through simulations relies on the following pillars of simulation methodology: Efficient simulation kernel; Sound and validated models; Simulation analysis tools; Campaign simulation management.

8.1.3. Inria Large Scale Initiative

8.1.3.1. C2S@Exa, Computer and Computational Sciences at Exascale, 4 years, 2013-2017

Participants: Hélène Coullon, Laurent Lefevre, Christian Perez, Jérôme Richard, Thierry Gautier.

Since January 2013, the team is participating to the C2S@Exa Inria Project Lab (IPL). This national initiative aims at the development of numerical modeling methodologies that fully exploit the processing capabilities of modern massively parallel architectures in the context of a number of selected applications related to important scientific and technological challenges for the quality and the security of life in our society. At the current state of the art in technologies and methodologies, a multidisciplinary approach is required to overcome the challenges raised by the development of highly scalable numerical simulation software that can exploit computing platforms offering several hundreds of thousands of cores. Hence, the main objective of C2S@Exa is the establishment of a continuum of expertise in the computer science and numerical mathematics domains, by gathering researchers from Inria project-teams whose research and development activities are tightly linked to high performance computing issues in these domains. More precisely, this collaborative effort involves computer scientists that are experts of programming models, environments and tools for harnessing massively parallel systems, algorithmists that propose algorithms and contribute to generic libraries and core solvers in order to take benefit from all the parallelism levels with the main goal of optimal scaling on very large numbers of computing entities and, numerical mathematicians that are studying numerical schemes and scalable solvers for systems of partial differential equations in view of the simulation of very large-scale problems.

8.1.3.2. DISCOVERY, DIstributed and COoperative management of Virtual Environments autonomousLY, 4 years, 2015-2019

Participants: Jad Darrous, Gilles Fedak, Christian Perez.

To accommodate the ever-increasing demand for Utility Computing (UC) resources, while taking into account both energy and economical issues, the current trend consists in building larger and larger Data Centers in a few strategic locations. Although such an approach enables UC providers to cope with the actual demand while continuing to operate UC resources through centralized software system, it is far from delivering sustainable and efficient UC infrastructures for future needs.

The DISCOVERY initiative aims at exploring a new way of operating Utility Computing (UC) resources by leveraging any facilities available through the Internet in order to deliver widely distributed platforms that can better match the geographical dispersal of users as well as the ever increasing demand. Critical to the emergence of such locality-based UC (LUC) platforms is the availability of appropriate operating mechanisms. The main objective of DISCOVERY is to design, implement, demonstrate and promote the LUC Operating System (OS), a unified system in charge of turning a complex, extremely large-scale and widely distributed infrastructure into a collection of abstracted computing resources which is efficient, reliable, secure and at the same time friendly to operate and use.

To achieve this, the consortium is composed of experts in research areas such as large-scale infrastructure management systems, network and P2P algorithms. Moreover two key network operators, namely Orange and RENATER, are involved in the project.

By deploying and using such a LUC Operating System on backbones, our ultimate vision is to make possible to host/operate a large part of the Internet by its internal structure itself: A scalable set of resources delivered by any computing facilities forming the Internet, starting from the larger hubs operated by ISPs, government and academic institutions, to any idle resources that may be provided by end-users.

8.1.3.3. HAC SPECIS, High-performance Application and Computers, Studying PErformance and Correctness In Simulation, 4 years, 2016-2020

Participants: Laurent Lefevre, Frédéric Suter.

Over the last decades, both hardware and software of modern computers have become increasingly complex. Multi-core architectures comprising several accelerators (GPUs or the Intel Xeon Phi) and interconnected by high-speed networks have become mainstream in HPC. Obtaining the maximum performance of such heterogeneous machines requires to break the traditional uniform programming paradigm. To scale, application developers have to make their code as adaptive as possible and to release synchronizations as much as possible. They also have to resort to sophisticated and dynamic data management, load balancing, and scheduling strategies. This evolution has several consequences:

First, this increasing complexity and the release of synchronizations are even more error-prone than before. The resulting bugs may almost never occur at small scale but systematically occur at large scale and in a non deterministic way, which makes them particularly difficult to identify and eliminate.

Second, the dozen of software stacks and their interactions have become so complex that predicting the performance (in terms of time, resource usage, and energy) of the system as a whole is extremely difficult. Understanding and configuring such systems therefore becomes a key challenge.

These two challenges related to correctness and performance can be answered by gathering the skills from experts of formal verification, performance evaluation and high performance computing. The goal of the HAC SPECIS Inria Project Laboratory is to answer the methodological needs raised by the recent evolution of HPC architectures by allowing application and runtime developers to study such systems both from the correctness and performance point of view.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. PaaSage

Participants: Pedro de Souza Bento Da Silva, Matthieu Imbert, Christian Perez.

Title: PaaSage: Model-based Cloud Platform Upperware

Type: Seventh Framework Programme

Instrument: Collaborative project

Duration: October 2012 - September 2016 (48 months)

Coordinator: Pierre Guisset (GEIE ERCIM)

Others partners: SINTEF, STFC, HLRS, University of Stuttgart, Inria, CETIC, FORTH, be.wan, EVRY, SysFera, Flexiant, Lufthansa Systems, AG GWDG, Automotive Simulation Center Stuttgart e.V.

See also: http://paasage.eu

Abstract: PaaSage will deliver an open and integrated platform, to support both deployment and design of Cloud applications, together with an accompanying methodology that allows model-based development, configuration, optimization, and deployment of existing and new applications independently of the existing underlying Cloud infrastructures. Specifically it will deliver an IDE (Integrated Development Environment) incorporating modules for design time and execution time optimizations of applications specified in the CLOUD Modeling Language (CLOUD ML), execution-level mappers and interfaces and a metadata database.

8.2.2. Collaborations in European Programs, Except FP7 & H2020

8.2.2.1. CHIST-ERA STAR

Participants: Radu Carpa, Marcos Dias de Assunção, Olivier Glück, Laurent Lefevre.

Title: SwiTching And tRansmission project

Type: CHIST-ERA (European Coordinated Research on Long-term Challenges in Information and Communication Sciences & Technologies ERA-Net)

Duration: 2013-2016

Coordinator: Jaafar Elmirghani (University of Leeds - UK)

Others partners: Inria ,University of Cambridge (UK), University of Leeds (UK), AGH University of Science and Technology Department of Telecommunications (Poland)

See also: http://www.chistera.eu/projects/star

Abstract: The Internet power consumption has continued to increase over the last decade as a result of a bandwidth growth of at least 50 to 100 times. Further bandwidth growth between 40% and 300% is predicted in the next 3 years as a result of the growing popularity of bandwidth intensive applications. Energy efficiency is therefore increasingly becoming a key priority for ICT organizations given the obvious ecological and economic drivers. In this project we adopt the GreenTouch energy saving target of a factor of a 100 for Core Switching and Routing and believe this ambitious target is achievable should the research in this proposal proven successful. A key observation in core networks is that most of the power is consumed in the IP layer while optical transmission and optical switching are power efficient in comparison, hence the inspiration for this project. Initial studies by the applicants show that physical topology choices in networks have the potential to significantly reduce the power consumption, however network optimization and the consideration of traffic and the opportunities afforded by large, low power photonic switch architectures will lead to further power savings. Networks are typically over provisioned at present to maintain quality of service. We will study optimum resource allocation to reduce the over-provisioning factor while maintaining the quality of service. Protection is currently provided in networks through the allocation of redundant paths and resources, and for full protection there is a protection route for every working route. Avalon is contributing to STAR in terms of software network protocols and services optimizations which will be combined with more efficient photonic switches in order to obtain a factor of 100 power saving in core networks. Avalon has put in place and deployed several experimental hardware (NetFPGA, low power processors, high performance servers) and software (SDN) platforms in order to validate the various energy efficient services.

8.2.2.2. COST IC1305 : Nesus

Participants: Marcos Dias de Assunção, Laurent Lefevre, Violaine Villebonnet.

Program: COST

Project acronym: IC1305

Project title: Network for Sustainable Ultrascale Computing (NESUS)

Duration: 2014-2019

Coordinator: Jesus Carretero (Univ. Madrid)

Abstract: Ultrascale systems are envisioned as large-scale complex systems joining parallel and distributed computing systems that will be two to three orders of magnitude larger that today's systems. The EU is already funding large scale computing systems research, but it is not coordinated across researchers, leading to duplications and inefficiencies. The goal of the NESUS Action is to establish an open European research network targeting sustainable solutions for ultrascale computing aiming at cross fertilization among HPC, large scale distributed systems, and big data management. The network will contribute to glue disparate researchers working across different areas and provide a meeting ground for researchers in these separate areas to exchange ideas, to identify synergies, and to pursue common activities in research topics such as sustainable software solutions (applications and system software stack), data management, energy efficiency, and resilience. In Nesus, Laurent Lefevre is co-chairing the Working on Energy Efficiency (WG5).

8.3. International Initiatives

8.3.1. Inria International Labs

8.3.1.1. Joint Laboratory for Extreme Scale Computing (JLESC) (2014-2018)

Participants: Hélène Coullon, Gilles Fedak, Thierry Gautier, Vincent Lanore, Christian Perez, Jérôme Richard.

Partners: NCSA (US), ANL (US), Inria (FR), Jülich Supercomputing Centre (DE), BSC (SP), Riken (JP). The purpose of the Joint Laboratory for Extreme Scale Computing (JLESC) is to be an international, virtual organization whose goal is to enhance the ability of member organizations and investigators to make the bridge between Petascale and Extreme computing. The founding partners of the JLESC are Inria and UIUC. Further members are ANL, BSC, JSC and RIKEN-AICS.

JLESC involves computer scientists, engineers and scientists from other disciplines as well as from industry, to ensure that the research facilitated by the Laboratory addresses science and engineering's most critical needs and takes advantage of the continuing evolution of computing technologies.

8.3.1.2. Associate Team DALHIS – Data Analysis on Large-scale Heterogeneous Infrastructures for Science (2013-2018)

Participant: Frédéric Suter.

Partners: EPC Myriads (Rennes, Bretagne Atlantique), Avalon (Grenoble, Rhône-Alpes), Data Science and Technology Department (LBNL,USA).

The goal of the Inria-LBL collaboration is to create a collaborative distributed software ecosystem to manage data lifecycle and enable data analytics on distributed data sets and resources. Specifically, our goal is to build a dynamic software stack that is user-friendly, scalable, energy-efficient and fault tolerant. We plan to approach the problem from two dimensions: (i) Research to determine appropriate execution environments that allow users to seamlessly execute their end-to-end dynamic data analysis workflows in various resource environments and scales while meeting energy-efficiency, performance and fault tolerance goals; (ii) Engagement in deep partnerships with scientific teams and use a mix of user research with system software R&D to address specific challenges that these communities face, and inform future research directions from acquired experience.

8.3.1.3. Informal International Partners

- Université Gaston Berger, Saint Louis, Sénégal. Contact: Pr. Ousmane Thiaré.
- École Centrale Mahindra, Hyderabad, India. Contact: Dr. Arya Kumar Bhattacharya.
- Center for Computing and Networking, Chinese Academy of Sciences, Beijing, China. Pr. Haiwu He.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

Alberto Cabrera, University of La Laguna, Spain, Jan 2016

Damian Fernandez Cerero, University of Sevilla, Spain, Sep 2016-Dec 2016

Pr. Haiwu He, Computer Network Information Center, Chinese Academy of Sciences, Beijing, China, Nov 2016-Jan 2017

Tchimou N'Takpé, Université Nangui Abrogoua, Côte d'Ivoire, Nov 2016-Dec 2016.

8.4.1.1. Internships

Daniel Ciugurean, University of Cluj, Romania, Jun-Sep 2016

Joel Faubert, University of Ottawa, Canada, May-Jul 2016

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

- Laurent Lefevre was :
  - Co-Workshop chair of Xgreen 2016 : Energy Efficiency in Large Scale Distributed Systems, Cartagena, Colombia, May 2016
  - Co-chair of the Special Session on Energy Efficient Management of Parallel Systems, Platforms, and Computations during PDP2016 : 24th Euromicro International Conference on Parallel, Distributed and Network based Processing, Heraklion, Greece, February 17-19, 2016
- Christian Perez was co-chair of the Topic 8 of Euro-Par 2016.

9.1.1.2. Member of the Organizing Committees

- Eddy Caron was:
  - Co-organizer of SC16 Inria Booth at Salt Lake City (Utah). November 13-18, 2016.
  - Co-organizer of SSS'2016 (The 18th International Symposium on Stabilization, Safety, and Security of Distributed Systems), Lyon, November 7-10, 2016.
  - Co-organizer of OpenStack WorkShop Lyon 2016 at ENS de Lyon. June 15, 2016.
- Hélène Coullon and Christian Perez were members of the organization team of the 5th workshop of the Joint Laboratory for Extreme Scale Computing, Lyon, 27-29 June 2016.
- Laurent Lefevre was :
  - Co-organizer of SC16 Inria Booth at Salt Lake City (Utah). November 13-18, 2016.
  - Co-organizer of the Ecoinfo conference on Eco-design of hardware", Grenoble, September 27, 2016
  - Co-organizer of the Atelier Compas 2016 : Economiser l'énergie dans les systèmes distribués, July 5, 2016 with Anne-Cécile Orgerie (IRISA, Rennes)
  - Co-organizer of the E3-RSD school on Energy Efficiency in Networks and Distributed Systems, Dinard, May 23-27, 2016 with Anne-Cécile Orgerie (IRISA, Rennes)
  - Tutorial Chair in CCGrid 2016: the 16th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing, Cartagena, Colombia, May 2016
- Frédéric Suter was the co-organizer of the 6th edition of the SimGrid Users Days, Fréjus, January 18-21, 2016.

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

- Eddy Caron was a member of the program committee of HCW'2016, ICACCI-2016, Xgreen 2016, CloudTech'16, CCGRID'2016
- Gilles Fedak was a member of the program committee of InterCloud'2016, CLoudCom'2016, Cluster 2016, Compass 2016, HPDC 2016, ICCCN'2016, ICPADS'2016.
- Olivier Glück was a member of the program committee of PDP 2016 (24th Euromicro International Conference on Parallel, Distributed, and Network-Based Processing) and the Xgreen2016 workshop of CCGrid 2016.
- Christian Perez was a member of the Workshop Committee at the 2016 ACM/IEEE International Conference on High Performance Computing, Networking, Storage and Analysis (SC16). He was a member of the program committee of the Grid'5000 winter School 2016. He served in the committee to select Outstanding Paper Award of HPCS 2016.
- Frédéric Suter was a member of the program committee of Vecpar 2016, ICCS 2016, ComPas 2016 and EuroMPI 2016

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- G. Fedak: Co-editor of Elsevier Journal of Cluster Computing

9.1.4. Invited Talks

Laurent Lefevre has been invited to give the following talks :

- "Reducing environmental impacts of ICT : challenges and solutions", Invited talk in "Agence de l'Eau Rhône Méditerranée et Corse", Lyon, December 15, 2016
- "Ecological digital world, is it possible ? / Numérique écologique, est ce possible ?", Invited Keynote for Université Ouverte de Lyon, Lyon, France, November 29, 2016
- "Grid'5000: French Nationwide Testbed for Research in Distributed Computing", Laurent Lefevre, BOF on Experimental Infrastructure and Methodology for HPC Cloud, Supercomputing 2016 Conference, Salt Lake City, USA, November 15, 2016
- "GreenFactory : orchestrating power capabilities and leverages at large scale for energy efficient infrastructures", Laurent Lefevre, CCDSC2016: Workshop on Clusters, Clouds, and Data for Scientific Computing, Dareize, France, October 3-6, 2016
- "Full life cycle in sustainable ICT for reaching energy reduction, energy efficiency and energy proportionality", Laurent Lefevre, Invited keynote talk, IEEE Tenth International Conference on Research Challenges in Information Science (RCIS2016) & Inforsid conference, Grenoble France, June 3, 2016

Gilles Fedak has been invited to give the following talks:

- “iEx.ec: Blockchain-based Cloud Computing”, Inria Blockchain Day, Paris, December 12, 2016
- “Active Data: Large scale data management based on data life cycle”, Journée Big Data de la Fédération Informatique de Lyon, December 9, 2016
- “Active Data, managing Data Life Cycle on heterogeneous systems and infrastructures”, Workshop Data preservation (PREDON) of the MADICS research group on Big Data, Paris, CNRS, December 2, 2016
- “Blockchain applications are coming, what's next” Panel at the workshop ParisInvest, HEC, December 1st, 2016
- “iEx.ec: Blockchain-based Distributed Cloud Computing”, Chaintech Meetup, Paris, November 29, 2016

- “iEx.ec: un Cloud distribué basé sur la blockchain”, CES-3 Innovation Forum, Paris, 29 Septembre 2016
- “iEx.ec: un Cloud distribué basé sur la blockchain”, EDF research Lab, Saclay, 28 Septembre 2016
- “iEx.ec: Blockchain-based Fully Distributed Cloud Computing”,CAS Shanghai University, Shanghai, September 23, 2016
- “iEx.ec: Fully Distributed Cloud Computing thanks to the Ethereum Smart Contracts”, Ethereum Developper Conference, Shanghai, September 21, 2016
- “iEx.ec: Blockchain-based Fully Distributed Cloud Computing”, CNIC Chinese Academy of Sciences, Beijing, September 18, 2016
- "Relocaliser les data-centers dans la ville intelligente grâce à la blockchain" Smart Building Alliance, Lyon, France September 15, 2016

Frédéric Suter has been invited to give the following talk:

- "Modeling Distributed Platforms from Application Traces for Realistic File Transfer Simulation", Information Sciences Institute, University of Southern California, December 21, 2016.

9.1.5. Leadership within the Scientific Community

- Laurent Lefevre is Animator and chair of the transversal action on "Energy" of the French GDR RSD ("Réseaux et Systèmes Distribués")
- Christian Perez is co-leader of the pole Distributed Systems of the French GDR RSD ("Réseaux et Systèmes Distribués").

9.1.6. Scientific Expertise

- Eddy Caron reviewed a project for the French National Research Agency (ANR).
- Olivier Glück is member of the CNU (Conseil National des Universités) section 27 (Computer Science). He participated to the 2016 "Qualifications" session.
- Olivier Glück evaluated a Ph.D. CIFRE proposal (industrial funded PhD student).
- Christian Perez reviewed a project for the French National Research Agency (ANR).

9.1.7. Research Administration

- Eddy Caron is a member of the Inria’s CDT (Commission de Développement Technologique) from Inria Rhone-Alpes center.
- Eddy Caron is the corresponding researcher “valorisation/transfert” in the Labex MILyon for the LIP laboratory.
- Olivier Glück is member of the "Conseil Académique" of Lyon 1 and Lyon University. He is also member of the "Conseil de la Faculté des Sciences et Technologies" of Lyon 1 University.
- Christian Perez is a member of the committee selection of the project call from the Rhône-Alpes region ARC6 (France). He is also a member of the Inria Grenoble Rhône-Alpes Strategic Orientation Committee.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence: Yves Caniou, Algorithmique programmation impérative, initiation, 10h, niveaux L1, Université Lyon 1, France

Licence: Yves Caniou, Système d’Exploitation, 35h, niveaux L3, Université Lyon 1, France

Licence: Yves Caniou, Système d’Exploitation, 35h, niveaux L2, Université Lyon 1, France

Licence: Yves Caniou, Programmation Concurrente, 33h, niveaux L3, Université Lyon 1, France

Licence: Yves Caniou, Réseaux, 36h, niveaux L3, Université Lyon 1, France

Master: Yves Caniou, Sécurité, 34h, niveaux M2, Université Lyon 1, France

Master: Yves Caniou, Projet, Bibliographie, Certification, 15h, niveaux M2, Université Lyon 1, France

Master: Yves Caniou, Sécurité, 20h, niveau M2, IGA Casablanca, Maroc

Master: Yves Caniou, Suivi d'étudiants (apprentissage, stage), 25h, niveaux M1 et M2, Université Lyon 1, France

Master: Yves Caniou, Responsible of professional Master SRIV (Systèmes Réseaux et Infrastructures Virtuelles), 30h, Université Lyon 1, France

Licence: Eddy Caron, Projet 1, 48h, L3, Ens de Lyon. France.

Licence: Eddy Caron, Architecture, Système et Réseaux, 48h, L3, Ens de Lyon. France.

Master: Eddy Caron, Projet Intégré, 42h, M1, Ens de Lyon. France.

Master: Eddy Caron, Système distribués, 30h, M1, Ens de Lyon. France.

Master: Eddy Caron, Distributed Computing: Models and Challenges, 8h, M2, Ens de Lyon. France.

Licence: Olivier Glück, Licence pedagogical advisor, 30h, niveaux L1, L2, L3, Université Lyon 1, France.

Licence: Olivier Glück, Initiation Réseaux, 2x9h, niveau L2, Université Lyon 1, France.

Licence: Olivier Glück, Réseaux, 2x70h, niveau L3, Université Lyon 1, France.

Master: Olivier Glück, Responsible of professional Master SIR (Systèmes Informatiques et Réseaux) located at IGA Casablanca, 20h, niveau M2, IGA Casablanca, Maroc

Master: Olivier Glück, Réseaux par la pratique, 20h, niveau M1, Université Lyon 1, France.

Master: Olivier Glück, Services et Protocoles Applicatifs sur Internet, 40h, niveau M2, Université Lyon 1, France.

Master: Olivier Glück, Services et Protocoles Applicatifs sur Internet, 24h, niveau M2, IGA Casablanca, Maroc

Master: Olivier Glück, Administration des Systèmes et des Réseaux, 16h, niveau M2, Université Lyon 1, France.

Master: Jean-Patrick Gelas, Programmation embarquée et mobile des objets, 17.5h, niveau M1, Université Lyon 1, France.

Master: Jean-Patrick Gelas, Introduction au Cloud Computing, 24h, niveau M2 (CCI), Université Lyon 1, France.

Master: Jean-Patrick Gelas, Système d'exploitation, 30h, niveau M2 (CCI), Université Lyon 1, France.

Master: Jean-Patrick Gelas, Projet en Informatique en Anglais, 10h, niveau M2 (CCI), Université Lyon 1, France.

Master: Jean-Patrick Gelas, Réseaux Avancés, 27h, niveau M2 (CCI), Université Lyon 1, France.

Master: Jean-Patrick Gelas, Sécurité et Admin des infra réseaux, 37.5h, niveau M2 (CCI), Université Lyon 1, France.

Master: Jean-Patrick Gelas, Technologies embarquées, 15h, niveau M2 (Image), Université Lyon 1, France.

Master: Jean-Patrick Gelas, Routage (BGP), Routeurs et IPv6, 16.5h, niveau M2, Université Lyon 1, France.

Master: Jean-Patrick Gelas, Systèmes embarqués (GNU/Linux, Android, ARM, Arduino), 39h, niveau M2, Université Lyon 1, France.

Master: Jean-Patrick Gelas, Analyse de performance, 3h, niveau M2 (TIW), Université Lyon 1, France.

Master: Jean-Patrick Gelas, Cloud Computing, 16h, niveau M2 (TIW), Université Lyon 1, France.

Master Informatique: Laurent Lefevre, "Parallelism", Université Claude Bernard, France. (18h), M1

Master Systèmes Informatique et Réseaux: Laurent Lefevre, "Advanced Networks", IGA Casablanca, Maroc (20h), M2

9.2.2. Supervision

PhD: Daniel Balouek-Thomert, *Ordonnancement et éco-efficacité dans les environnements virtualisés*, 09/2013, Eddy Caron (dir), Laurent Lefevre (co-dir), Gilles Cieza (NewGen society, co-dir), defended December 5th, 2016

PhD: Violaine Villebonnet, *Proportionnalité énergétique dans les systèmes distribués à grande échelle*, 9/2013, Laurent Lefevre (dir), Jean-Marc Pierson (IRIT, Toulouse, co-dir), defended December 6th, 2016

PhD in progress: Radu Carpa, *Efficacité énergétique des échanges de données dans une fédération d'infrastructures distribuées à grande échelle*, 10/2014, Laurent Lefèvre (dir), Olivier Glück (co-dir).

PhD in progress: Hadrien Croubois, *Étude et conception d'un système de gestion de workflow autonomique conçu pour l'animation 3D* , 10/2015, Eddy Caron.

PhD in progress: Pedro Silva, *Application model and co-scheduling algorithm for dynamic and evolutive data-intensive application*, 10/2014, Christian Perez (dir), Frédéric Desprez (co-dir).

PhD in progress: Issam Rais, *Multi criteria scheduling for exascale infrastructures*, 10/2014, Laurent Lefevre (dir), Anne Benoit (Roma Team, LIP, ENS Lyon, co-dir) and Anne-Cécile Orgerie (CNRS, Myriads team, Irisa Rennes, co-dir)

PhD in progress: Jérôme Richard, *Conception of a software component model with task scheduling for many-core based parallel architecture, application to the Gysela5D code*, 11/2014, Christian Perez (dir), Julien Bigot (CEA, co-dir).

PhD in progress: Alexandre Veith : *Elastic Mechanisms for Big-Data Stream Analytics*, Labex MiLyon, Laurent Lefevre (dir), Marcos Dias de Assuncao (co-dir) (2016-2019)

PhD in progress: Valentin Lorentz : *Energy traceability of data*, Gilles Fedak (dir), Laurent Lefevre (co-dir) (2016-2019)

PhD in progress: Hayri Acar, *Towards a green and sustainable software*, Parisa Ghodous (dir), Gulfem Alptekin (co-dir), Jean-Patrick Gelas (co-dir) (2014-2017)

PhD in progress: Jad Darrous : *Geo-distributed storage for distributed Cloud*, Gilles Fedak (dir), Shadi Ibrahim (co-dir, Kerdata team, Inria Rennes) (2016-2019)

PhD in progress: Anchen Chai: *Simulation of the Distributed Execution of a Medical Imaging Simulator*, Hugues Benoit-Cattin (co-dir, CREATIS, INSA Lyon), Frédéric Suter (co-dir).

PhD in progress: Aurélie Kong-Win-Chang: *Techniques de résilience pour l'ordonnancement de workflows sur plates-formes décentralisées (cloud computing) avec contraintes de sécurité*, Yves Robert (dir, ROMA, ÉNS-Lyon), Eddy Caron (co-dir) et Yves Caniou (co-dir).

9.2.3. Juries

Eddy Caron has been member of the following PhD jury:

- Mohamed Hamza Kaaouachi: "Une approche distribuée pour les problèmes de couverture dans les systèmes hautement dynamiques.", January 2016, Reviewer, UPMC.
- Divya Gupta: "Towards Performance and Dependability Benchmarking of Distributed Fault Tolerance Protocols", March 2016, Reviewer, Université Grenoble Alpes.
- Bassirou Gueye: " Services auto-adaptatifs pour les grilles pair-a`-pair", May 2016, Reviewer, Université de Reims Champagne-Ardenne.

Gilles Fedak has been member of the following PhD jury:

- Walid Saad: “Gestion de données pour le calcul scientifique dans les environnements grilles et cloud”, October 2016, Reviewer, University of Sfax, Tunisia

Laurent Lefevre has been member of the following PhD juries:

- Chakadit Thaenchaikun : "Energy efficiency in wired networks : traffic engineering and switching off", University of Toulouse, November 2016, Reviewer
- Pablo Llopis Sanmillan : "Enhancing the programmability and energy efficiency of storage in HPC and virtualized environments", Universidad Carlos III de Madrid, Spain, July 2016, Jury member - president.
- Sareh Fotuhi Piraghaj : "Energy-Efficient Management of Resources in Enterprise and Container-based Clouds", University of Melbourne, Australia, June 2016, Reviewer
- Mohammed Hussein : "Energy Efficiency in LEO Satellite and Terrestrial Wired Environments", University of Toulouse, June 2016, Reviewer
- Fouad Hanna, : "Etude et développement du nouvel algorithme distribué de consensus FLC", University of Franche-Comté, Besancon, February 2016, Reviewer

Christian Perez has been member of the following HdR and PhD juries:

- Fabrice Huet, HdR: "From HPC to Big Data: Models and Tools for Large Scale Middleware", University of Nice Sophia-Antipolis, France., Feb 2016, Reviewer.
- Tomasz Buchert, PhD: "Managing large-scale, distributed systems research experiments with control-flows", University of Lorraine, France., Jan. 2016, jury member.
- Naweiluo Zhou, PhD: "Autonomic Thread Parallelism and Mapping Control for Software Transactional Memory”, University of Grenoble, France., Oct 2016, president.

9.3. Popularization

- Laurent Lefevre has been :
  - Interviewed in "Interception" Radio Magazine on "To click, is to pollute" ("Cliquer c’est polluer"), France Inter Radio, 6 November 2016
  - Interviewed with Françoise Berthoud, "Télévision : Changement de norme = grand gâchis écologique - Site Reporterre.net, - 5 April 2016
- Gilles Fedak has been interviewed in Bitcoin.fr, November 2016

10. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] D. Balouek-Thomert.*Scheduling on Clouds considering energy consumption and performance trade-offs: from modelization to industrial applications* , Ecole Normale Supérieure de Lyon - ENS LYON, December 2016, https://hal.inria.fr/tel-01436822.

[2] V. Villebonnet.*Scheduling and Dynamic Provisioning for Energy Proportional Heterogeneous Infrastructures*, Université de Lyon, December 2016, https://tel.archives-ouvertes.fr/tel-01419440.

Articles in International Peer-Reviewed Journal

[3] E. CARON, A. K. DATTA, C. TEDESCHI, F. PETIT.*Self-Stabilizing Prefix Tree Based Overlay Networks*, in "International Journal of Foundations of Computer Science", 2016, vol. 27, n^o 5, p. 607–630 [*DOI :* 10.1142/S0129054116500192], http://hal.upmc.fr/hal-01347457.

[4] J.-G. DUMAS, T. GAUTIER, C. PERNET, J.-L. ROCH, Z. SULTAN.*Recursion based parallelization of exact dense linear algebra routines for Gaussian elimination*, in "Parallel Computing", September 2016, vol. 57, p. 235–249 [*DOI :* 10.1016/J.PARCO.2015.10.003], https://hal.archives-ouvertes.fr/hal-01084238.

[5] M.-D. FAYE, E. CARON, O. THIARE.*A self-stabilizing algorithm for a hierarchical middleware self-adaptive deployment : specification, proof, simulations*, in "Revue Africaine de la Recherche en Informatique et Mathématiques Appliquées", 2016, vol. 25, n^o Special Issue, CNRIA 2015, p. 1-20, https://hal.archives-ouvertes.fr/hal-01311153.

[6] S. LAMBERT, P. ANANTH, P. VETTER, K.-L. LEE, J. LI, X. YIN, H. CHOW, J.-P. GELAS, L. LEFÈVRE, D. CHIARONI, B. LANNOO, M. PICKAVET.*The road to energy efficient optical access: GreenTouch final results*, in "Journal of Optical Communications and Networking", March 2017, To appear, https://hal.inria.fr/hal-01369267.

[7] M. MOCA, C. LITAN, G. C. SILAGHI, G. FEDAK.*Multi-criteria and satisfaction oriented scheduling for hybrid distributed computing infrastructures*, in "Future Generation Computer Systems", 2016, vol. 55 [*DOI :* 10.1016/J.FUTURE.2015.03.022], https://hal.inria.fr/hal-01239218.

[8] A. ROUSSEL, J.-M. GRATIEN, T. GAUTIER. *Using Runtime Systems Tools to Implement Efficient Preconditioners for Heterogeneous Architectures*, in "Oil & Gas Science and Technology – Rev. IFP Energies nouvelles", November 2016, vol. 71, n^o 6, 65 [*DOI :* 10.2516/OGST/2016020], https://hal-ifp.archives-ouvertes.fr/hal-01396153.

[9] B. TANG, M. TANG, G. FEDAK, H. HE.*Availability/Network-aware MapReduce over the Internet*, in "Information Sciences", 2016, vol. 379, p. 94–111, https://hal.inria.fr/hal-01426393.

Articles in Non Peer-Reviewed Journal

[10] J. CARRETERO, R. ČIEGIS, E. JEANNOT, L. LEFÈVRE, G. RÜNGER, D. TALIA, Ž. JULIUS.*HeteroPar 2014, APCIE 2014, and TASUS 2014 Special Issue*, in "Concurrency and Computation: Practice and Experience", 2016, 2, https://hal.inria.fr/hal-01253278.

International Conferences with Proceedings

[11] D. BALOUEK-THOMERT, A. K. BHATTACHARYA, E. CARON, K. GADIREDDY, L. LEFÈVRE.*Parallel Differential Evolution approach for Cloud workflow placements under simultaneous optimization of multiple objectives*, in "Congress on Evolutionary Computation (IEEE CEC 2016)", Vancouver, Canada, July 2016, https://hal.inria.fr/hal-01289176.

[12] E. CARON, M. DIAS DE ASSUNCAO.*Multi-Criteria Malleable Task Management for Hybrid-Cloud Platforms*, in "2nd International Conference on Cloud Computing Technologies and Applications (CloudTech'16)", Marrakech, Morocco, May 2016, https://hal.inria.fr/hal-01355682.

[13] E. Caron, A. Lefray, J. Rouzaud-Cornabas.*Secured Systems in Clouds with Model-Driven Orchestration*, in "The 2nd IEEE Workshop on Security and Privacy in the Cloud (SPC 2016). In conjunction with the IEEE CNS conference", Philadelphia, United States, The 2nd IEEE Workshop on Security and Privacy in the Cloud (SPC 2016), IEEE, October 2016, https://hal.inria.fr/hal-01355681.

[14] R. Carpa, M. Dias De Assuncao, O. Glück, L. Lefèvre, J.-C. Mignot.*Responsive Algorithms for Handling Load Surges and Switching Links On in Green Networks*, in "IEEE International Conference on Communications - IEEE ICC'16 - Green Communications Systems and Networks Symposium", Kuala Lumpur, Malaysia, May 2016, https://hal.inria.fr/hal-01266279.

[15] M. Dias De Assuncao, R. Carpa, O. Glück, L. Lefèvre.*On Designing SDN Services for Energy-Aware Traffic Engineering*, in "Tridentcom2016 : 11th EAI International Conference on Testbeds and Research Infrastructures for the Development of Networks & Communities", Hangzhou, China, June 2016, https://hal.inria.fr/hal-01346596.

[16] M. Dias De Assuncao, L. Lefèvre, F. Rossigneux.*On the Impact of Advance Reservations for Energy-Aware Provisioning of Bare-Metal Cloud Resources*, in "CNSM 2016", Montreal, Canada, October 2016, https://hal.inria.fr/hal-01382662.

[17] C. Herzog, J.-M. Pierson, L. Lefèvre.*A Multi Agent System for Understanding the Impact of Technology Transfer Offices in Green-IT*, in "PRIMA 2016 : International Conference on Principles and practice of multi-agent systems", Phuket, Thailand, August 2016, https://hal.inria.fr/hal-01355687.

[18] C. Herzog, J.-M. Pierson, L. Lefèvre.*Modelling technology transfer in Green IT with Multi Agent System*, in "ICLIE'16 : The International Conference on Leadership, Innovation and Entrepreneurship", Dubai, United Arab Emirates, Springer (editor), April 2016, https://hal.inria.fr/hal-01290038.

[19] T. N 'takpé, F. Suter.*Prise en compte de tâches non-prioritaires dans l'ordonnancement batch*, in "Conférence d'informatique en Parallélisme, Architecture et Système (Compas 2016)", Lorient, France, July 2016, https://hal.inria.fr/hal-01420693.

[20] I. Rais, L. Lefèvre, A. Benoit, A.-C. Orgerie.*An Analysis of the Feasibility of Energy Harvesting with Thermoelectric Generators on Petascale and Exascale Systems*, in "Workshop Optimization of Energy Efficient HPC & Distributed Systems (OPTIM 2016) - The 2016 International Conference on High Performance Computing & Simulation (HPCS 2016)", Innsbruck, Austria, Proceedings of the 2016 International Conference on High Performance Computing & Simulation (HPCS 2016), July 2016, https://hal.inria.fr/hal-01348554.

[21] I. Rais, A.-C. Orgerie, M. Quinson.*Impact of Shutdown Techniques for Energy-Efficient Cloud Data Centers*, in "International Conference on Algorithms and Architectures for Parallel Processing (ICA3PP)", Granada, Spain, December 2016, https://hal.inria.fr/hal-01362530.

[22] P. Silva, C. Pérez, F. Desprez.*Efficient Heuristics for Placing Large-Scale Distributed Applications on Multiple Clouds*, in "16th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (CCGrid'16)", Cartagena, Colombia, 2016 16th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (CCGrid), May 2016 [*DOI :* 10.1109/CCGrid.2016.77], https://hal.archives-ouvertes.fr/hal-01301382.

[23] V. VILLEBONNET, G. DA COSTA, L. LEFÈVRE, J.-M. PIERSON, P. STOLF.*Dynamically Building Energy Proportional Data Centers with Heterogeneous Computing Resources*, in "IEEE Cluster", Taipei, Taiwan, September 2016, short paper, https://hal.inria.fr/hal-01346600.

[24] V. VILLEBONNET, G. DA COSTA, L. LEFÈVRE, J.-M. PIERSON, P. STOLF.*Energy Aware Dynamic Provisioning for Heterogeneous Data Centers*, in "SBAC-PAD : 28th International Symposium on Computer Architecture and High Performance Computing", Los Angeles, United States, October 2016, https://hal.inria.fr/hal-01355452.

[25] V. VILLEBONNET, G. DA COSTA, L. LEFÈVRE, J.-M. PIERSON, P. STOLF.*Energy Proportionality in Heterogeneous Data Center Supporting Applications with Variable Load*, in "IEEE International Conference on Parallel and Distributed Systems (ICPADS)", Wuhan, China, December 2016, https://hal.inria.fr/hal-01396947.

[26] P. VIROULEAU, F. BROQUEDIS, T. GAUTIER, F. RASTELLO.*Using data dependencies to improve task-based scheduling strategies on NUMA architectures*, in "Euro-Par 2016", Grenoble, France, Euro-Par 2016, August 2016, https://hal.inria.fr/hal-01338761.

[27] P. VIROULEAU, A. ROUSSEL, F. BROQUEDIS, T. GAUTIER, F. RASTELLO, J.-M. GRATIEN.*Description, Implementation and Evaluation of an Affinity Clause for Task Directives*, in "IWOMP 2016", Nara, Japan, IWOMP 2016 - LLCS 9903, October 2016, https://hal.inria.fr/hal-01343442.

National Conferences with Proceeding

[28] C. HERZOG, J.-M. PIERSON, L. LEFÈVRE.*Modélisation du transfert technologique par système multi-agent : illustration à l'informatique verte*, in "JFSMA 2016 : 24 èmes journées Francophones sur les systèmes Multi-Agents", Rouen, France, October 2016, https://hal.inria.fr/hal-01369283.

Conferences without Proceedings

[29] H. ACAR, G. I. ALPTEKIN, J.-P. GELAS, P. GHODOUS.*Beyond CPU: Considering Memory Power Consumption of Software*, in "Smartgreens 2016", Rome, Italy, April 2016, https://hal.archives-ouvertes.fr/hal-01314070.

[30] I. RAIS, A. BENOIT, L. LEFÈVRE, A.-C. ORGERIE.*An Analysis of the Feasibility of Energy Harvesting with Thermoelectric Generators on Petascale and Exascale Systems*, in "Conférence d'informatique en Parallélisme, Architecture et Système (COMPAS 2016)", Lorient, France, Actes de COMPAS, la Conférence d'informatique en Parallélisme, Architecture et Système, July 2016, https://hal.inria.fr/hal-01348555.

[31] A. ROUSSEL.*Comparaison de moteurs exécutifs pour la parallélisation de solveurs linéaires itératifs*, in "Conférence d'informatique en Parallélisme, Architecture et Système (Compas'2016)", Lorient, France, July 2016, https://hal-ifp.archives-ouvertes.fr/hal-01343151.

[32] P. VIROULEAU.*Amélioration des stratégies d'ordonnancement sur architectures NUMA à l'aidedes dépendances de données*, in "Compas 2016", Lorient, France, July 2016, https://hal.inria.fr/hal-01338750.

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[33] H. COULLON, J. BIGOT, C. PÉREZ.*The Multi-Stencil Language: orchestrating stencils with a mesh-agnostic DSL*, Inria - Research Centre Grenoble – Rhône-Alpes, October 2016, n° RR-8962, 30, https://hal.inria.fr/hal-01380607.

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Project-Team BEAGLE

Artificial Evolution and Computational Biology

IN COLLABORATION WITH: Laboratoire d'InfoRmatique en Image et Systèmes d'information (LIRIS)

IN PARTNERSHIP WITH:
CNRS

Institut national des sciences appliquées de Lyon

Université Claude Bernard (Lyon 1)

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Computational Biology

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Project-Team BEAGLE

Creation of the Team: 2011 June 17, updated into Project-Team: 2013 January 01

Keywords:

Computer Science and Digital Science:

3.3.2. - Data mining
5.1.5. - Body-based interfaces
5.7.2. - Music
5.11.1. - Human activity analysis and recognition
6.1.1. - Continuous Modeling (PDE, ODE)
6.1.3. - Discrete Modeling (multi-agent, people centered)
6.1.4. - Multiscale modeling
6.2.7. - High performance computing
7.2. - Discrete mathematics, combinatorics

Other Research Topics and Application Domains:

1. - Life sciences
1.1.2. - Molecular biology
1.1.3. - Cellular biology
1.1.8. - Evolutionnary biology
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1.1.11. - Systems biology
1.3.1. - Understanding and simulation of the brain and the nervous system
9.2.1. - Music, sound
9.2.4. - Theater

1. Members

Research Scientists

Hugues Berry [Inria, Senior Researcher, HDR]
Eric Tannier [Inria, Researcher, HDR]

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Carole Knibbe [Univ. Lyon I, Associate professor]
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Ilya Prokin [Inria]
Charles Rocabert [Inria, granted by FP7 EVOEVO project]
Yoram Vadée Le Brun [Min. de l'Education Nationale]

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Maurizio de Pittà [FP7 MC IOF Post-doctoral fellow]
Priscila Do Nascimento Biller [Inria, from Nov 2016]

Administrative Assistant
Caroline Lothe [Inria]

2. Overall Objectives

2.1. Overall Objectives

The expanded name for the BEAGLE research group is "Artificial Evolution and Computational Biology". Our aim is to position our research at the interface between biology and computer science and to contribute new results in biology by modeling biological systems. In other words we are making artifacts – from the Latin *artis factum* (an entity made by human art rather than by Nature) – and we explore them in order to understand Nature. The team is an Inria Project-Team since January, 2014. It gathers researchers from Inria, INSA, UCBL, who are members of three different labs, the LIRIS [0], the LBBE [0], and CARMEN [0]. It is led by Prof. Guillaume Beslon (INSA-Lyon, LIRIS, Computer Science Dept.).

Our research is based on an interdisciplinary scientific strategy: we are developing computer science formalisms and software for complex system modeling in synergy with multidisciplinary cooperations in the area of life sciences. Using computational approaches we study abstractions of biological systems and processes in order to unravel the organizational principles of cellular systems. More precisely, the scientific activity of the BEAGLE group focuses on two different topics. Both topics are strongly complementary. Indeed, on the short time scales, biological systems are constrained by the physical nature of their substrate but, on long time scales, they are also constrained by their evolutionary history. Thus, studying both time scales and both constraints – including their interactions – gives us a global viewpoint on the roots of biological organization.

Computational Cell Biology We develop models of the spatio-temporal dynamics of cells and their molecular components. More precisely, we study the complex interplay between the reaction and the diffusion processes when the medium is not homogeneous or when the number of molecules is too low to account for a perfect mixing hypothesis. We particularly focus on the consequences on the signaling networks and on the stochasticity of transcription. In this domain, we always try to mix up modeling and "wet" experimental approaches by developing close collaborations with experimental biologists.

Models of Genome Evolution To better understand the cellular structures (genome organization, transcription networks or signaling cascades) we propose to study their historical – evolutionary – origin. Individual-based evolutionary models (*in silico experimental evolution*) allow us to study how evolution leads to some specific structures shaped by the needs of robustness, variability or evolvability, depending on some specific conditions (e.g., large vs. small efficient population sizes, high vs. low

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[0] Laboratoire de Biometrie et Biologie Evolutive: UMR CNRS 5558, Univ. Claude Bernard Lyon 1.

[0] Laboratoire de Recherche en Cardiovasculaire, Métabolisme, Diabétologie et Nutrition: UMR U1060 INSERM, INSA-Lyon, INRA 1235, Univ. Claude Bernard Lyon 1.

mutation rates, stable vs. unstable environments). Models can also be used for predictive purposes on real data: we reconstruct the evolutionary events that have shaped the extant real genomes, including small substitutions as well as large genome reorganizations. By comparing the reconstructed historical events and the laws inferred from artificial experiments, we can explain some patterns of today's organisms and biodiversity.

The scientific objective of the BEAGLE team is to develop a consistent set of concepts and tools – mainly based on computational science – to *in fine* contribute to knowledge discovery in systems biology. Our strategy is to develop strong interactions with life science researchers to become active partners of the biological discovery process. Thus, our aim as a team is not to be a computer science team interacting with biologists, nor to be a team of biologists using computer science tools, but rather to stay in the middle and to become a *trading zone* [57] between biology and computer science. Our very scientific identity is thus fuzzy, melting components from both sciences. Indeed, one of the central claims of the team is that interdisciplinarity involves permanent exchanges between the disciplines. Such exchanges can hardly be maintained between distant teams. That's why the BEAGLE team tries to develop local collaborations with local scientists. That's also why BEAGLE also tries to organize itself as an intrinsically interdisciplinary group, gathering different sensibilities between biology and computer science inside the group. Our ultimate objective is to develop interdisciplinarity at the individual level, all members of the team being able to interact efficiently with specialists from both fields.

3. Research Program

3.1. Introduction

As stated above, the research topics of the BEAGLE Team are centered on the modelisation and simulation of cellular processes. More specifically, we focus on two specific processes that govern cell dynamics and behavior: Evolution and Biophysics. This leads to two main topics: computational cell biology and models for genome evolution.

3.2. Computational Cell Biology

BEAGLE contributes computational models and simulations to the study of cell signaling in prokaryotic and eukaryotic cells, with a special focus on the dynamics of cell signaling both in time and in space. Importantly, our objective here is not so much to produce innovative computer methodologies, but rather to improve our knowledge of the field of cell biology by means of computer methodologies.

This objective is not accessible without a thorough immersion in experimental cell biology. Hence, one specificity of BEAGLE is to be closely associated inside each research project with experimental biology groups. For instance, all the current PhD students implicated in the research projects below have strong interactions with experimenters, most of them conducting experiments themselves in our collaborators' labs. In such a case, the supervision of their PhD is systematically shared between an experimentalist and a theoretician (modeler/computer scientist).

Standard modeling works in cell biochemistry are usually based on mean-field equations, most often referred to as "laws of mass-action". Yet, the derivation of these laws is based on strict assumptions. In particular, the reaction medium must be dilute, perfectly-mixed, three-dimensional and spatially homogeneous and the resulting kinetics are purely deterministic. Many of these assumptions are obviously violated in cells. As already stressed out before, the external membrane or the interior of eukaryotic as well as prokaryotic cells evidence spatial organization at several length scales, so that they must be considered as non-homogeneous media. Moreover, in many case, the small number of molecule copies present in the cell violates the condition for perfect mixing, and more generally, the "law of large numbers" supporting mean-field equations.

When the laws-of-mass-action are invalidated, individual-based models (IBM) appear as the best modeling alternative to evaluate the impact of these specific cellular conditions on the spatial and temporal dynamics of the signaling networks. We develop Individual-Based Models to evaluate the fundamental impact of non-homogeneous space conditions on biochemical diffusion and reaction. More specifically, we focus on the effects of two major sources of non-homogeneity within cells: macromolecular crowding and non-homogeneous diffusion. Macromolecular crowding provides obstacles to the diffusive movement of the signaling molecules, which may in turn have a strong impact on biochemical reactions [45]. In this perspective, we use IBM to renew the interpretation of the experimental literature on this aspect, in particular in the light of the available evidence for anomalous subdiffusion in living cells. Another pertinent source of non-homogeneity is the presence of lipid rafts and/or caveolae in eukaryotic cell membranes that locally alter diffusion. We showed several properties of these diffusion gradients on cells membranes. In addition, combining IBMs and cell biology experiments, we investigate the spatial organization of membrane receptors in plasmic membranes and the impact of these spatial features on the initiation of the signaling networks [49]. More recently, we started to develop IBMs to propose experimentally-verifiable tests able to distinguish between hindered diffusion due to obstacles (macromolecular crowding) and non-homogeneous diffusion (lipid rafts) in experimental data.

The last aspect we tackle concerns the stochasticity of gene expression. Indeed, the stochastic nature of gene expression at the single cell level is now a well established fact [55]. Most modeling works try to explain this stochasticity through the small number of copies of the implicated molecules (transcription factors, in particular). In collaboration with the experimental cell biology group led by Olivier Gandrillon at the Centre de Génétique et de Physiologie Moléculaire et Cellulaire (CGPhyMC, UMR CNRS 5534), Lyon, we study how stochastic gene expression in eukaryotic cells is linked to the physical properties of the cellular medium (e.g., nature of diffusion in the nucleoplasm, promoter accessibility to various molecules, crowding). We have already developed a computer model whose analysis suggests that factors such as chromatin remodeling dynamics have to be accounted for [51]. Other works introduce spatial dimensions in the model, in particular to estimate the role of space in complex (protein+ DNA) formation. Such models should yield useful insights into the sources of stochasticity that are currently not explained by obvious causes (e.g. small copy numbers).

3.3. Models of genome evolution

Classical artificial evolution frameworks lack the basic structure of biological genome (i.e. a double-strand sequence supporting variable size genes separated by variable size intergenic sequences). Yet, if one wants to study how a mutation-selection process is likely (or not) to result in particular biological structures, it is mandatory that the effect of mutation modifies this structure in a realistic way. We have developed an artificial chemistry based on a mathematical formulation of proteins and of the phenotypic traits. In our framework, the digital genome has a structure similar to prokaryotic genomes and a non-trivial genotype-phenotype map. It is a double-stranded genome on which genes are identified using promoter-terminator- like and start-stop-like signal sequences. Each gene is transcribed and translated into an elementary mathematical element (a "protein") and these elements - whatever their number - are combined to compute the phenotype of the organism. The Aevol (Artificial EVOLution) model is based on this framework and is thus able to represent genomes with variable length, gene number and order, and with a variable amount of non-coding sequences (for a complete description of the model, see [63]).

As a consequence, this model can be used to study how evolutionary pressures like the ones for robustness or evolvability can shape genome structure [64], [61], [62], [71]. Indeed, using this model, we have shown that genome compactness is strongly influenced by indirect selective pressures for robustness and evolvability. By genome compactness, we mean several structural features of genome structure, like gene number, amount of non functional DNA, presence or absence of overlapping genes, presence or absence of operons [64], [61], [72]. More precisely, we have shown that the genome evolves towards a compact structure if the rate of spontaneous mutations and rearrangements is high. As far as gene number is concerned, this effect was known as an error-threshold effect [54]. However, the effect we observed on the amount of non functional DNA was unexpected. We have shown that it can only be understood if rearrangements are taken into account: by promoting large duplications or deletions, non functional DNA can be mutagenic for the genes it surrounds.

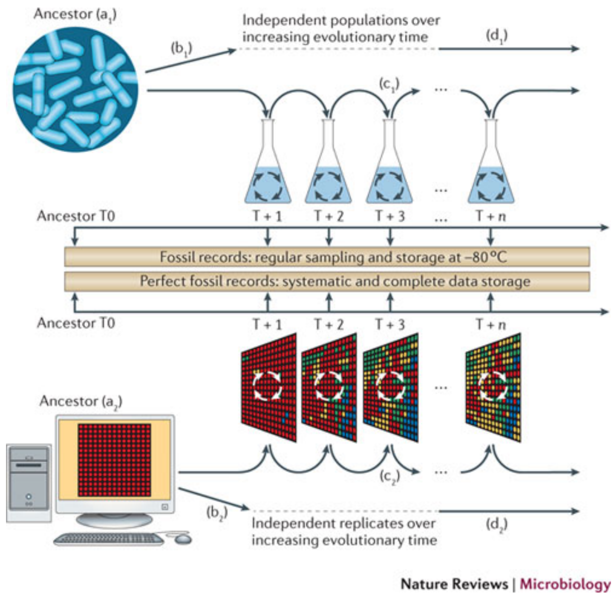

Figure 1. Parallel between experimental evolution and artificial evolution

We have extended this framework to include genetic regulation (R-Aevol variant of the model). We are now able to study how these pressures also shape the structure and size of the genetic network in our virtual organisms [47], [46], [48],[29]. Using R-Aevol we have been able to show that (i) the model qualitatively reproduces known scaling properties in the gene content of prokaryotic genomes and that (ii) these laws are not due to differences in lifestyles but to differences in the spontaneous rates of mutations and rearrangements [46]. Our approach consists in addressing unsolved questions on Darwinian evolution by designing controlled and repeated evolutionary experiments, either to test the various evolutionary scenarios found in the literature or to propose new ones. Our experience is that “thought experiments” are often misleading: because evolution is a complex process involving long-term and indirect effects (like the indirect selection of robustness and evolvability), it is hard to correctly predict the effect of a factor by mere thinking. The type of models we develop are particularly well suited to provide control experiments or test of null hypotheses for specific evolutionary scenarios. We often find that the scenarios commonly found in the literature may not be necessary, after all, to explain the evolutionary origin of a specific biological feature. No selective cost to genome size was needed to explain the evolution of genome compactness [64], and no difference in lifestyles and environment was needed to explain the complexity of the gene regulatory network [46]. When we unravel such phenomena in the individual-based simulations, we try to build “simpler” mathematical models (using for instance population genetics-like frameworks) to determine the minimal set of ingredients required to produce the effect. Both approaches are complementary: the individual-based model is a more natural tool to interact with biologists, while the mathematical models contain fewer parameters and fewer ad-hoc hypotheses about the cellular chemistry.

At this time, simulating the evolution of large genomes during hundreds of thousands of generation with the Aevol software can take several weeks or even months. It is worse with R-aevol, where we not only simulate mutations and selection at the evolutionary timescale, but also simulate the lifetime of the individuals, allowing them to respond to environmental signals. Previous efforts to parallelize and distribute Aevol had yielded limited results due to the lack of dedicated staff on these problems. Since September 2014, we have been improving the performance of (R-)Aevol. Thanks to the ADT Aevol, one and a half full time engineers work on improving Aevol and especially to parallelize it. Moreover, we are working to formalize the numerical computation problems with (R-)Aevol to use state-of-the-art optimization techniques from the HPC community. It ranges from dense and sparse matrix multiplication and their optimizations (such as Tridiagonal matrix algorithm) to using new generation accelerator (Intel Xeon Phi and NVidia GPU). However, our goal is not to become a HPC nor a numerical computation team but to work with well-established teams in these fields, such as through the Joint Laboratory for Extreme-Scale Computing, but also with Inria teams in these fields (e.g. ROMA, Avalon, Corse, Storm, DataMove). By doing so, (R-)Aevol simulations will be faster, allowing us to study more parameters in a shorter time. Furthermore, we will also be able to simulate more realistic population sizes, that currently do not fit into the memory of a single computer.

In 2016 we have improved both the quality and the performance of the code. We are currently investigating advance usage of OpenMP to be able to offload part of our execution to accelerator. In particular, we are currently evaluating the performance of the OpenMP version of Aevol on Xeon Phi KNL and on NVidia GPU. In collaboration with the Avalon team and with the help of a shared internship (Mehdi Ghesh), we have build a benchmark for ordinary differential equation (ODE). This benchmark is based on a representative sample of the ODEs (formalizing the genetic network) found within the R-Aevol model. Thanks to this benchmark, we can compare different ODE solvers and methods. Furthermore, researchers working on ODE solvers and methods could use it to evaluate the quality of their approach. We are now working with Avalon team on an algorithm that will automatically choose at runtime the best fitting solver and method (from a performance and a quality of results point of view). Through this collaboration, we have also extended the execo experimental engine [59] to support Aevol and R-Aevol. By doing so, we have now a complete automatic workflow to conduct large scale campaign experiments with thousands of different parameters of our model and use the resources of distributed platform (Grid'5000, CC-IN2P3 and a dedicated cluster).

Since 2014, we are also working on a second model of genome evolution.This new model, developed by the team within the Evoevo european Project, encompasses not only the gene regulation network (as R-aevol does) but also the metabolic level [8]. It allows us to have a real notion of resources and thus to have more complex ecological interactions between the individuals. To speed up computations, the genomic level is simplified compared to aevol, as a chromosome is modelled as a sequence of genes and regulatory elements and not as a sequence of nucleotides. Both models are thus complementary.

Little has been achieved concerning the validation of these models, and the relevance of the observed evolutionary tendencies for living organisms. Some comparisons have been made between Avida and experimental evolution [65], [58], but the comparison with what happened in a long timescale to life on earth is still missing. It is partly because the reconstruction of ancient genomes from the similarities and differences between extant ones is a difficult computational problem which still misses good solutions for every type of mutations, in particular the ones concerning changes in the genome structure.

There exist good phylogenic models of punctual mutations on sequences [56], which enable the reconstruction of small parts of ancestral sequences, individual genes for example [66]. But models of whole genome evolution, taking into account large scale events like duplications, insertions, deletions, lateral transfer, rearrangements are just being developped [74], [52]. Integrative phylogenetic models, considering both nucleotide subsitutions and genome architectures, like Aevol does, are still missing.

Partial models lead to evolutionary hypotheses on the birth and death of genes [53], on the rearrangements due to duplications [44], [73], on the reasons of variation of genome size [60], [67]. Most of these hypotheses are difficult to test due to the difficulty of *in vivo* evolutionary experiments.

To this aim, we develop evolutionary models to reconstruct the history of organisms from the comparison of their genome, at every scale, from nucleotide substitutions to genome organisation rearrangements. These models include large-scale duplications as well as loss of DNA material, and lateral gene transfers from distant species. In particular we have developed models of evolution by rearrangements [68], methods for reconstructing the organization of ancestral genomes [69], [50], [70], or for detecting lateral gene transfer events [43], [10]. It is complementary with the Aevol development because both the model of artificial evolution and the phylogenetic models we develop emphasize on the architecture of genomes. So we are in a good position to compare artificial and biological data on this point.

We improve the phylogenetic models to reconstruct ancestral genomes, jointly seen as gene contents, orders, organizations, sequences. It requires integrative models of genome evolution, which is desirable not only because they will provide a unifying view on molecular evolution, but also because they will shed light onto the relations between different kinds of mutations, and enable the comparison with artificial experiments from models like Aevol.

Based on this experience, the BEAGLE team contributes individual-based and mathematical models of genome evolution, in silico experiments as well as historical reconstruction on real genomes, to shed light on the evolutionary origin of the complex properties of cells.

4. Highlights of the Year

4.1. Highlights of the Year

EvoMove

We completed the implementation of the EvoMove system, an evolving music generation system based on performer moves. The moves are not predefined, they are identified by an evolutionary subspace clustering algorithm that builds on-the-fly move categories. Such a category is created when similar moves are repeated, but it remains flexible in the sense that it can adapt to gradual changes of the moves. A category can also be forgotten when the corresponding moves do not occur any longer. We run working sessions with dancers and record parts of these performances on videos. The first prototype of EvoMove has been tested with the Anou Skan company (https://www.youtube.com/channel/UCoyfXJx_izpQZi6hD8w5M3A). The system immediately convinced the dancers of its interest and we are now working on the creation of a short play with Claire Lurin, an INSA-Lyon student who is also a semi-professional dancer.

ECAL

The Beagle team was chosen by the board of the ISAL (International Society For Artificial Life) to organize ECAL 2017, the 14th European Conference on Artificial Life. ECAL is the offical conference of the ISAL on odd years. Organizing ECAL 2017 will confirm the Beagle team as a major player in the international artificial life community and as the domain leader in France.

5. New Software and Platforms

5.1. DeCoSTAR

KEYWORDS: Bioinformatics - Evolution

FUNCTIONAL DESCRIPTION Given a set of gene trees, a species tree and adjacency relations between extant genes, DeCoSTAR reconstructs adjacencies between ancestral genes

- Contact: Eric Tannier
- URL: http://pbil.univ-lyon1.fr/software/DeCoSTAR/

5.2. EvoEvo

Evolution of Evolution

KEYWORDS: Bioinformatics - Biology - Evolution

FUNCTIONAL DESCRIPTION In the context of the EvoEvo european project we are developing an integrated model of microorganisms evolution. This model will extend the current evolutionary models developped in the team (Aevol and R-Aevol) by adding a metabolic level and an ecosystem level. In 2014, a first version has been developed and released that includes the genomic, genetic and metabolic levels.

- Participants: Guillaume Beslon, Charles Rocabert and Carole Knibbe
- Contact: Guillaume Beslon
- URL: http://www.evoevo.eu/

5.3. FluoBacTracker

KEYWORDS: Bioinformatics - Biology - Biomedical imaging

FUNCTIONAL DESCRIPTION FluoBacTracker is an ImageJ plugin designed to segment and track growing E. Coli cells from microscopy images and movies. FluoBacTracker is a software tool to : 1) Select regions of interest in each image (detect the colony) 2) Denoise and renormalize the images 3) Identify each cells in each image (segmentation) 4) Follow cells through the whole movie (tracking) 5) Detect divisions and construct cell lineage in the population FluoBacTracker is an open-source software (under a tailored license agrement), downloadable free of charge for academics.

- Participants: Magali Vangkeosay, David Parsons and Hugues Berry
- Partner: Université Descartes
- Contact: Hugues Berry
- URL: http://fluobactracker.inrialpes.fr

5.4. Tewep

Simulator of the dynamics of Transposable Elements Within Expanding Populations

KEYWORDS: Simulator - Transposable elements - Population genetics - Geographic expansion

FUNCTIONAL DESCRIPTION Transposable elements, found in the genomes of most living organisms (including humans), are pieces of DNA able to replicate themselves and to proliferate. Their presence is a source of mutations which are, most of the time, detrimental to their host. As a consequence, natural selection usually limits their spread. There are, however, some conditions where natural selection cannot be efficient enough to remove them, for example when the population size is small. It is also hypothesized that when a population geographically expands, the efficiency of natural selection could be reduced at the expansion front. TEWEP is an individual-based simulator designed to test whether transposable elements could proliferate in large expanding populations. It combines several population genetics models to simulate the evolution of the number of transposable elements in each individual of an expanding population.

- Partner: Laboratoire de Biométrie et Biologie Evolutive (LBBE) - UMR CNRS 5558
- Contact: Carole Knibbe
- URL: https://gforge.inria.fr/projects/tewep/

5.5. aevol

Artificial Evolution

FUNCTIONAL DESCRIPTION Aevol is a digital genetics model: populations of digital organisms are subjected to a process of selection and variation, which creates a Darwinian dynamics. By modifying the characteristics of selection (e.g. population size, type of environment, environmental variations) or variation (e.g. mutation rates, chromosomal rearrangement rates, types of rearrangements, horizontal transfer), one can study experimentally the impact of these parameters on the structure of the evolved organisms. In particular, since Aevol integrates a precise and realistic model of the genome, it allows for the study of structural variations of the genome (e.g. number of genes, synteny, proportion of coding sequences). The simulation platform comes along with a set of tools for analysing phylogenies and measuring many characteristics of the organisms and populations along evolution. An extension of the model (R-Aevol), integrates an explicit model of the regulation of gene expression, thus allowing for the study of the evolution of gene regulation networks.

- Participants: Carole Knibbe, Guillaume Beslon, Jonathan Rouzaud-Cornabas, Bérénice Batut, David Parsons, Vincent Liard, Dusan Misevic and Antoine Frénoy
- Partners: Insa de Lyon - INSERM - UCBL Lyon 1 - Université Paris-Descartes
- Contact: Carole Knibbe
- URL: http://www.aevol.fr/

5.6. evowave

KEYWORDS: Data stream - Clustering - Evolution - Wireless network

FUNCTIONAL DESCRIPTION This package is a toolbox to analyse signal strength in wifi activity logfiles. It includes three main modules. The first is a preprocessing module to agregate logfile contents. The second one is a subspace clustering module, based on an evolutionary algorithm, to identify similar wifi activity contexts. This similarity is defined on signal strength of wifi devices and the clusters can change over time. The third module is a visualisation tool to display the cluster modifications over time.

- Participants: Jonas Abernot, Guillaume Beslon, Leo Lefebvre, Sergio Peignier, Anthony Rossi and Christophe Rigotti
- Contact: Christophe Rigotti
- URL: http://evoevo.liris.cnrs.fr/download/4_-_deliverables/wp5/Deliverable_D5.1_software_archive.zip

6. New Results

6.1. Open-Ended Novelty: Requirements, Guidelines, and Challenges

Participants: G. Beslon

We started in 2014 a collective reflexion on the concept of "Open-Endedness". This reflexion led to a collective paper published this year in "Theory in Biosciences" [12]. The open-endedness of a system is often defined as a continual production of novelty. In this paper we pin down this concept more fully by defining several types of novelty that a system may exhibit, classified as variation, innovation, and emergence. We then provide a meta-model for including levels of structure in a system's model. From there, we define an architecture suitable for building simulations of open-ended novelty-generating systems and discuss how previously proposed systems fit into this framework. We discuss the design principles applicable to those systems and close with some challenges for the community.

6.2. Endocannabinoid dynamics gate spike timing dependent depression and potentiation

Participants: I. Prokin and H. Berry, in collaboration with L. Venance lab, CIRB, Collège de France, Paris.

Learning and memory depend on processes that alter the connections – or synapses – between neurons in the brain. For example, molecules called endocannabinoids can alter synapses to decrease the influence that one neuron has on another neuron's activity. This "synaptic depression" is an important mechanism through which the brain can adapt to an experience. However, recent research also suggests that endocannabinoids might also increase the influence one neuron has on another neuron's activity by strengthening the synaptic connection between neurons. This opposite process is known as synaptic potentiation, and is also important for learning from experience. But how do endocannabinoids manage to produce opposing effects? Using a combination of electrophysiological recording experiments from our experimental collaborator lab and mathematical modeling, we have deciphered the molecular mechanisms that govern the action of endocannabinoids at key synapses in rat brain slices. This revealed that both the levels and timing of endocannabinoid release control changes in the strength of the synaptic connections. Electrical stimulations that produced moderate amounts of endocannabinoids over a prolonged period led to synaptic depression. However, stimulation that produced short but large endocannabinoid peaks caused synaptic potentiation. The enzymes that control endocannabinoid levels thus play a crucial role in determining whether a given stimulation leads to the strengthening or weakening of a synaptic connection. In the type of synapses studied, changes to synaptic strength also depend on another chemical called dopamine. Abnormal dopamine production is implicated in a number of disorders, including Parkinson's disease and addiction. These results have been published in eLife [16].

6.3. Quantitative convergence towards a self similar profile in an age-structured renewal equation for subdiffusion

Participants: A. Mateos Gonzalez and H. Berry, in collaboration with T. Lepoutre, EPI Dracula, Inria.

Continuous-time random walks are generalisations of random walks frequently used to account for the consistent observations that many molecules in living cells undergo anomalous diffusion, i.e. subdiffusion. We described the subdiffusive continuous-time random walk using age-structured partial differential equations with age renewal upon each walker jump, where the age of a walker is the time elapsed since its last jump. In the spatially-homogeneous (zero-dimensional) case, we followed the evolution in time of the age distribution. An approach inspired by relative entropy techniques allows us to obtain quantitative explicit rates for the convergence of the age distribution to a self-similar profile, which corresponds to convergence to a stationnary profile for the rescaled variables. An important difficulty arises from the fact that the equation in self-similar variables is not autonomous and we do not have a specific analyitcal solution. Therefore, in order to quantify the latter convergence, we estimate attraction to a time-dependent "pseudo-equilibrium", which in turn converges to the stationnary profile. These results have been published in Acta Applicandae Mathematicae [13].

6.4. Modulation of Synaptic Plasticity by Glutamatergic Gliotransmission

Participants: M. De Pittà in collaboration with N. Brunel, Dept of Neuroscience and Statistics, University of Chicago, USA.

Glutamatergic gliotransmission, that is the release of glutamate from perisynaptic astrocyte processes in an activity-dependent manner, has emerged as a potentially crucial signal-ing pathway for regulation of synaptic plasticity, yet its modes of expression and function in vivo remain unclear. We focused on two experimentally well-identified gliotransmitter patwhays: (i) modulations of synaptic release and (ii) postynaptic slow inward currents mediated by glutamate released from astrocytes, and investigate their possible functional relevance on synaptic plasticity in a biophysical model of an astrocyte-regulated synapse. Our model predicts that both pathways could profoundly affect both short-and long-term plasticity. In particular, activity-dependent glutamate release from astrocytes, could dramatically change spike-timing–dependent plasticity, turning potentiation into depression (and vice versa) for the same protocol. These results have been published in Neural plasticity [17] and in a review targetting a biologist audience in the journal Neuroscience [18].

6.5. Comparative Genomics and artificial life

Participants: P Biller, C Knibbe, G Beslon, E Tannier

Molecular evolutionary methods and tools are difficult to validate as we have almost no direct access to ancient molecules. Inference methods may be tested with simulated data, producing full scenarios they can be compared with. But often simulations design is concomitant with the design of a particular method, developed by a same team, based on the same assumptions, when both should be blind to each other. In silico experimental evolution consists in evolving digital organisms with the aim of testing or discovering complex evolutionary processes. Models were not designed with a particular inference method in mind, only with basic biological principles. As such they provide a unique opportunity to blind test the behavior of inference methods. We give a proof of this concept on a comparative genomics problem: inferring the number of inversions separating two genomes. We use Aevol, an in silico experimental evolution platform, to produce benchmarks, and show that most combinatorial or statistical estimators of the number of inversions fail on this dataset while they were behaving perfectly on ad-hoc simulations. We argue that biological data is probably closer to the difficult situation.

This work has been published in the article [23] and presented at the Jobim conference [25] and provided the inspiration for a new estimator of the evolutionary distance between two genomes (see below).

6.6. Breaking good

Participants: P Biller, C Knibbe, E Tannier, in collaboration with L Guéguen, University of Lyon 1.

Models of evolution by genome rearrangements are prone to two types of flaws: one is to ignore the diversity of susceptibility to breakage across genomic regions, the other is to suppose that susceptibility values are given. Without necessarily supposing their precise localization, we call "solid" the regions that are improbably broken by rearrangements and "fragile" the regions outside solid ones. We propose a model of evolution by inversions where breakage probabilities vary across fragile regions and over time. It contains as a particular case the uniform breakage model on the nucleotidic sequence, where breakage probabilities are proportional to fragile region lengths. This is very different from the frequently used pseudo-uniform model where all fragile regions have the same probability to break. Estimations of rearrangement distances based on the pseudo-uniform model completely fail on simulations with the truly uniform model. On pairs of amniote genomes, we show that identifying coding genes with solid regions yields incoherent distance estimations, especially with the pseudo-uniform model, and to a lesser extent with the truly uniform model. This incoherence is solved when we co-estimate the number of fragile regions with the rearrangement distance. The estimated number of fragile regions is surprisingly small, suggesting that a minority of regions are recurrently used by rearrangements. Estimations for several pairs of genomes at different divergence times are in agreement with a slowly evolvable co-localization of active genomic regions in the cell.

This work has been published in an article for a reference biology journal [14].

6.7. Subspace clustering

Participants: S Peignier, C Rigotti

We developed an algorithm to tackle the subspace clustering problem over a data stream containing clusters than change over time. Very few subspace clustering algorithms can handle such streams. Our starting point was the work made in the team on evolution of evolution mechanisms and on a preliminary bio-inspired algorithm that we have proposed last year. This previous algorithm included many bio-like features like variable genome length and organization, functional and non-functional elements, and variation operators including chromosomal rearrangements. It achieved satisfying results on standard benchmark data sets but was not designed to process dynamic streams. The new algorithm finds and adapts changing clusters over such streams, while preserving high cluster quality. It has been successfully used to build the evolving music generation system EvoMove.

7. Partnerships and Cooperations

7.1. Regional Initiatives

- Labex Ecofect IntraCellXevo. Participants: E Tannier, in collaboration with T Henry, Insem Lyon. This projects mixes an experimental evolution of *Franscicella tumarensis* in the cytosol and a bioinformatics analysis of the adaptive mutations. There is one publication associated with this project [19]. It has been funded by ANR and Investissements d'Avenir up to 120keuros.

7.2. National Initiatives

7.2.1. ANR

- Ancestrome (2012-2017): phylogenetic reconstruction of ancestral "-omes", a five-year project, call "Bioinformatics" of the "Investissements d'avenir". Supervisor: V Daubin (CNRS, LBBE, Lyon) ; with Institut Pasteur, ENS Paris, ISEM (Univ Montpellier 2) Participant: E Tannier.
- Aucomsi (2013-2016) (Models of the vocal tract to study auditory circuits): a 4-year project funded by a grant from the ANR-NSF-NIH Call for French-US Projects in Computational Neuroscience. With F. Theunissen, UC Berkeley, CA, USA. Supervisor: H. Soula (for France) and F. Theunissen (for US). Participants: H. Soula, M. Fernandez.
- Dopaciumcity (2014-2017): Dopamine modulation of calcium influx underlying synaptic plasticity, a 4-year project funded by a grant from the ANR-NSF-NIH Call for French-US Projects in Computational Neuroscience. With L. Venance, College de France, CIRB, CNRS/UMR 7241 - INSERM U1050, Paris, France and K Blackwell, Krasnow Institute of Advanced Studies, George Mason University, Fairfax, VA, USA. Supervisor: L Venance (for France) and K.L. Blackwell (for US). Participants: H Berry, I Prokin, A Foncelle
- Dallish (2016-2020): Data Assimilation and Lattice LIght SHeet imaging for endocytosis/exocytosis pathway modeling in the whole cell, Call AAPG ANR 2016. With C. Kervrann (Inria Rennes), J. Salamero (Institute Curie, Paris), B. Laroche (INRA, Jouy-en-Josas). Participants: H. Berry.

7.2.2. Inria

- ADT Phylophile. Participants: E Tannier, in collaboration with D Parsons, Inria, V Daubin, B Boussau, CNRS, Université de Lyon 1. This project aims at producing an easy to use software integrating modern algorithmic methods to build gene trees. It has been funded by Inria by a 24 month software engineer.
- ADT Aevol. Participants: C Kinbbe, G Beslon, V Liard, J Rouzaud-Cornabas, D Parsons. This project aims at speeding and scaling and maintaining the code for our most complex software, aevol. It has been funded by Inria by a 24 month software engineer.

7.3. European Initiatives

7.3.1. FP7 & H2020 Projects

7.3.1.1. EvoEvo

Title: Evolution of Evolution

Programm: FP7

Duration: November 2013 - October 2016

Coordinator: Inria

Partners:

Instituto de Biología Molecular y Celular de Plantas, Agencia Estatal Consejo Superior de Investigaciones Cientificas (Spain)

LIRIS, Institut National des Sciences Appliquees de Lyon (France)

LIRIS, Universite Lyon 1 Claude Bernard (France)

LAPM, Universite Joseph Fourier Grenoble 1 (France)

Bioinformatics and Theoretical Biology, Universiteit Utrecht (Netherlands)

Computer science department, University of York (United Kingdom)

Inria contact: Guillaume Beslon

Evolution is the major source of complexity on Earth, at the origin of all the species we can observe, interact with or breed. On a smaller scale, evolution is at the heart of the adaptation process for many species, in particular micro-organisms (e.g. bacteria, viruses...). Microbial evolution results in the emergence of the species itself, and it also contributes to the organisms' adaptation to perturbations or environmental changes. These organisms are not only organised by evolution, they are also organised to evolve. The EvoEvo project will develop new evolutionary approaches in information science and will produce algorithms based on the latest understanding of molecular and evolutionary biology. Our ultimate goal is to address open-ended problems, where the specifications are either unknown or too complicated to express, and to produce software able to operate in unpredictable, varying conditions. We will start from experimental observations of micro-organism evolution, and abstract this to reproduce EvoEvo, in biological models, in computational models, and in application software. Our aim is to observe EvoEvo in action, to model EvoEvo, to understand EvoEvo and, ultimately, to implement and exploit EvoEvo in software and computational systems. The EvoEvo project will have impact in ICT, through the development of new technologies. It will also have impact in biology and public health, by providing a better understanding of micro-organism adaptation (such as the emergence of new pathogens or the development of antibiotic resistances).

7.3.1.2. Neuron-Astro-Nets

Title: Neuron-Astro-Nets

Programm: FP7 Marie-Curie International Outgoing Fellowship (IOF)

Duration: 2013-2017

Partners: Inria Grenoble-Rhone-Alpes; Dept Statistics and Neurobiology, University of Chicago, USA (N. Brunel)

Inria contact: H. Berry

This project aims at developing a new model of synaptic plasticity that takes into account astrocyte signaling, its extension to astrocytes-synapse biochemical interactions in ensembles of synapses enwrapped by the same astrocyte and, eventually, to the firing of a single neuron or networks. The project funds Maurizio De Pittá's postdoc for 4 years (June 2013- May 2017). M. De Pittá´ spent two years in N. Brunel's group in Chicago (06/2014-05/2016) then one year back in Beagle in Lyon (06/2016-05/2017).

7.4. International Initiatives

- The Beagle team is part of the LIA (Laboratoire International Associé) EvoAct (Evolution in action with living and artificial organisms). EvoAct is a joint laboratory gathering researchers from Dominique Schneider's team (UJF, LAPM, UMR CNRS 5163, France), Richard Lenski's team (Michigan State University, Beacon center, US) and the Beagle team.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. General Chair, Scientific Chair

- The team has been accepted as the main organizer of ECAL 2017
- Organization and chair of the second EvoEvo workshop (satellite workshop of CSS 2016), Amsterdam, September 20th 2016

8.1.1.2. Member of the Organizing Committees

- Co-organization of the minisymposium "Modeling Spatiotemporal Calcium Dynamics" at ECMTB 2016 (10th European Conference on Mathematical and Theoretical Biology), The University of Nottingham, UK, 11-15 July 2016 (H. Berry and R. Thüll, U Nottingham)
- Co-organization the thematic school "EIEFB 2016: Ecole interdisciplinaire d'échanges et de formation en biologie", Paris, 13-15 June 2016 (H. Berry and B. Abou, Univ. Paris Diderot).
- Co-organization of the module "Molecular assembling and dynamics: from experimentation to modeling" at the thematic school "Functional Microscopy in Biology" (MiFoBio 2016), Seignosse, France, 30 Sep-07 Oct 2016 (H. Berry, C. Favard, CNRS Montpellier and L. Héliot, CNRS Lille).
- E Tannier is a member of the organizing committee of ICGT 2018 (International Conference on Graph Theory)

8.1.2. Scientific Events Selection

8.1.2.1. Member of the Conference Program Committees

- C Knibbe is a member of the Program committee of Alife XV, Cancun, Mexico, July 2016
- C Rigotti is a member of the Program committee of ACM International Conference on Knowledge Discovery and Data Mining (KDD)
- E Tannier is a member of Recomb Comparative Genomics 2016 program Committee
- E Tannier is a member of ECCB 2016 program Committee
- E Tannier is a member of SEMOVI (séminaire de modélisation du vivant) program Committee
- G Beslon is a member of the Program committee of ALife 2016 (Cancun, Mexico)
- G Beslon is a member of the Program committee of Jobim 2016 (Lyon, France)
- G Beslon is a member of the Program Committee of MUME 2016 (Paris, France)

8.1.2.2. Reviewer

- CPM 2016, RECOMB 2016 (E Tannier)
- ECCB 2016 (C Knibbe)
- EuroPar 2016 (J Rouzaud-Cornabas)

8.1.3. Journal

8.1.3.1. Member of the Editorial Boards

- E Tannier is a member of the editorial committee of *Peer Community in Evolutionary Biology*, an open archive labeling system alternative to publications.
- H Berry is a member of the editorial committee of AIMS Biophysics

8.1.3.2. Reviewer - Reviewing Activities

- PLoS One, Systematic Biology, Bioinformatics, Discrete Applied Mathematics, PLoS Computational Biology, BMC evolutionary Biology, Genome Biology and Evolution, Bulletin of Mathematical Biology (E Tannier)
- Scientific Reports, Physical Biology, Frontiers Synaptic Neuroscience, PLoS Computational Biology, Journal Mathematical Neuroscience, New Journal of Physics (H Berry)
- Entropy, PLoS Computational Biology (G Beslon)
- IEEE Geoscience, Remote Sensing Letters (C Rigotti)
- IEEE Transaction on Cloud Computing (J Rouzaud-Cornabas)

8.1.4. Invited Talks

- J Rouzaud-Cornabas, "Performance Optimization for Computational Biolog", Perfomance Analysis Day, Lyon, December 2016
- C Knibbe, "Insights on genome dynamics from in silico experimental evolution and mathematical modelling", Séminaire de Modélisation du Vivant (SeMoVi), 28th of September 2016, Lyon, France.
- C Knibbe, "Genome size evolution: Putting intuition to the test with modeling and simulation", Jacques Monod Conference on "Evolutionary genomics and systems biology: bringing together theoretical and experimental approaches", 10-14th of October 2016, Roscoff, France.
- G Beslon, Hybrid Systems Biology workshop (Grenoble, France) at the Semideev meeting (Saclay, France), at the FET technical seminar (Brussels, Belgium)
- H Berry, "Estimating the impact of anomalous diffusion on intracellular biochemical kinetics", workshop "Stochastic Modelling of Transport Processes In Biology", 30th-31st March 2016, Manchester, UK
- H Berry, "Estimating the effects of spatial non-homogeneities in intracellular diffusion-reactions", meeting of the BIOSS Working-Group, July 1st 2016, Lyon
- H Berry, "Calcium signals in astrocytes: from intercellular to subcellular models", workshop "In vitro and in silico modelling of neuron-astrocyte communication" of the 2016 Bernstein Conference, September 20-21 2016, Berlin, Germany
- H Berry, "The many dimensions of cortico-striatal STDP", meeting of the GDR BioComp, 10-12 Oct 2016, Lyon
- H Berry, "Anomalous diffusion in cells: experimental data and modelling", CIMPA School "Mathematical models in biology and medicine", December 05-16 2016, Moka, Mauritius.
- E Tannier, "The second root of molecular evolution" Genetic depatment of the Trinity College, Dublin, Feruary 2017
- E Tannier, "Molecules as documents of evolutionary history: 50 years before", Jacques Monod Conference *Molecules as Documents of Evolutionary History*, Roscoff, May 2016
- E Tannier, "Breaking bad", workshop *Pattern Avoidance and Genome Sorting*, Dagstuhl, February 2016

8.1.5. Leadership within the Scientific Community

- H Berry is a Member of the Scientific Board (comité scientifique) of GdR MIV (Microscopie et Imagerie du Vivant, GdR 2588)
- H Berry is a Member of the Steering Commitee (comité de pilotage) of GdR IMaBIO (Imagerie et Microscopie pour la BIOlogie, submitted)

8.1.6. Scientific Expertise

- H Berry is a Reviewer for the US National Science Foundation (NSF), call "Early-career Program"
- H Berry is a Member of the evaluation committee for research program ROSIRIS of the IRSN (Institut de Radioprotection et de Sûreté Nucléaire)
- E Tannier is a Member of the evaluation committee for the FRNQT, Research program in Quebec.

8.1.7. Research Administration

- C Knibbe is a member of Inria Grenoble-Rhône Alpes Comité de Développement Technologique (CDT)
- C Knibbe is a member of the Selection committee in CNU section 67/64 at Université Paris Diderot
- C Knibbe is a member of the Conseil de Laboratoire LIRIS (UMR 5205 CNRS)

- C Rigotti is an elected member of Insa Scientific board (Conseil scientifique)
- G Beslon member of the CoNRS (Section 6 and CID 51)
- G Beslon member of the scientific commission 5 (CSS5) of the IRD (Institut de Recherche pour le Developpement)
- H Berry is Vice-Chair of Inria's "Evaluation Committee" (Commission d'Evaluation)
- H Berry is Chair of the Search Committee for "Junior Research Scientists" (Président Jury d'admissibilité CR2) of Inria Grenoble Research Center
- H Berry is Elected member of Inria's "Scientific Board" (Conseil Scientifique)
- H Berry is Member of Inria's "Parity-Equality" Committee
- H Berry is Member of the Science Steering Committee of the Rhône-Alpes Complex Systems Institute (IXXI)
- E Tannier is an elected member of Inria Administration Council
- E Tannier is the scientific referent of the Inria symposium committee

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

License: J Rouzaud-Cornabas, Programmation orientée objets, 20heqTD, L3, INSA-Lyon, France

Master: J Rouzaud-Cornabas, Systèmes, 10heqTD, M1, INSA-Lyon, France

Master: J Rouzaud-Cornabas, Interface Homme Machine, 50heqTD, M1, INSA-Lyon, France

Master: J Rouzaud-Cornabas, Évaluation de performance et reproducibilité, 6heqTD, M2, INSA-Lyon, France

Master: J Rouzaud-Cornabas, Computational Science and High Performance Computing, 6heqTD, M2, INSA-Lyon, France

Master: J Rouzaud-Cornabas, Parallel Computing, 80heqTD, M2, INSA-Lyon, France

Master: J Rouzaud-Cornabas, Parallel Computing for Bio-informatics, 10heqTD, M2, INSA-Lyon, France

Licence: C Rigotti, Object-Oriented Programming and Graphical User Interfaces, 86h, L2, Department 1er cycle of INSA-Lyon.

Licence: C Rigotti, Simulation of Chemical Reactions, 26h, L2, Department 1er cycle of INSA-Lyon.

Licence: C Rigotti, Numerical Modelling for Engineering, 60h, L2, Department 1er cycle of INSA-Lyon.

Master: C Rigotti, Data Mining, 25h, M1, Bioinformatics and Modeling Department of INSA-Lyon.

Master: E Tannier, Algorithmics for Bioinformatics, 18h, M1, Bioinformatics and Modeling Department of INSA-Lyon.

Master: E Tannier, Algorithmics for Bioinformatics, 12h, M1, University of Lyon 1.

Licence: C Knibbe, Algorithmique et programmation procédurale, 123h eqTD, L2 Informatique, Université Lyon 1, France

Master: C Knibbe, Programmation web, 40h eqTD, M1 Informatique, Université Lyon 1, France

Master: C Knibbe, Connaissance métier pour la recherche, 24h eqTD, M2 Informatique, Université Lyon 1, France

Master: C Knibbe, Intelligence artificielle bio-inspirée, 22h eqTD, M2 Informatique, Université Lyon 1, France

Licence: C Knibbe, Applications en mathématiques et informatique, 39h eqTD, L1 Informatique, Université Lyon 1, France

Licence: C Knibbe, Programmation fonctionnelle pour le web, 20h eqTD, L2 Informatique, Université Lyon 1, France

Master: C Knibbe, Programmation orientée objets pour la bioinformatique, 52h eqTD, M1 Bioinformatique, Université Lyon 1, France

Master: C Knibbe, Projet en bioinformatique, 25h eqTD, M1 Bioinformatique, Université Lyon 1, France

8.2.2. Supervision

PhD : Ilya Prokin, “Modeling and simulation of signal transduction in living cells: synaptic plasticity of basal ganglia neurons”, INSA Lyon, Ph.D. defended: December 02, 2016, Supervisor: H. Berry

PhD in progress : Marie Fernandez, “Extraction and analysis of the acoustic network of social birds: tools for population tracking”, Starting date Oct 2016, co-supervision: H. Berry, H. Soula (CRC, Univ. P&M Curie, Paris) and C. Vignal (Univ. J. Monnet, Saint-Etienne)

PhD in progress : Audrey Denizot, “Simulation of calcium signaling in fine astrocytic processes”, Starting date Oct 2016, co-supervision: H. Berry and H. Soula (CRC, Univ. P&M Curie, Paris)

PhD in progress : Alexandre Foncelle, ‘Modeling the signaling pathway implicated in STDP: the role of endocannabinoid and dopamine signaling”, Starting date Oct 2014, supervision: H. Berry

PhD in progress : Alvaro Mateos Gonzalez; “Anomalous subdiffusion equations as diffusion limits to integro PDEs with age structure”, Starting date Sep 2014, co-supervision: H. Berry, Vincent Calvez (EPI Numed) and Thomas Lepoutre (EPI Dracula).

PhD in progress : Wandrille Duchemin; "Phylogénie des dépendences, dépendances des phylogénies", Starting date 2015, co-supervision: E Tannier and V Daubin (CNRS, Univ Lyon 1)

PhD in progress : Yoann Anselmetti; "Evolution de l’organisation des génomes en présence de génomes non assemblés", Starting date 2015, co-supervision: E Tannier and S Bérard (Univ Montpellier)

PhD in progress : Damir Hasic; "Gene tree Species tree reconciliation in the presence of gene conversion", Starting date 2016, co-supervision: E Tannier (Univ Sarajevo)

PhD in progress: Sergio Peignier, Subspace clustering algorithms based on biological evolution mechanisms, INSA de Lyon, started in September 2014, C Rigotti and G Beslon.

PhD in progress : Charles Rocabert, Studying Evolution of Evolution of Bacterial Microorganisms by Computer Simulation Approaches, started in October 2013, supervised by G Beslon and C Knibbe

PhD in progress: Yoram Vadee Le Brun, "Evolution expérimentale in silico de réseaux de régulation génétique", INSA-Lyon (now Min. Enseignement National), Starting date Sep 2013, co-supervision: G Beslon, J Rouzaud-Cornabas

PhD in progress: Vincent Liar, "Towards a quantitative digital genetics platform", INSA-Lyon, Starting date Oct 2016, co-supervision: G Beslon, J Rouzaud-Cornabas, C Ofria (Michigan State University, BEACON Center)

8.2.3. Juries

- C Knibbe is a reviewer of the PhD thesis Gaël Jalowicki, University College Dublin, October 2016
- H Berry is a Member (reviewer) of the PhD jury for Guillaume Rodriguez, “Modélisation des bases neuronales de la mémoire de travail paramétrique dans le cortex préfrontal” Univ. P & M Curie, Paris, Oct 20, 2016.
- H Berry is a Member (reviewer) of the HdR jury for Dominique Martinez, “Modélisation biologique, biocapteurs et inspiration pour la robotique autonome”, Univ. Nancy-Lorraine, Nancy, 2017

- H Berry is a Member of the Search committee for two tenured Full Professor positions in Systems Biology at University P & M Curie, Paris, 2016 (64PR0596 and 65PR3266)
- G Beslon is a member of the Jury of Ilya Prokins (INSA-Lyon, Lyon, France)
- G Beslon is a reviewer of the PhD thesis of Arthur Bertrand (UPMC, Paris, France)
- G Beslon is a reviewer of the PhD thesis of Sandro Colizzi (Utrecht University, Utrecht, NL)

8.3. Popularization

- E Tannier gave a series of lectures for a large public at "Université Populaire de Lyon", on "anarchy in biology".

9. Bibliography

Major publications by the team in recent years

[1] P. BILLER, L. GUÉGUEN, C. KNIBBE, E. TANNIER.*Breaking Good: Accounting for Fragility of Genomic Regions in Rearrangement Distance Estimation*, in "Genome Biology and Evolution", 2016, vol. 8, n^{o} 5, p. 1427-1439 [*DOI :* 10.1093/GBE/EVW083], https://hal.archives-ouvertes.fr/hal-01334923.

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Project-Team BIPOP

Modelling, Simulation, Control and Optimization of Non-Smooth Dynamical Systems

IN COLLABORATION WITH: Laboratoire Jean Kuntzmann (LJK)

IN PARTNERSHIP WITH:
Institut polytechnique de Grenoble

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Optimization and control of dynamic systems

Table of contents

Project-Team BIPOP

Creation of the Project-Team: 2004 April 01

Keywords:

Computer Science and Digital Science:

5.5. - Computer graphics
5.5.1. - Geometrical modeling
5.10. - Robotics
5.10.4. - Robot control
5.10.5. - Robot interaction (with the environment, humans, other robots)
6. - Modeling, simulation and control
6.1.1. - Continuous Modeling (PDE, ODE)
6.2. - Scientific Computing, Numerical Analysis & Optimization
6.2.1. - Numerical analysis of PDE and ODE
6.2.6. - Optimization
6.4. - Automatic control
6.4.1. - Deterministic control
6.4.3. - Observability and Controlability
6.4.4. - Stability and Stabilization

Other Research Topics and Application Domains:

1.3.1. - Understanding and simulation of the brain and the nervous system
5. - Industry of the future
5.6. - Robotic systems
9.4. - Sciences
9.4.2. - Mathematics

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2. Overall Objectives

2.1. Overall Objectives

Generally speaking, this project deals with non-smooth systems, control, modelling and simulation, with emphasis on

- dynamic systems, mostly mechanical systems with unilateral constraints, impacts and set-valued friction models (like Coulomb's friction), but also electrical circuits with ideal diodes and transistors Mos, sliding-mode controllers, biological neural networks, etc;
- numerical methods for nonsmooth optimization, and more generally the connection between continuous and combinatorial optimization.

3. Research Program

3.1. Dynamic non-regular systems

nonsmooth mechanical systems, impacts, friction, unilateral constraints, complementarity problems, modeling, analysis, simulation, control, convex analysis

Dynamical systems (we limit ourselves to finite-dimensional ones) are said to be *non-regular* whenever some nonsmoothness of the state arises. This nonsmoothness may have various roots: for example some outer impulse, entailing so-called *differential equations with measure*. An important class of such systems can be described by the complementarity system

$$\left\{\begin{array}{l} \dot{x} = f(x,u,\lambda)\,, \\ 0 \le y \perp \lambda \ge 0\,, \\ g(y,\lambda,x,u,t) = 0\,, \\ \text{re-initialization law of the state } x(\cdot), \end{array}\right. \tag{1}$$

where $\perp$ denotes orthogonality; u is a control input. Now (1) can be viewed from different angles.

- Hybrid systems: it is in fact natural to consider that (1) corresponds to different models, depending whether $y_i = 0$ or $y_i > 0$ (y_i being a component of the vector y). In some cases, passing from one mode to the other implies a jump in the state x; then the continuous dynamics in (1) may contain distributions.
- Differential inclusions: $0 \le y \perp \lambda \ge 0$ is equivalent to $-\lambda \in \mathrm{N}_K(y)$, where K is the nonnegative orthant and $\mathrm{N}_K(y)$ denotes the normal cone to K at y. Then it is not difficult to reformulate (1) as a differential inclusion.
- Dynamic variational inequalities: such a formalism reads as $\langle \dot{x}(t) + F(x(t),t), v - x(t)\rangle \ge 0$ for all $v \in K$ and $x(t) \in K$, where K is a nonempty closed convex set. When K is a polyhedron, then this can also be written as a complementarity system as in (1).

Thus, the 2nd and 3rd lines in (1) define the modes of the hybrid systems, as well as the conditions under which transitions occur from one mode to another. The 4th line defines how transitions are performed by the state x. There are several other formalisms which are quite related to complementarity. See [7], [8], [15] for a survey on models and control issues in nonsmooth mechanical systems.

3.2. Nonsmooth optimization

optimization, numerical algorPierre-Brice Wieber.ithm, convexity, Lagrangian relaxation, combinatorial optimization.

Here we are dealing with the minimization of a function f (say over the whole space R^n), whose derivatives are discontinuous. A typical situation is when f comes from dualization, if the primal problem is not strictly convex – for example a large-scale linear program – or even nonconvex – for example a combinatorial optimization problem. Also important is the case of spectral functions, where $f(x) = F(\lambda(A(x)))$, A being a symmetric matrix and λ its spectrum.

For these types of problems, we are mainly interested in developing efficient resolution algorithms. Our basic tool is bundling and we act along two directions:

- To explore application areas where nonsmooth optimization algorithms can be applied, possibly after some tayloring. A rich field of such application is combinatorial optimization, with all forms of relaxation.
- To explore the possibility of designing more sophisticated algorithms. This implies an appropriate generalization of second derivatives when the first derivative does not exist, and we use advanced tools of nonsmooth analysis.

$\Longrightarrow$*The optimization scientific activity in BIPOP is no longer existing after Jérôme Malick left BIPOP to lead the DAO team in the Laboratoire Jean Kuntzman.*

4. Application Domains

4.1. Computational neuroscience

Modeling in neuroscience makes extensive use of nonlinear dynamical systems with a huge number of interconnected elements. Our current theoretical understanding of the properties of neural systems is mainly based on numerical simulations, from single cell models to neural networks. To handle correctly the discontinuous nature of integrate-and-fire networks, specific numerical schemes have to be developed. Our current works focus on event-driven, time-stepping and voltage-stepping strategies, to simulate accurately and efficiently neuronal networks. Our activity also includes a mathematical analysis of the dynamical properties of neural systems. One of our aims is to understand neural computation and to develop it as a new type of information science [16], [17].

4.2. Electronic circuits

Whether they are integrated on a single substrate or as a set of components on a board, electronic circuits are very often a complex assembly of many basic components with non linear characteristics. The IC technologies now allow the integration of hundreds of millions of transistors switching at GHz frequencies on a die of 1cm^2. It is out of the question to simulate a complete IC with standard tools such as the SPICE simulator. We currently work on a dedicated plug-in able to simulate a whole circuit comprising various components, some modelled in a nonsmooth way [1].

4.3. Walking robots

As compared to rolling robots, the walking ones – for example hexapods – possess definite advantages whenever the ground is not flat or free: clearing obstacles is easier, holding on the ground is lighter, adaptivity is improved. However, if the working environment of the system is adapted to man, the biped technology must be preferred, to preserve good displacement abilities without modifying the environment. This explains the interest displayed by the international community in robotics toward humanoid systems, whose aim is to back man in some of his activities, professional or others. For example, a certain form of help at home to disabled persons could be done by biped robots, as they are able to move without any special adaptation of the environment.

4.4. Computer graphics animation

Computer graphics animation is dedicated to the numerical modeling and simulation of physical phenomena featuring a high visual impact. Typically, deformable objects prone to strong deformation, large displacements, complex and nonlinear or even nonsmooth behavior, are of interest for this community. We are interested in two main mechanical phenomena: on the one hand, the behavior of slender (nonlinear) structures such as rods, plates and shells; on the other hand, the effect of frictional contact between rigid or deformable bodies. In both cases the goal is to design realistic, efficient, robust, and controllable computational models. Whereas the problem of collision detection has become a mature field those recent years, simulating the collision response (in particular frictional contacts) in a realistic, robust and efficient way, still remains an important challenge. We have focussed in the past years on the simulation of heterogeneous objects such as granular or fibrous materials, both with a discrete element point of view [11], and, more recently, with a macroscopic (continuum) point of view [23]. We also pursue some study on the design of high-order models for slender structures such as rods, plates or shells. Our current activity includes the static inversion of mechanical objects, which is of great importance in the field of artistic design, for the making of movies and video games for example. Such problems typically involve geometric fitting and parameters identification issues, both resolved with the help of constrained optimization. Finally, we are interested in studying certain discrepancies (inexistence of solution) due to the combination of incompatible models such as contacting rigid bodies subject to Coulomb friction.

4.5. Multibody Systems: Modeling, Control, Waves, Simulation

Multibody systems are assemblies of rigid or flexible bodies, typically modeled with Newton-Euler or Lagrange dynamics, with bilateral and unilateral constraints, with or without tangential effects like friction. These systems are highly nonlinear and nonsmooth, and are therefore challenging for modeling aspects (impact dynamics, especially multiple –simultaneous– collisions), feedback control [10], state observation, as well as numerical analysis and simulation (software development) [2], [4], [5]. Biped robots are a particular, interesting subclass of multibody systems subject to various constraints. Granular materials are another important field, in which nonlinear waves transmissions are crucial (one celebrated example being Newton's cradle) [15], [12], [6], [13]. Fibers assemblies [11], circuit breakers, systems with clearances, are also studied in the team.

4.6. Stability and Feedback Control

Lyapunov stability of nonsmooth, complementarity dynamical systems is challenging, because of possible state jumps, and varying system's dimension (the system may live on lower-dimensional subspaces), which may induce instability if not incorporated in the analysis [8], [9], [7]. On the other hand, the nonsmoothness (or the set-valuedness) may be introduced through the feedback control, like for instance the well-known sliding-mode controllers or state observers. The time-discretisation of set-valued controllers is in turn of big interest [3]. The techniques we study originate from numerical analysis in Contact Mechanics (the Moreau-Jean time-stepping algorithm) and are shown to be very efficient for chattering suppression and Lyapunov finite-time stability.

5. New Software and Platforms

5.1. ACEF

- Participants: Vincent Acary and Olivier Bonnefon (previous Expert Engineer now at INRA).
- Contact: Vincent Acary.

5.2. Approche

KEYWORD: Geometric computing

- Participants: Alexandre Derouet-Jourdan, Florence Descoubes and Joelle Thollot
- Contact: Florence Descoubes
- URL: http://bipop.inrialpes.fr/~bertails/Papiers/floatingTangents3d.html

5.3. CloC

Super Space Clothoids in C
KEYWORD: Physical simulation
FUNCTIONAL DESCRIPTION

Reference software implementing the paper "Super Space Clothoids", R. Casati and F. Bertails-Descoubes, ACM Transactions on Graphics, 2013

- Participants: Florence Descoubes and Romain Casati
- Partner: UJF
- Contact: Florence Descoubes
- URL: http://bipop.inrialpes.fr/people/casati/publications/codes/ssc.html

5.4. MECHE-COSM

Modeling Entangled fiber with frictional Contact in Hair
KEYWORDS: Physical simulation - Frictional contact - Thin elastic rod
FUNCTIONAL DESCRIPTION

Implements super-helices [Bertails et al. 2006] coupled together by a hybrid algorithm for frictional contact [Daviet et al. 2011].

- Participants: Gilles Daviet, Florence Bertails Descoubes and Florent Cadoux
- Contact: Florence Descoubes

5.5. SALADYN MULTIBODY

- Participants: Vincent Acary and Olivier Bonnefon
- Contact: Vincent Acary

5.6. SICONOS

KEYWORDS: NSDS - MEMS - DCDC - SD - Collision - Friction - Mechanical multi-body systems
FUNCTIONAL DESCRIPTION

Siconos is an open-source scientific software primarily targeted at modeling and simulating nonsmooth dynamical systems in C++ and in Python: - Mechanical systems (rigid or solid) with unilateral contact and Coulomb friction and impact (nonsmooth mechanics, contact dynamics, multibody systems dynamics or granular materials). - Switched Electrical Circuit such as electrical circuits with ideal and piecewise linear components: power converter, rectifier, Phase-Locked Loop (PLL) or Analog-to-Digital converter. - Sliding mode control systems. - Biology (Gene regulatory network). Other applications are found in Systems and Control (hybrid systems, differential inclusions, optimal control with state constraints), Optimization (Complementarity systems and Variational inequalities), Fluid Mechanics, and Computer Graphics.

- Participants: Vincent Acary, Olivier Bonnefon, Maurice Bremond and Franck Perignon
- Contact: Bernard Brogliato
- URL: http://siconos.gforge.inria.fr

5.7. Platforms: SICONOS

5.7.1. Platform A : SICONOS

Participants: Vincent Acary, Maurice Brémond, Olivier Huber, Franck Pérignon.

In the framework of the FP5 European project Siconos (2002-2006), Bipop was the leader of the Work Package 2 (WP2), dedicated to the numerical methods and the software design for nonsmooth dynamical systems. This has given rise to the platform SICONOS which is the main software development task in the team. The aim of this work is to provide a common platform for the simulation, modeling, analysis and control of abstract nonsmooth dynamical systems. Besides usual quality attributes for scientific computing software, we want to provide a common framework for various scientific fields, to be able to rely on the existing developments (numerical algorithms, description and modeling software), to support exchanges and comparisons of methods, to disseminate the know-how to other fields of research and industry, and to take into account the diversity of users (end-users, algorithm developers, framework builders) in building expert interfaces in Python and end-user front-end through Scilab.

After the requirement elicitation phase, the Siconos Software project has been divided into 5 work packages which are identified to software products:

1. SICONOS/NUMERICS This library contains a set of numerical algorithms, already well identified, to solve non smooth dynamical systems. This library is written in low-level languages (C,F77) in order to ensure numerical efficiency and the use of standard libraries (Blas, Lapack, ...)
2. SICONOS/KERNEL This module is an object-oriented structure (C++) for the modeling and the simulation of abstract dynamical systems. It provides the users with a set of classes to describe their nonsmooth dynamical system (dynamical systems, intercations, nonsmooth laws, ...) and to perform a numerical time integration and solving.
3. SICONOS/FRONT-END. This module is mainly an auto-generated wrapper in Python which provides a user-friendly interface to the Siconos libraries. A scilab interface is also provided in the Front-End module.
4. SICONOS/CONTROL This part is devoted to the implementation of control strategies of non smooth dynamical systems.
5. SICONOS/MECHANICS. This part is dedicated to the modeling and the simulation of multi-body systems with 3D contacts, impacts and Coulomb's friction. It uses the Siconos/Kernel as simulation engine but relies on a industrial CAD library (OpenCascade and pythonOCC) to deal with complex body geometries and to compute the contact locations and distances between B-Rep description and on Bullet for contact detection between meshes.

Further informations may be found at http://siconos.gforge.inria.fr/

6. New Results

6.1. The contact complementarity problem, and Painlevé paradoxes

Participants: Bernard Brogliato, Florence Bertails-Descoubes, Alejandro Blumentals.

The contact linear complementarity problem is an set of equalities and complementarity conditions whose unknowns are the acceleration and the contact forces. It has been studied in a frictionless context with possibly singular mass matrix and redundant constraints, using results on well-posedness of variational inequalities obtained earlier by the authors. This is also the topic of the first part of the Ph.D. thesis of Alejandro Blumentals where the frictional case is treated as a perturbation of the frictionless case [22]. With R. Kikuuwe from Kyushu University, we have also proposed a new formulation of the Baumgarte's stabilisation method, for unilateral constraints and Coulomb's friction , which sheds new light on Painlevé paradoxes [27]. It relies on a particular limiting process of normal cones.

6.2. Discrete-time sliding mode control

Participants: Vincent Acary, Bernard Brogliato, Olivier Huber.

This topic concerns the study of time-discretized sliding-mode controllers. Inspired by the discretization of nonsmooth mechanical systems, we propose implicit discretizations of discontinuous, set-valued controllers [3]. This is shown to result in preservation of essential properties like simplicity of the parameters tuning, suppression of numerical chattering, reachability of the sliding surface after a finite number of steps, and disturbance attenuation by a factor h or h^2 [25]. This work was part of the ANR project CHASLIM. Within the framework of CHASLIM we have performed many experimental validations on the electropneumatic setup of IRCCyN (Nantes), which nicely confirm our theoretical and numerical predictions: the implicit implementation of sliding mode control, drastically improves the input and output chattering behaviours, both for the classical order-one ECB-SMC and the twisting algorithms [26], [25], [39]. In particular the high frequency bang-bang controllers which are observed with explicit discretizations, are completely suppressed. The implicit discretization has been applied to the classical equivalent-based-control SMC, and also to the twisting sliding-mode controller. Incidentally an error in a previous article is corrected in [19]. The previous results deal with disturbances which are matched and uniformly upperbounded. In [48], [49] they are extended to the case of parametric uncertainties, which are more difficult to handle because they may yield unmatched equivalent disturbances, and these disturbances are not uniformly upperbounded by a constant. Finally the results in [20] deal with the numerical analysis (and not the discrete-time control, which is a different problem) of Lagrangian systems with set-valued controllers. An implicit Euler method is used, and the convergence is shown.

6.3. Lur'e set-valued dynamical systems

Participants: Bernard Brogliato, Christophe Prieur, Alexandre Vieira.

Lur'e systems are quite popular in Automatic Control since the fifties. Set-valued Lur'e systems possess a static feedback nonlinearity that is a multivalued function. We study in [31] state observers for particular Lur'e systems which are Moreau's sweeping processes modelling Lagrange dynamics with frictionless unilateral constraints. The observers are themselves set-valued (first order sweeping process with measures), a complete analysis (existence of solutions, stability of the error system) is led. In [51], we extend previous results in the team and also more recently by Camlibel and Schumacher, to solve the problem of output regulation for evolution variational inequalities (in a convex analysis setting). In the PhD thesis of A. Vieira, we attack the problem of optimal control of linear complementarity systems. In the first part of this thesis, the case when the LCS is equivalent to an ODE with Lipschitz continuous right-hand side, is treated. Starting from first-order necessary conditions stated in a broad context by Clarke, we show that the Pontryagin's conditions are a mixed LCS, that yield so-called MPEC problems.

6.4. Numerical analysis of multibody mechanical systems with constraints

This scientific theme concerns the numerical analysis of mechanical systems with bilateral and unilateral constraints, with or without friction [2]. They form a particular class of dynamical systems whose simulation requires the development of specific simulators.

6.4.1. Numerical time–integration methods for event-detecting schemes.

Participants: Vincent Acary, Bernard Brogliato, Mounia Haddouni.

The CIFRE thesis of M. Haddouni concerns the numerical simulation of mechanical systems subject to holonomic bilateral constraints, unilateral constraints and impacts. This work is performed in collaboration with ANSYS and the main goal is to improve the numerical time–integration in the framework of event-detecting schemes. Between nonsmooth events, time integration amounts to numerically solving a differential algebraic equations (DAE) of index 3. We have compared dedicated solvers (Explicit RK schemes, Half-explicit schemes, generalizes α-schemes) that solve reduced index formulations of these systems. Since the drift of the constraints is crucial for the robustness of the simulation through the evaluation of the index sets of active contacts, we have proposed some recommendations on the use of the solvers of dedicated to index-2 DAE. A manuscript has been submitted to Multibody System Dynamics.

6.4.2. Multibody systems with clearances (dynamic backlash)

Participants: Vincent Acary, Bernard Brogliato, Narendra Akadkhar.

The PhD thesis of N. Akadkhar under contract with Schneider Electric concerns the numerical simulation of mechanical systems with unilateral constraints and friction, where the presence of clearances in imperfect joints plays a crucial role. A first work deals with four-bar planar mechanisms with clearances at the joints, which induce unilateral constraints and impacts, rendering the dynamics nonsmooth. The objective is to determine sets of parameters (clearance value, restitution coefficients, friction coefficients) such that the system's trajectories stay in a neighborhood of the ideal mechanism (*i.e.* without clearance) trajectories. The analysis is based on numerical simulations obtained with the projected Moreau-Jean time-stepping scheme. These results have been reported in [21]. It is planned to extend these simulations to frictional cases and to mechanisms of circuit breakers.

6.5. Nonlinear waves in granular chains

Participants: Guillaume James, Bernard Brogliato.

Granular chains made of aligned beads interacting by contact (e.g. Newton's cradle) are widely studied in the context of impact dynamics and acoustic metamaterials. While much effort has been devoted to the theoretical and experimental analysis of solitary waves in granular chains, there is now an increasing interest in the study of breathers (spatially localized oscillations) in granular systems. Due to their oscillatory nature and associated resonance phenomena, static or traveling breathers exhibit much more complex dynamical properties compared to solitary waves. Such properties have strong potential applications for the design of acoustic metamaterials allowing to efficiently damp or deviate shocks and vibrations. In the work [29], the existence of static breathers is analyzed in granular metamaterials consisting of hollow beads with internal masses. Using multiple scale analysis and exploiting the unilateral character of Hertzian interactions, we show that long-lived breather solutions exist but time-periodic breathers do not (breather solutions actually disperse on long time scales). In [28], we consider the effect of adding precompression to the above system and establish that the envelope of small ampliude oscillations is governed by a nonlinear Schrödinger equation. This allows us to show that, depending on the applied precompression, normal modes can become modulationally unstable and evolve towards traveling breathers. Moreover, in a collaboration with Y. Starosvetsky and D. Meimukhin (Technion), we numerically study the persistence of traveling breathers in granular chains with local potentials under the effect of contact damping. Using a viscoelastic damping model (Hertz-Kuwabara-Kono model), we show that breathers can be generated by simple impacts in granular chains made from various materials (breathers propagate over a significant number of sites before being damped). The design of an experimental setup to test these theoretical predictions is underway. Another work in progress concerns more specifically the modeling and numerical analysis of dissipative impacts (James, Brogliato). The methodology is based on the introduction of appropriate variables and simplifications for different models of contact damping. A postdoctoral fellow will work on this topic in the team, starting January 2017.

6.6. Travelling waves in a spring-block chain sliding down a slope

Participants: Guillaume James, Jose Eduardo Morales Morales, Arnaud Tonnelier.

In this work we study the dynamics of an infinite chain of identical blocks sliding on a slope under the effet of gravity. Each block is coupled to its nearest neighbour through linear springs and is subjected to a nonlinear friction force. For a piecewise-linear spinodal friction law, a closed-form expression of front waves is derived. Pulse waves are obtained as the matching of two travelling fronts with identical wave speeds. Explicit formulas are obtained for the wavespeed and the wave form in the anti-continuum limit. The link with propagating phenomena in the Burridge-Knopoff model is briefly discussed. These results have been reported in [44].

6.7. Solitary waves in the excitable Burridge-Knopoff model

Participants: Guillaume James, Jose Eduardo Morales Morales, Arnaud Tonnelier.

The Burridge-Knopoff model is a lattice differential equation describing a chain of blocks connected by springs and pulled over a surface. This model was originally introduced to investigate nonlinear effects arising in the dynamics of earthquake faults. One of the main ingredients of the model is a nonlinear velocity-dependent friction force between the blocks and the fixed surface. For some classes of non-monotonic friction forces, the system displays a large response to perturbations above a threshold, which is characteristic of excitable dynamics. Using extensive numerical simulations, we show that this response corresponds to the propagation of a solitary wave for a broad range of friction laws (smooth or nonsmooth) and parameter values. These solitary waves develop shock-like profiles at large coupling (a phenomenon connected with the existence of weak solutions in a formal continuum limit) and propagation failure occurs at low coupling. We introduce a simplified piecewise linear friction law (reminiscent of the McKean nonlinearity for excitable cells) which allows us to obtain analytical expression of solitary waves and study some of their qualitative properties, such as wavespeed and propagation failure. We propose a possible physical realization of this system as a chain of impulsively forced mechanical oscillators. In certain parameter regimes, non-monotonic friction forces can also give rise to bistability between the ground state and limit-cycle oscillations and allow for the propagation of fronts connecting these two stable states. These results have been reported in [45]. In addition, an existence theorem for solitary waves in the Burridge-Knopoff model is proved in the weak coupling limit and for a piecewise-linear friction force.

6.8. Propagation in space-discrete excitable systems

Participant: Arnaud Tonnelier.

We introduce a simplified model of excitable systems where the response of an isolated cell to an incoming signal is described by a fixed pulse-shape function. When the total activity of the cell reaches a given threshold a signal is sent to its N nearest neighbors. We show that a chain of such excitable cells is able to propagate a set of simple traveling waves where the time interval between the firing of two successive cells remains constant. A comprehensive study is done for a transmission line with $N = 2$ and $N = 3$. It is shown that, depending on initial copnditions, the network may propagate signals with different velocities. Some necessary conditions for multistationarity are derived for an arbitrary N.

6.9. Direct and inverse modeling of thin elastic rods and shells

6.9.1. Experimental validation of the inverse statics of a thin elastic rod

Participants: Florence Bertails-Descoubes, Victor Romero.

In collaboration with Arnaud Lazarus (UPMC, Laboratoire Jean le Rond d'Alembert), we have built an experimental set-up to fabricate thin elastic rods and measure their deformation, with the aim to validate our full process for inverse static design. This work is still ongoing.

6.9.2. Strain-based modeling of inextensible and developable shells

Participants: Florence Bertails-Descoubes, Romain Casati, Alejandro Blumentals.

We have worked out the analagous of a super-helix element for modeling an inextensible and developable shell patch, using only two material curvatures. As for the super-helix model, the terms of the dynamics can be integrated formally, leading to a rich and efficient dynamical model [36]. How to connect different patches together is a topic for future work.

6.9.3. Inverse statics of plates and shells with frictional contact

Participants: Florence Bertails-Descoubes, Romain Casati, Gilles Daviet.

We study the problem of cloth inverse design, relying on a nodal shell model for modeling garments. We have shown how to formulate draping as a local constrained minimization problem, and we have generalized the adjoint method to handle constrained cases, e.g., frictional contact between the garment and the body [43].

6.10. Continnum modeling of granular materials

6.10.1. Continuum modeling of granular materials

Participants: Florence Bertails-Descoubes, Gilles Daviet.

We have proposed a new numerical framework for the continuous simulation of dilatable materials with pressure-dependent (Coulomb) yield stress, such as sand or cement. Relying upon convex optimization tools, we have shown that the continuous equations of motion coupled to the macroscopic nonsmooth Drucker-Prager rheology can be interpreted as the exact analogous of the solid frictional contact problem at the heart of Discrete Element Methods (DEM), extended to the tensorial space. Combined with a carefully chosen finite-element discretization, this new framework allowed us to avoid regularizing the continuum rheology while benefiting from the efficiency of nonsmooth optimization solvers, mainly leveraged by DEM methods so far. Our numerical results were successfully compared to analytic solutions on model problems, such as the silo discharge, and we retrieved qualitative flow features commonly observed in reported experiments of the literature. This work, published at the Journal of Non Newtonian Fluid Mechanics [24], has been extended the approach to account for flows with a varying density, leveraging the Material Point Method to discretize the Drucker Prager yield criterion without linearization. We have also included the handling of anisotropic flow, as well as the coupling of the flow with rigid bodies. These extensions led to a publication at ACM SIGGRAPH 2016 [23].

6.11. Robust Model Predictive Control for biped walking motion generation

Participants: Pierre-Brice Wieber, Diana Serra, Alexander Sherikov, Dimitar Dimitrov.

One of the main sources of nonlinearity in the Newton and Euler equations of motion of biped walking robots lie in the vertical motion of the Center of Mass. We proposed last year an approach that considers this nonlinearity as an uncertainty, in what would else be a linear system. We proposed then to use a robust linear MPC approach accordingly. The use of a linear approach allows fast computations to generate walking motions online. This year, we further developed this approach, by adapting the bounds on the uncertainty at each iteration of a Newton scheme, when solving the original nonlinear problem [35]. By using a robust approach within a Newton scheme, every iteration can be ensured to satisfy all dynamic constraints, so that we can limit the number iterations depending on the available computing power and always obtain a feasible solution. We also developed this year an application of this MPC approach to cases of collaborative carrying of heavy objects with a human partner [32].

6.12. Lexicographic Model Predictive Control for collision avoidance in dynamic environments

Participants: Pierre-Brice Wieber, Nestor Alonso Bohorquez Dorante, Alexander Sherikov, Dimitar Dimitrov.

Collision avoidance may not always be feasible in dynamic environments, when new obstacles can appear too late and move too fast with respect to the dynamic limitations of the system. A typical situation is with a biped robot walking in a compact and uncooperative crowd, with limited field of view. This year, we have investigated and compared 3 different relaxations of the collision avoidance constraint in this setting [33]. In the first case, collisions are accepted if the robot first comes to a stop, what corresponds to standard ISO norms for the safety of robots. In the second case, collisions are actively minimised by the robot, what gives significantly better results. In the third case, for the sake of completeness, the robot is allowed to fall in order to further avoid collisions. All three options were implemented with different formulations of lexicographic relaxation of the constraints in a standard MPC scheme for biped walking motion generation. This work raises important issues regarding safety norms for robots in human environments and how they are implemented.

6.13. Lexicographic Programming

Participants: Pierre-Brice Wieber, Alexander Sherikov, Dimitar Dimitrov, Adrien Escande.

Lexicographic Programming has proved to be a very valuable tool in the last few years for relaxing selectively various constraints and objectives in the control of complex systems such as biped humanoid robots. A major difficulty however is that solutions to such problems very often lie at singular points, making the convergence of standard Newton schemes difficult. We have shown this year how a trust region with filter method can help improve convergence, at least in simple situations [40].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- CIFRE PhD thesis (N. Akhadkar) with Schneider Electric.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

- SLOFADYBIO Slow-fast dynamics applied to the biosciences (january 2015 – december 2016), coordinateur: Mathieu Desroches (Inria Rocquencourt).

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. GEM

Title: from GEometry to Motion, inverse modeling of complex mechanical structures

Programm: H2020

Type: ERC

Duration: September 2015 - August 2020

Coordinator: Inria

Inria contact: Florence BERTAILS

With the considerable advance of automatic image-based capture in Computer Vision and Computer Graphics these latest years, it becomes now affordable to acquire quickly and precisely the full 3D geometry of many mechanical objects featuring intricate shapes. Yet, while more and more geometrical data get collected and shared among the communities, there is currently very little study about how to infer the underlying mechanical properties of the captured objects merely from their geometrical configurations. The GEM challenge consists in developing a non-invasive method for inferring the mechanical properties of complex objects from a minimal set of geometrical poses, in order to predict their dynamics. In contrast to classical inverse reconstruction methods, my proposal is built upon the claim that 1/ the mere geometrical shape of physical objects reveals a lot about their underlying mechanical properties and 2/ this property can be fully leveraged for a wide range of objects featuring rich geometrical configurations, such as slender structures subject to frictional contact (e.g., folded cloth or twined filaments). To achieve this goal, we shall develop an original inverse modeling strategy based upon a/ the design of reduced and high-order discrete models for slender mechanical structures including rods, plates and shells, b/ a compact and well-posed mathematical formulation of our nonsmooth inverse problems, both in the static and dynamic cases, c/ the design of robust and efficient numerical tools for solving such complex problems, and d/ a thorough experimental validation of our methods relying on the most recent capturing tools. In addition to significant advances in fast image-based measurement of diverse mechanical materials stemming from physics, biology, or manufacturing, this research is expected in the long run to ease considerably the design of physically realistic virtual worlds, as well as to boost the creation of dynamic human doubles.

8.2.1.2. COMANOID

Title: Multi-contact Collaborative Humanoids in Aircraft Manufacturing

Programm: H2020

Duration: January 2015 - December 2018

Coordinator: CNRS (Lirmm)

Partners:

Centre national de la recherche scientifique (France)

Deutsches Zentrum für Luft - und Raumfahrt Ev (Germany)

Airbus Groups (France)

Universita Degli Studi di Roma Lapienza (Italy)

Inria contact: Francois Chaumette

COMANOID investigates the deployment of robotic solutions in well-identified Airbus airliner assembly operations that are laborious or tedious for human workers and for which access is impossible for wheeled or rail-ported robotic platforms. As a solution to these constraints a humanoid robot is proposed to achieve the described tasks in real-use cases provided by Airbus Group. At a first glance, a humanoid robotic solution appears extremely risky, since the operations to be conducted are in highly constrained aircraft cavities with non-uniform (cargo) structures. Furthermore, these tight spaces are to be shared with human workers. Recent developments, however, in multi-contact planning and control suggest that this is a much more plausible solution than current alternatives such as a manipulator mounted on multi-legged base. Indeed, if humanoid robots can efficiently exploit their surroundings in order to support themselves during motion and manipulation, they can ensure balance and stability, move in non-gaited (acyclic) ways through narrow passages, and also increase operational forces by creating closed-kinematic chains. Bipedal robots are well suited to narrow environments specifically because they are able to perform manipulation using only small support areas. Moreover, the stability benefits of multi-legged robots that have larger support areas are largely lost when the manipulator must be brought close, or even beyond, the support borders. COMANOID aims at assessing clearly how far the state-of-the-art stands from such novel technologies. In particular the project focuses on implementing a real-world humanoid robotics solution using the best of research and innovation. The main challenge will be to integrate current scientific and technological advances including multi-contact planning and control; advanced visual-haptic servoing; perception and localization; human-robot safety and the operational efficiency of cobotics solutions in airliner manufacturing.

8.3. International Research Visitors

8.3.1. Visits to International Teams

8.3.1.1. Sabbatical programme

- Vincent Acary, Inria Chile from September 2014 to August 2016.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

- Guillaume James, Chairman of the Euromech Colloquium 580 “Strongly Nonlinear Dynamics and Acoustics of Granular Metamaterials”, 11 July-13 July 2016, Grenoble. http://580.euromech.org/

9.1.1.2. Member of the Organizing Committees

- Gilles Daviet, Alexandre Vieira, Jose Morales, Bernard Brogliato, members of local organization committee of the Euromech Colloquium 580 “Strongly Nonlinear Dynamics and Acoustics of Granular Metamaterials”, 11 July-13 July 2016, Grenoble. http://580.euromech.org/.

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

- Vincent Acary, member of ENOC (European Nonlinear Oscillations Conference) Committee.

- Florence Bertails-Descoubes, member of the ACM SIGGRAPH Asia 2016 Technical Program Committee.
- Pierre-Brice Wieber, Associate Editor for Humanoids 2016 and ICRA 2017.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- Bernard Brogliato, Associate Editor at Nonlinear Analysis: Hybrid Systems
- Bernard Brogliato, Associate Editor at ASME Journal of Computational and Nonlinear Dynamics
- Pierre-Brice Wieber, Associate Editor at IEEE Transactions on Robotics

9.1.3.2. Reviewer - Reviewing Activities

- Bernard Brogliato, reviewer for IEEE Transactions on Automatic Control, Multibody System Dynamics, SIAM Journal on Optimization and Control, European Journal of Mechanics A/Solids, Nonlinear Dynamics, ASME Journal of Computational and Nonlinear Dynamics.
- Florence Bertails-Descoubes, reviewer for ACM Transactions on Graphics, ACM SIGGRAPH, ACM SIGGRAPH Asia, Eurographics, Symposium on Computer Animation, Computer-Aided Design, Computer-Aided Geometric Design, International Journal of Solids and Structures.
- Arnaud Tonnelier, reviewer for Scientific Reports, SIADS, PRE, PhysicaD.
- Vincent Acary, reviewer for several journals in Mechanics and Automatic Control.

9.1.4. Invited Talks

- Bernard Brogliato, invited seminar at Mathematics Department, INSA de Lyon, 09 June 2016 (contact: A. Petrov).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master 1 : Florence Bertails-Descoubes, Module IRL (découverte recherche), supervision stage Mickaël Ly, ENSIMAG 2A (Grenoble INP)

9.2.2. Supervision

HdR : Vincent Acary, Analysis, simulation and control of nonsmooth dynamical systems, Université de Grenoble Alpes, 16 juillet 2015.

PhD : Narendra Akhadkar, Modélisation numérique des mécanismes. Influence des jeux, de la déformation et des impacts multiples, Université Grenoble-Alpes, CIFRE I-MEP2 avec Schneider-Electric, 25 avril 2016, Vincent Acary et Bernard Brogliato

PhD : Gilles Daviet, Modèles et Algorithmes pour la Simulation du Contact Frottant dans les Matériaux Complexes : Application aux Milieux Fibreux et Granulaires, Universite' Grenoble-Alpes, 15 décembre 2016, Florence Bertails-Descoubes.

PhD : José Eduardo Morales Morales, Ondes localisées dans des systèmes mécaniques discrets excitables, Universite' Grenoble-Alpes, 29 novembre 2016, Guillaume James et Arnaud Tonnelier

PhD in progress : Alexandre Vieira, Commande Optimale de Systèmes Linéaires de Complémentarité, 01 octobre 2015, Christophe Prieur et Bernard Brogliato.s/'e

PhD in progress : Alejandro Blumentals, Analyse et Simulation de Systèmes Mécaniques avec Contact Frottant, 01 octobre 2013, Florence Bertails-Descoubes et Bernard Brogliato.

PhD in progress: Nestor Bohorquez Dorante, Control of Biped Robots, 01 octobre 2015, Pierre-Brice Wieber.

PhD in progress: Nahuel Vila, Control of Biped Robots, 01 octobre 2016, Pierre-Brice Wieber.

9.2.3. Juries

- Bernard Brogliato, member of Habilitation à Diriger des Recherches committee of Constantin Irinel Morarescu, CRAN Nancy (MCF université de Nancy), 03 novembre 2016.
- Bernard Brogliato, member of Habilitation à Diriger des Recherches committee of Stéphane Redon, Inria Grenoble (CR Inria), 27 mai 2016.
- Bernard Brogliato, member of Ph.D. Thesis committee of T.L. Nguyen (15 janvier 2016), INSA de Rennes (directeurs de thèse M. Hjiaj and C. Sansour).
- Bernard Brogliato, member of Ph.D. Thesis committee of O. Montano (20 mai 2016), CICESE Ensenada, Mexico (directeur de thèse Y. Orlov).
- Arnaud Tonnelier, member of Ph.D. Thesis committee of Catalina Vich Llompart (août 2016), Universitat de les Illes Balears (directeurs de thèse : Antoni Guillamon Grabolosa (UPC) and Dr. Prohens Rafel Sastre (UIB)).
- Arnaud Tonnelier, member of Ph.D. Thesis committee of Elif Köksal Ersöz (décembre 2016), Université Pierre et Marie Curie (directeurs de thèse: F. Clement et J.P. Françoise).

9.3. Popularization

- Modélisation de matériaux granulaires (Florence Bertails-Descoubes, Gilles Daviet) : participation à l'écriture d'un article court pour le CNRS, "Représenter du sable sans poudre aux yeux", http://www.cnrs.fr/ins2i/spip.php?article2175

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Team CHROMA

Cooperative and Human-aware Robot Navigation in Dynamic Environments

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Robotics and Smart environments

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Team CHROMA

Creation of the Team: 2015 March 01

Keywords:

Computer Science and Digital Science:

1.5.2. - Communicating systems
5.1. - Human-Computer Interaction
5.10.2. - Perception
5.10.3. - Planning
5.10.5. - Robot interaction (with the environment, humans, other robots)
5.10.6. - Swarm robotics
5.10.7. - Learning
5.11.1. - Human activity analysis and recognition
6.1.3. - Discrete Modeling (multi-agent, people centered)
6.2.3. - Probabilistic methods
6.2.6. - Optimization
6.4.3. - Observability and Controlability
7.3. - Optimization
7.14. - Game Theory
8.2. - Machine learning
8.5. - Robotics
8.6. - Decision support
8.7. - AI algorithmics

Other Research Topics and Application Domains:

5.2.1. - Road vehicles
5.6. - Robotic systems
7.1.2. - Road traffic
8.4. - Security and personal assistance

1. Members

Research Scientists

Christian Laugier [Inria, Senior Researcher, HDR]
Agostino Martinelli [Inria, Researcher]

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Jilles Dibangoye [INSA Lyon, Associate Professor]
Laetitia Matignon [Univ. Lyon I, Associate Professor, from Sep 2016]
Fabrice Jumel [CPE Lyon, Associate Professor]
Jacques Saraydaryan [CPE Lyon, Associate Professor]

Technical Staff

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Stephane d'Alu [INSA Lyon, Research Engineer, from Sept 2016]
Julia Chartre [Inria, until Nov 2016]
Jean-Alix David [Inria]
Guillaume Fortier [Inria, until Jun 2016]
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Lukas Rummelhard [Inria]

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Stefan Chitic [INSA Lyon]
Mihai-Ioan Popescu [Région/INSA Lyon]
Tiana Rakotovao Andriamahefa [CEA]
David Sierra Gonzalez [Inria/Toyota]
Pavan Vasishta [Inria, from Feb 2016]

Post-Doctoral Fellow

Victor Romero Cano [Inria, from Apr 2016]

Administrative Assistant

Marina Da Graca [Inria]

Others

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Simon Bultmann [INSA Lyon, Student trainee, from Feb 2016 until Jun 2016]
Ahmed Yahia Trad [INSA Lyon, Student trainee, from Feb 2016 until Jun 2016]

2. Overall Objectives

2.1. Origin of the project

The Chroma group was created in the beginning of year 2015 (March). It regroups researchers who address perception and decision-making issues in mobile robotics and who share common approaches that mainly relates to the field of artificial intelligence. The group is gathering some members of the previous eMotion Inria project-team led by Christian Laugier (2002-2014) and of teacher-researchers from INSA [0][0] Lyon working in the robotic group led by Prof. Olivier Simonin in CITI Lab. [0] (since 2013). The team is distributed on two sites : the Centre Inria Grenoble and the INSA Lyon campus.

The Chroma group was initially composed of Olivier Simonin (Prof. INSA Lyon), Christian Laugier (Inria researcher DR1), Jilles Dibangoye (Asso. Prof. INSA Lyon), Agostino Martinelli (Inria researcher CR1) and Dizan Vasquez (Inria starting researcher SRP). On December 1, 2015, Anne Spalanzani (Asso. Prof. Univ. Grenoble, habilite) has joined the group (she was previously in Prima and eMotion Inria teams). In January 2016, Dizan Vasquez has left the group to join the Apple company.

2.2. Overall Objectives

The overall objective of Chroma team is to address fundamental and open issues that lie at the intersection of the emerging research fields called “Human Centered Robotics” [0] and “Multi-Robot Systems (MRS) [0]"

[0] National Institute of Applied Sciences
[0] INSA Lyon is part of the Université de Lyon
[0] Centre of Innovation in Telecommunications and Integration of Service, see http://www.citi-lab.fr/
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[0] IEEE RAS Multi-Robot Systems http://multirobotsystems.org/

More precisely, our goal is to design algorithms and develop models allowing mobile robots to navigate and cooperate in dynamic and human-populated environments. Chroma is involved in all decision aspects pertaining to single and multi robot navigation tasks, including perception and motion-planning.

The general objective is to build robotic behaviors that allow one or several robots to operate safely among humans in partially known environments, where time, dynamics and interactions play a major role. Recent advances on embedded computational power, on sensor and communication technologies, and on miniaturized mechatronic systems, make the required technological breakthroughs possible (including from the scalability point of view).

Chroma is clearly positioned in the third challenge of the **Inria 2013-2017 Strategic Plan "Interacting with the real and digital worlds: interaction, uses and learning"**.

2.3. Research themes

Our approach for addressing the previous challenge is to bring together probabilistic methods, planning techniques and multi-agent decision models. This will be done in cooperation with other disciplines such as sociology for the purpose of taking into account human models. Two main research themes of mobile robotics are addressed : i) Perception and situation awareness ii) Navigation and Cooperation in Dynamic Environments. Next, we elaborate more about these two research axes.

- **Perception and Situation Awareness.** The main problem is to understand complex dynamic scenes involving mobile objects and human beings, by exploiting prior knowledge and a stream of perceptual data coming from various sensors. Our approach for solving this problem is to develop three complementary problem domains:
  - **Bayesian Perception**: How to take into account prior knowledge and uncertain sensory data in a dynamic context?
  - **Situation awareness** : How to interpret the perceived scene and to predict their likely future motion (including near future collision risk) ?
  - **Robust state estimation**: acquire a deep understanding on several sensor fusion problems and investigate their observability properties in the case of unknown inputs.
- **Navigation and Cooperation in Dynamic Environments.** The challenge is to build models allowing robots to move and to coordinate efficiently in dynamic environments. We focus on two problems : navigation in human-populated environment (social navigation) and cooperation in large distributed fleet of robots (scalability and robustness issues).
  - **Motion-planning in human-populated environment.** How to plan trajectories that take into account the uncertainty of human-populated environments and that can respect the social rules of humans ? Such a challenge requires human behavior models, or to learn them, and planning algorithms that take into account them.
  - **Decision Making in Multi-robot systems.** The goal of this axis is to develop models and algorithms that provide both scalability and performance guarantees in real-world robotic systems. Our methodology builds upon complementary advantages of two orthogonal approaches, Multi-Agent Sequential Decision Making (MA-SDM) and Swarm Intelligence (SI).

The Chroma project is also concerned with applications and transfer of the scientific results. Our main application domains concern autonomous connected vehicles and service robotics. They are presented in Sections 4.2 and 4.3. Chroma have currently projects developed with industrial (as Renault and Toyota) and startup partners.

3. Research Program

3.1. Introduction

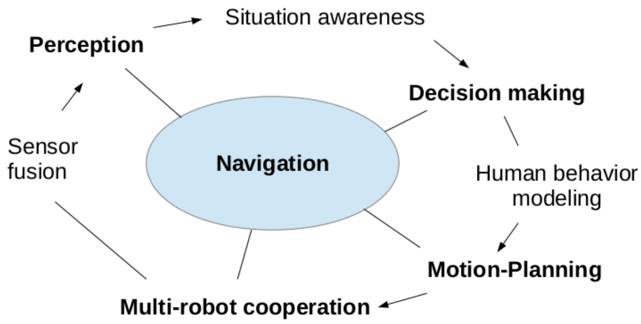

Figure 1. Research themes of the team and their relation

The Chroma team aims to deal with different issues of autonomous mobile robotics : perception, decision-making and cooperation. Figure 1 schemes the different themes and sub-themes investigated by Chroma.

We present here after our approaches to address these different theme of research, and how they combine to contribute to the general problem of robotic navigation. Chroma pays particular attention to current challenges that are autonomous navigation in highly dynamic environments populated by humans and cooperation in (large) multi-robot systems. These challenges are common with other major robotic laboratories/teams in the world, such as Autonomous Systems Lab at ETH Zurich, Robotic Embedded Systems Laboratory at USC, KIT [0] (Prof Christoph Stiller lab and Prof Ruediger Dillmann lab), UC Berkeley, Vislab Parma (Prof. Alberto Broggi), iCeiRA [0] laboratory in Taipei. Chroma is collaborating at various levels (visits, postdocs, research projects, common publications, etc.) with most of these laboratories, see Sections 9.3 and 9.4.

3.2. Perception and Situation Awareness

Participants: Christian Laugier, Agostino Martinelli, Jilles S. Dibangoye, Anne Spalanzani, Olivier Simonin.

Robust perception in open and dynamic environments populated by human beings is an open and challenging scientific problem. Traditional perception techniques do not provide an adequate solution for these problems, mainly because such environments are uncontrolled [0] and exhibit strong constraints to be satisfied (in particular high dynamicity and uncertainty). This means that **the proposed solutions have to simultaneously take into account characteristics such as real time processing, temporary occultations, dynamic changes or motion predictions**.

3.2.1. Bayesian perception

Context and previous work. Perception is known to be one of the main bottleneck for robot motion autonomy, in particular when navigating in open and dynamic environments is subject to strong real-time and uncertainty constraints. Traditional object-level solutions [0] still exhibit a lack of efficiency and of robustness when operating in such complex environments. In order to overcome this difficulty, we have proposed in the scope of the former e-Motion team, a new paradigm in robotics called “Bayesian Perception”. The foundation of this approach relies on the concept of “Bayesian Occupancy Filter (BOF)” initially proposed in the PhD thesis of Christophe Coué [42] and further developed in the team [58] [0].

[0] Karlsruhe Institut fur Technologie
[0] International Center of Excellence in Intelligent Robotics and Automation Research.
[0] partially unknown and open
[0] object recognition based on image processing
[0] The *Bayesian programming formalism* developed in e-Motion, pioneered (together with the contemporary work of Thrun, Burgards and Fox [94]) a systematic effort to formalize robotics problems under Probability theory –an approach that is now pervasive in Robotics.

Figure 2. Illustrations of the HSBOF model and experiment with the Zoe car

The basic idea is to combine a Bayesian filter with a probabilistic grid representation of both the space and the motions, see illustration Fig. 2. This new approach can be seen as an extension for uncertain dynamic scenes, of the initial concept of "Occupancy Grid" proposed in 1989 by Elfes [0]. It allows the filtering and the fusion of heterogeneous and uncertain sensors data, by taking into account the history of the sensors measurements, a probabilistic model of the sensors and of the uncertainty, and a dynamic model of the observed objects motions.

In the scope of the Chroma team and of several academic and industrial projects, we went on with the development and the extension under strong embedded implementation constraints, of our Bayesian Perception concept. This work has already led to the development of more powerful models and more efficient implementations, e.g. the *HSBOF*[0] approach [76] and the *CMCDOT*[0] framework [84] which is still under development.

Current and future work address the extension of this model and its software implementation.

Objective — Extending the Bayesian Perception paradigm to the object level — We aim at defining a complete framework extending the Bayesian Perception paradigm to the object level. The main objective is to be simultaneously more robust, more efficient for embedded implementations, and more informative for the subsequent scene interpretation step.

We propose to integrate in a robust way higher level functions such as multiple objects detection and tracking or objects classification. The idea is to avoid well known object level detection errors and data association problems, by simultaneously reasoning at the *grid level* and at the *object level* by extracting / identifying / tracking / classifying clusters of dynamic cells (first work has been published in [84]).

Software development : new approaches for software / hardware integration The objective is to improve the efficiency of the approach (by exploiting the highly parallel characteristic of our approach), while drastically reducing important factors such as the required memory size, the size of the hardware component, its price and the required energy consumption. This work is absolutely necessary for studying *embedded solutions* for the future generation of mobile robots and autonomous vehicles.

3.2.2. Situation Awareness and Prediction

Context. Prediction of the evolution of the perceived actors is an important ability required for navigation in dynamic and uncertain environments, in particular to allow on-line safe decisions. We have recently shown that an interesting property of the Bayesian Perception approach is to generate short-term conservative [0] predictions on the likely future evolution of the observed scene, even if the sensing information is temporary incomplete or not available [76]. But in human populated environments, estimating more abstract properties (e.g. object classes, affordances, agents intentions) is also crucial to understand the future evolution of the scene.

[0] A. Elfes."Occupancy grids: A probabilistic framework for robot perception and navigation", Ph.D. dissertation, Carnegie Mellon University, Pittsburgh, USA, 1989.
[0] Hybrid Sampling Bayesian Occupancy Filter
[0] Conditional Monte Carlo Dense Occupancy Tracker
[0] i.e. when motion parameters are supposed to be stable during a small amount of time

Objective We aim to develop an integrated approach for "Situation Awareness & Risk Assessment" in complex dynamic scenes involving multiples moving agents (e.g vehicles, cyclists, pedestrians ...), whose behaviors are most of the time unknown but predictable.

Our approach relies on combining machine learning to build a model of the agent behaviors and generic motion prediction techniques (Kalman-based, GHMM [98], Gaussian Processes [92]). A strong challenge of prediction in multiple moving agents environments is to take into consideration the interactions between the different agents (traffic participants). Existing interaction-aware approaches estimate exhaustively the intent of all road users [59], assume a cooperative behavior [88], or learn the policy model of drivers using supervised learning [50]. In contrast, we adopt a *planning-based motion prediction approach*, which is a framework to predict human behavior [102], [56][27]. Planning-based approaches assume that humans, when they perform a task, they do so by minimizing a cost function that depends on their preferences and the context. Such a cost function can be obtained, for example, from demonstrations using *Inverse Reinforcement Learning* [75], [36]. This constitutes an intuitive approach and, more importantly, enables us to overcome the limitations of other approaches, namely, high complexity [59], unrealistic assumptions [88], and overfitting [50]. We have recently demonstrated the predictive potential of our approach in [26].

Towards an On-line Bayesian Decision-Making framework. The team aims at building a general framework for perception and decision-making in multi-robot/vehicle environments. The navigation will be performed under both dynamic and uncertainty constraints, with contextual information and a continuous analysis of the evolution of the probabilistic collision risk (see above). Results have recently been obtained in cooperation with Renault and Berkeley, by using the "Intention / Expectation" paradigm and Dynamic Bayesian Networks; these results have been published in [60], [61] and patented.

We are currently working on the generalization of this approach, in order to take into account the dynamics of the vehicles and multiple traffic participants. The objective is to design a new framework, allowing to overcome the shortcomings of rules-based reasoning approaches usually showing good results [64] [49], but leading to a lack of scalability and long terms predictions. Our research work is carried out through several cooperative projects (Toyota, Renault, project Prefect of IRT Nanoelec, European project ECSEL Enable-S3) and related PhD theses.

3.2.3. Robust state estimation (Sensor fusion)

Context. In order to safely and autonomously navigate in an unknown environment, a mobile robot is required to estimate in real time several physical quantities (e.g., position, orientation, speed). These physical quantities are often included in a common state vector and their simultaneous estimation is usually achieved by fusing the information coming from several sensors (e.g., camera, laser range finder, inertial sensors). The problem of fusing the information coming from different sensors is known as the *Sensor Fusion* problem and it is a fundamental problem which plays a major role in robotics.

Objective. A fundamental issue to be investigated in any sensor fusion problem is to understand whether the state is observable or not. Roughly speaking, we need to understand if the information contained in the measurements provided by all the sensors allows us to carry out the estimation of the state. If the state is not observable, we need to detect a new observable state. This is a fundamental step in order to properly define the state to be estimated. To achieve this goal, we apply standard analytic tools developed in control theory together with some new theoretical concepts we introduced in [68] (concept of continuous symmetry). Additionally, we want to account the presence of disturbances in the observability analysis.

Our approach is to introduce general analytic tools able to derive the observability properties in the nonlinear case when some of the system inputs are unknown (and act as disturbances). We recently obtained a simple analytic tool able to account the presence of unknown inputs [71], which extends a heuristic solution derived by the team of Prof. Antonio Bicchi [40] with whom we collaborate (Centro Piaggio at the University of Pisa).

Fusing visual and inertial data. A special attention is devoted to the fusion of inertial and monocular vision sensors (which have strong application for instance in UAV navigation). The problem of fusing visual and inertial data has been extensively investigated in the past. However, most of the proposed methods require a state initialization. Because of the system nonlinearities, lack of precise initialization can irreparably damage the entire estimation process. In literature, this initialization is often guessed or assumed to be known [38], [63], [46]. Recently, this sensor fusion problem has been successfully addressed by enforcing observability constraints [51], [52] and by using optimization-based approaches [62], [45], [66], [53], [74]. These optimization methods outperform filter-based algorithms in terms of accuracy due to their capability of relinearizing past states. On the other hand, the optimization process can be affected by the presence of local minima. We are therefore interested in a deterministic solution that analytically expresses the state in terms of the measurements provided by the sensors during a short time-interval.

For some years we explore deterministic solutions as presented in [69] and [70]. Our objective is to improve the approach by taking into account the biases that affect low-cost inertial sensors (both gyroscopes and accelerometers) and to exploit the power of this solution for real applications. This work is currently supported by the ANR project VIMAD [0] and experimented with a quadrotor UAV. We have a collaboration with Prof. Stergios Roumeliotis (the leader of the MARS lab at the University of Minnesota) and with Prof. Anastasios Mourikis from the University of California Riverside. Regarding the usage of our solution for real applications we have a collaboration with Prof. Davide Scaramuzza (the leader of the Robotics and Perception group at the University of Zurich) and with Prof. Roland Siegwart from the ETHZ.

3.3. Navigation and cooperation in dynamic environments

Participants: Olivier Simonin, Anne Spalanzani, Jilles S. Dibangoye, Christian Laugier, Laetitia Matignon, Fabrice Jumel, Jacques Saraydaryan.

In his reference book *Planning algorithms*[0] S. LaValle discusses the different dimensions that made the motion-planning problem complex, which are the number of robots, the obstacle region, the uncertainty of perception and action, and the allowable velocities. In particular, it is emphasized that complete algorithms require at least exponential time to deal with multiple robot planning in complex environments, preventing them to be scalable in practice (p. 320). Moreover, dynamic and uncertain environments, as human-populated ones, expand this complexity.

In this context, we aim at **scale up decision-making in human-populated environments and in multi-robot systems, while dealing with the intrinsic limits of the robots (computation capacity, limited communication)**.

3.3.1. Motion-planning in human-populated environment

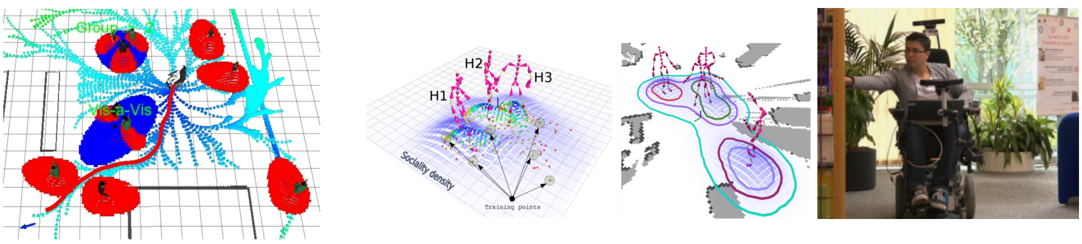

Figure 3. Illustrations of a. the Risk-RRT planning b. the human interaction space model c. experiment with the wheelchair.

[0]Navigation autonome des drones aériens avec la fusion des données visuelles et inertielles, lead by A. Martinelli, Chroma.
[0]Steven M. LaValle, Planning Algorithms, Cambridge University Press, 2006.

Context. Motion planning in dynamic and human-populated environments is a current challenge of robotics. Many research teams work on this topic. We can cite the Institut of robotic in Barcelone [44], the MIT [37], the Autonomous Intelligent Systems lab in Freiburg [41], or the LAAS [77]. In Chroma, we explore different issues : **integrating the risk (uncertainty) in planning processes, modeling and taking into account human behaviors and flows.**

Objective We aim to give the robot some socially compliant behaviors by anticipating the near future (trajectories of mobile obstacle in the robot's surroundings) and by integrating knowledge from psychology, sociology and urban planning. In this context, we will focus on the following 3 topics.

Risk-based planning. Unlike static or controlled environments [0] where global path planning approaches are suitable, dealing with highly dynamic and uncertain environments requires to integrate the notion of risk (risk of collision, risk of disturbance). This risk can be computed by methods proposed in the section 3.2.2. Then, we examine how motion planning approaches can integrate this risk in the generation and selection of the paths. An algorithm called RiskRRT was proposed in the eMotion team. This algorithm plans goal oriented trajectories that minimize the risk estimated at each instant. It fits environments that are highly dynamic and adapts to a representation of uncertainty [90] (see Figure 3.a for illustration). Now, we aim to extend this principle to be adapted to various risk evaluation methods (proposed in 3.2) and various situation (highways, urban environments, even in dense traffic or in crowds).

Sharing the physical space with humans. Robots are expected to share their physical space with humans. Hence, robots need to take into account the presence of humans and to behave in a socially acceptable way. Their trajectories must be safe but also predictable, that is why they must follow social conventions, respecting proximity constraints, avoiding people interacting or joining a group engaged in conversation without disturbing. For this purpose, we proposed earlier to integrate some knowledge from the psychology domain (i.e. proxemics theory), see figure 3.b. We aim now to integrate semantic knowledge [0] and psycho-social theories of human behavior [00] in the navigation framework we have developed for a few years (i.e. the Risk-based navigation algorithms [48], [90], [97]). These concepts were tested on our automated wheelchair (see figure 3.c) but they have and will be adapted to autonomous cars, telepresence robots and companion robots. This work is currently supported by the ANR Valet, the TENSIVE project and the Associated team Sampen (with Iceira Lab, Taipei).

Mapping human flows. We investigate the problem of modeling recurring human displacements to improve robots navigation in such dense populated environments. It has been shown that such recurring behaviours can be mapped from spatial-temporal observations, as in [95]. In this context we address the problem of mapping human flows from robot(s) perception. We started to propose counting-based mapping models [30] that contain motion probabilities in the grid cells. Then such a grid can be exploited to define path-planning functions (eg. A* based) that take into account the probability to encounter humans in opposite direction. We also aim at demonstrating the efficiency of the approach whith real robots evolving in dense human-populated environments.

3.3.2. Decision Making in Multi-robot systems

Context. A central challenge in Chroma is to define **decision-making algorithms that scale up to large multi-robot systems**. This work takes place in the general framework of Multi-Agent Systems (MAS). The objective is to compute/define agent behaviors that provide cooperation and adaptation abilities. Solutions must also take into account the agent/robot computational limits.

We can abstract the challenge in three objectives :
i) mastering the complexity of large fleet of robots/vehicles (scalability),

[0] known environment without uncertainty
[0] B. Kuipers, The Spatial Semantic Hierarchy, Artificial Intelligence, Volume 119, Issues 1–2, May 2000, Pages 191-233
[0] Gibson, J. (1977). The theory of affordances, in Perceiving, Acting, and Knowing. Towards an Ecological Psychology. Number eds Shaw R., Bransford J. Hoboken,NJ: John Wiley & Sons Inc.
[0] Hall, E. (1966). The hidden dimension. Doubleday Anchor Books.

ii) dealing with limited computational/memory capacity
iii) building adaptive solutions (robustness).

Combining Decision-theoretic models and Swarm intelligence.

Over the past few years, our attempts to address multi-robot decision-making are mainly due to Multi-Agent Sequential Decision Making (MA-SDM) and Swarm Intelligence (SI). MA-SDM builds upon well-known decision-theoretic models (e.g., Markov decision processes and games) and related algorithms, that come with strong theoretical guarantees. In contrast, the expressiveness of MA-SDM models has limited scalability in face of realistic multi-robot systems [0], resulting in computational overload. On their side, SI methods, which rely on local rules – generally bio-inspired – and relating to Self-Organized Systems [0], can scale up to multiple robots and provide robustness to disturbances, but with poor theoretical guarantees [0]. Swarm models can also answer to the need of designing tractable solutions [89], but they remain not geared to express complex realistic tasks or to handle (point-to-point) communication between robots. This motivates our work to go beyond these two approaches and to combine them.

First, we plan to investigate **incremental expansion mechanisms in anytime decision-theoretic planning**, starting from local rules (from SI) to complex strategies with performance guarantees (from MA-SDM) [43]. This methodology is grounded into our research on anytime algorithms, that are guaranteed to stop at anytime while still providing a reliable solution to the original problem. It further relies on decision theoretical models and tools including: Decentralized and Partially Observable Markov Decision Processes and Games, Dynamic Programming, Distributed Reinforcement Learning and Statistical Machine Learning.

Second, we plan to extend the SI approach by considering **the integration of optimization techniques at the local level**. The purpose is to force the system to explore solutions around the current stabilized state – potentially a local optimum – of the system. We aim at keeping scalability and self-organization properties by not compromising the decentralized nature of such systems. Introducing optimization in this way requires to measure locally the performances, which is generally possible from local perception of robots (or using learning techniques). The main optimization methods we will consider are Local Search (Gradient Descent), Distributed Stochastic Algorithm and Reinforcement Learning. We have shown in [96] the interest of such an approach for driverless vehicle traffic optimization. In 2016, we started a new PHD in collaboration with the VOLVO Group to deal with global-local optimization for goods distribution using a fleet of autonomous vehicles.

Both approaches must lead to **master the complexity** inherent to large and open multi-robot systems. Such systems are prone to combinatorial problems, in term of state space and communication, when the number of robots grows. To cope with this complexity we started to develop a methodology which relies on incrementally refining the environment representation while the robots perform their tasks.

Mastering the computational cost involved in cooperative decision-making relies also on building heuristics. We explore how exact (global) solutions can be decentralized in local computation allocated to group of robots or to each robot. We started to apply this methodology to dynamic problems such as the patrolling of moving persons (see [87]).

Beyond this methodological work, we aim to evaluate our models on benchmarks from the literature, by using simulation tools as a complement of robotic experiments. This will lead us to develop simulators, allowing to deploy thousands of humans and robots in constrained environments.

Towards adaptive connected robots.

[0] Martin L. Puterman, Markov Decision Processes; Stuart Russell and Peter Norvig, Artificial Intelligence - A Modern Approach
[0] D. Floreano and C. Mattiussi, Bio-Inspired Artificial Intelligence - Theories, Methods, and Technologies, MIT Press, 2008.
[0] S. A. Brueckner, G. Di Marzo Serugendo, A. Karageorgos, R. Nagpal (2005). Engineering Self-Organising Systems, Methodologies and Applications. LNAI 3464 State-of-the-Art Survey, Springer book.

Mobile robots and autonomous vehicles are becoming more connected to one another and to other devices in the environment (concept of cloud of robots [0] and V2V/V2I connectivity in transportation systems). Such robotic systems are open systems as the number of connected entities is varying dynamically. Network of robots brought with them new problems, as the need of (online) adaption to changes in the system and to the variability of the communication.

In Chroma, we address the problem of adaptation by considering machine learning techniques and local mechanisms as discussed above (SI models). More specifically we investigate the problem of maintaining the connectivity between robots which perform dynamic version of tasks such as patrolling, exploration or transportation, i.e. where the setting of the problem is constinuously changing and growing (see [25]).

Robot fleets should be able to adapt their behavior and organisation to communication limits and variation. It has been shown that wireless communication are very changing in time and space [65]. So we explore how robots can optimize their behaviors by perceiving and learning the quality of their communication in the environment. In Lyon, the CITI Lab. conducts research in many aspects of telecommunication, from signal theory to distributed computation. In this context, Chroma develops cooperations with the Inria team Urbanet [25] (wireless communication protocols) and with the Dynamid team [19] (middlleware and cloud aspects), that we wish to reinforce in the next years.

4. Application Domains

4.1. Introduction

Applications in Chroma are organized in two main domains : **i) Future cars and transportation systems and ii) Services robotics.** These domains correspond to the experimental fields initiated in Grenoble (eMotion team) and in Lyon (CITI lab). However, the scientific objectives described in the previous sections are intended to apply equally to both applicative domains. Even our work on Bayesian Perception is today applied to the intelligent vehicle domain, we aim to generalize to any mobile robots. The same remark applies to the work on multi-agent decision making. We aim to apply algorithms to any fleet of mobile robots (service robots, connected vehicles, UAVs). This is the philosophy of the team since its creation.

Figure 4. Most of the Chroma platforms: the Pepper robot, a fleet of (22) Turtlebot 2, one of the 4 Bebop drones and the equipped Toyota Lexus.

4.2. Future cars and transportation systems

Thanks to the introduction of new sensor and ICT technologies in cars and in mass transportation systems, and also to the pressure of economical and security requirements of our modern society, this application domain is quickly changing. Various technologies are currently developed by both research and industrial

[0] see for instance the first International Workshop on Cloud and Robotics, 2016.

laboratories. These technologies are progressively arriving at maturity, as it is witnessed by the results of large scale experiments and challenges such as the Google's car project and several future products announcements made by the car industry. Moreover, the legal issue starts to be addressed in USA (see for instance the recent laws in Nevada and in California authorizing autonomous vehicles on roads) and in several other countries (including France).

In this context, we are interested in the development of ADAS [0] systems aimed at improving comfort and safety of the cars users (e.g., ACC, emergency braking, danger warnings), and of Fully Autonomous Driving functions for controlling the displacements of private or public vehicles in some particular driving situations and/or in some equipped areas (e.g., automated car parks or captive fleets in downtown centers or private sites).

Since about 8 years, we are collaborating with Toyota and with Renault-Nissan on these applications (bilateral contracts, PhD Theses, shared patents), but also recently with Volvo group (PhD thesis started in 2016). We are also strongly involved (since 2012) in the innovation project Perfect of the IRT [0] Nanoelec (transportation domain). In 2016, we have been awarded a European H2020 ECSEL project [0] involving major European automotive constructors and car suppliers. In this project, Chroma is focusing on the embedded perception component (models and algorithms, including the certification issue), in collaboration with Renault, Valeo and also with the Inria team TAMIS (Rennes). Chroma is also involved in the ANR project "Valet" (2015-2018) coordinated by the Inria team RITS (Rocquencourt), dealing with automatic redistribution of car-sharing vehicles and parking valet; Chroma is involved in the pedestrian-vehicle interaction for a safe navigation.

In this context, Chroma has two experimental vehicles equipped with various sensors (a Toyota Lexus and a Renault Zoe, see. Fig. 4 and Fig. 2), which are maintained by Inria-SED [0] and that allow the team to perform experiments in realistic traffic conditions (Urban, road and highway environments). The Zoe car will be automated in December 2016 through our collaboration with the team of P. Martinet (IRCCyN Lab, Nantes) that will open us to new experiments and work.

4.3. Services robotics

Service robotics is an application domain quickly emerging, and more and more industrial companies (e.g., IS-Robotics, Samsung, LG) are now commercializing service and intervention robotics products such as vacuum cleaner robots, drones for civil or military applications, entertainment robots ... One of the main challenges is to propose robots which are sufficiently robust and autonomous, easily usable by non-specialists, and marked at a reasonable cost. We are involved in developing observation and surveillance systems, by using ground robots (Turtlebot fleet) or aerial ones (ANR VIMAD [0]), see Fig. 4.

A more recent challenge for the coming decade is to develop robotized systems for assisting elderly and/or disabled people. In the continuity of our work in the IPL PAL [0], we aim to propose smart technologies to assist electric wheelchair users in their displacements (see Figure 2 for illustration). We address the problem of assisting the user for joining a group of people and navigating in crowded environments, in cooperation with Inria Lagadic team (Rennes).

Another emerging application to assist people is telepresence robot. In 2016 we started the TENSIVE project, funded by the Region, with the team of G. Bailly from GIPSA Lab (Grenoble) and with the Awabot and Hoomano companies (in Lyon). The project aims to improve the driving of such robots by providing a social and autonomous navigation (PhD of R. Cambuzat). Moreover, the project is supported by INSA-CITI Lab. through the acquisition of a Pepper robot (see Fig. 4).

[0] Advanced Driver Assistance Systems
[0] Institut de Recherche Technologique
[0] ENABLE-S3: European Initiative to Enable Validation for Highly Automated Safe and Secure Systems.
[0] Service Expérimentation et Développement
[0] Navigation autonome des drones aériens avec la fusion des données visuelles et inertielles, lead by A. Martinelli, Chroma.
[0] Personnaly assisted Living

5. Highlights of the Year

5.1. Highlights of the Year

- Laetitia Matignon, Associate Professor at Université de Lyon and LIRIS Lab has obtained an Inria delegation to join the Chroma team (half-time).
- Stephane d'Alu, research engineer at CITI lab., has joinded the team for one year, half-time.
- Christian Laugier is a co-author with A. Broggi, A. Zelinski and U. Ozguner, of the chapter "Intelligent Vehicles" of the 2nd edition of the "Hanbook of Robotics" edited by B. Sicilano and O. Khatib and published in July 2016.
- A new collaboration has been built with the team of Gabriella Czibula, from University of Babes-Bolyai in Cluj-Napoca, Romania. We obtained a bilateral french-romanian PHC project, called DRONEM, to support the collaboration for the period 2017-2018.
- A new collaboration has been built with the Volvo Group in Lyon, through the co-supervision of the PhD thesis of Guillaume Bono funded by the INSA-Volvo Chair.
- A new collaboration has been built with the GIPSA Lab in Grenoble and the team of Gerard Bailly (CNRS), through the co-supervision of the PhD thesis of Remi Cambuzat funded by the Region.
- The Chroma team has been reconducted for 2017 as a Nvidia CUDA lab, for his work related to "embedded perception and autonomous vehicles".
- A new Research contract on "robust sensor fusion involving vision data" has been signed with Toyota Motor Europe in 2016. The results have been patented by Inria and Toyota.
- The results obtained in the scope of the Research contract on "autonomous driving" have been patented by Inria, Insa and Toyota.
- Acquisition of a Pepper robot, funded by INSA de Lyon and CITI-Inria lab., and acquisition of 4 Crazyflies robots, funded by the CITI lab.

5.1.1. Awards

- Christian Laugier was awarded IROS Fellow at IROS 2016 and recieved the IROS Distinguished Award citation for his Outstanding Services to IROS Advisory/Steering Committee and IROS Conferences.

6. New Software and Platforms

6.1. CUDA-HSBOF

FUNCTIONAL DESCRIPTION

This software implements the HSBOF (Hybrid Sampling Bayesian Occupancy Filter) on GPU. It facilitates the integration of the model in an embedded chip.

- Participants: Lukas Rummelhard, Christian Laugier and Amaury Nègre
- Contact: Christian Laugier

6.2. DATMO (Detection and Tracking of Moving Objects)

FUNCTIONAL DESCRIPTION

This software is developped in the context of the autonomous driving assistance. It allows to detect, to track, and to classify mobile objects from LIDAR and mono-camera data. It can be linked or not with our previous implementation of the HSBOF software. The software is divided in 4 modules : Fusion, Detection, Tracking and Classification.

- Authors: Trong Tuan Vu and Christian Laugier
- Contact: Christian Laugier

6.3. E.R.C.I.

Estimation of collision risks at road intersections

- Participants: Stéphanie Lefevre, Christian Laugier and Javier Ibanez-Guzman
- Contact: Christian Laugier

6.4. Embedded Perception

FUNCTIONAL DESCRIPTION

The method for computing occupancy grids from a stereoscopic sensor, developped in the e-motion team, has been implemented on GPU, using NVIDIA CUDA. This allows a real time implementation and an online processing within the Lexus experimental platform.

- Participants: Amaury Nègre, Christian Laugier and Mathias Perrollaz
- Contact: Christian Laugier

6.5. GPU BOF

Bayesian Occupancy Filter on GPU
FUNCTIONAL DESCRIPTION

This software is an implementation of the Occupancy Bayesian Filter (BOF) on GPU.

- Participants: Yong Mao, Christian Laugier, Amaury Nègre and Mathias Perrollaz
- Contact: Christian Laugier

6.6. GPU Stro Occupancy Grid

GPU Stereo Occupancy Grid

- Participants: Amaury Nègre and Mathias Perrollaz
- Contact: Christian Laugier

6.7. VI-SFM

FUNCTIONAL DESCRIPTION

Software in C++ for estimation based on the closed form solution

- Authors: Guillaume Fortier and Agostino Martinelli
- Contact: Agostino Martinelli

6.8. kinetics

FUNCTIONAL DESCRIPTION

Software computing decision support strategies and decision-making

- Contact: Jilles Dibangoye

7. New Results

7.1. Bayesian Perception

Participants: Christian Laugier, Lukas Rummelhard, Amaury Nègre [Gipsa Lab since June 2016], Jean-Alix David, Julia Chartre, Jerome Lussereau, Tiana Rakotovao, Nicolas Turro [SED], Jean-François Cuniberto [SED], Diego Puschini [CEA DACLE], Julien Mottin [CEA DACLE].

7.1.1. Conditional Monte Carlo Dense Occupancy Tracker (CMCDOT)

Participants: Lukas Rummelhard, Amaury Nègre, Christian Laugier.

The research work on *Bayesian Perception* has been done as a continuation and an extension of some previous research results obtained in the scope of the former Inria team-project e-Motion and of the more recent developments done in 2015 in the scope of the Chroma team. This work exploits the *Bayesian Occupancy Filter (BOF)* paradigm [42], developed and patented by the team several years ago [0]. It also extends the more recent concept of *Hybrid Sampling BOF (HSBOF)* [76], whose purpose was to adapt the concept to highly dynamic scenes and to analyze the scene through a static-dynamic duality. In this new approach, the static part is represented using an occupancy grid structure, and the dynamic part (motion field) is modeled using moving particles. The *HSBOF* software has been implemented and tested on our experimental platforms (equipped Toyota Lexus and Renault Zoe) in 2014 and 2015; it has also been implemented in 2015 on the experimental autonomous car of Toyota Motor Europe in Brussels.

The objective of the research work performed in the period 2015-16 was to overcome some of the shortcomings of the initial *HSBOF* approach [0] , and to obtain a better understanding of the observed dynamic scenes through the introduction of an additional object level into the model. The new framework, whose development has been continued in 2016, is called *Conditional Monte Carlo Dense Occupancy Tracker (CMCDOT)* [84]. The whole CMCDOT framework and its results are presented and explained on a video posted on Youtube [0]. This work has mainly been performed in the scope of the project *Perfect* of IRT Nanoelec [0] (financially supported by the French ANR agency [0]), and also used in the scope of our long-term collaboration with Toyota.

In 2016, most of the efforts have been focused on the optimization of the implementation of our grid-based Bayesian filtering CMCDOT framework. Since the beginning of the development of this framework, we have chosen to construct models and algorithms specially designed to attain real-time performances on embedded devices, through a massively parallelization of the involved processes. The whole system have been implemented and scrupulously optimized in Cuda, in order to fully benefit from the Nvidia GPUs and technologies. Starting from the use of the Titan X and GTX980 GPUs (the hardware used in our computers and experimental platforms), we have successfully adapted and transferred our whole real-time perception chain on Nvidia dedicated-to-automotive cards Jetson K1 and X1 [0]. A specific optimization has been performed in term of data access and processing, allowing us to obtain real-time results when processing the data from the 8 lidar layers generated by our IBEO sensors, by using a grid containing 1400x600 cells and 65536 dynamic particles (for motion estimation). The observation grid generation and fusion (representing the input of the CMCDOT) is made in 17ms on Jetson K1 and only in 0.7ms on Jetson X1; a CMCDOT filtering update is performed in 70ms on Jetson K1 and only in 17ms on Jetson X1.

[0] The *Bayesian programming formalism* developed in e-Motion, pioneered (together with the contemporary work of Thrun, Burgards and Fox [94]) a systematic effort to formalize robotics problems under Probability theory –an approach that is now pervasive in Robotics.

[0] In the current implementation of the HSBOF algorithm, many particles are still allocated to irrelevant areas, since no specific representation models are associated to dataless areas. Moreover, if the filtered low level representation can directly be used for various applications (for example mapping process, short-term collision risk assessment [47], [85], etc), the retrospective object level analysis by dynamic grid segmentation can be computationally expensive and subjected to some data association errors.

[0] https://www.youtube.com/watch?v=uwIrk1TLFiM

[0] Nanoelec Technological Research Institute (Institut de Recherche Technologique Nanoelec)

[0] National Research Agency (Agence Nationale de la recherche)

[0] These new Nvidia devices are more suited for embedded applications, in term of power consumption and dimensions.

Figure 5. Jetson X1 card, Nvidia device dedicated to automotive applications

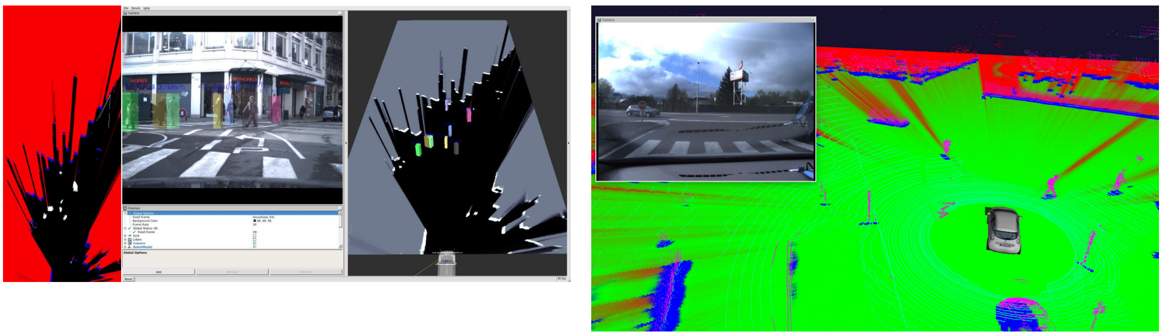

Figure 6. a) CMCDOT results : filtered occupancy grids, enhanced with motion estimations (vectors) and object detection (colored boxes) b) Example of an occupancy grid generated using the classified point cloud and the ground model

7.1.2. A new sensor model for 3D sensors, by Ground Estimation, Data segmentation and adapted Occupancy Grid construction

Participants: Lukas Rummelhard, Amaury Nègre, Anshul Paigwar, Christian Laugier.

As a starting point for the Bayesian perception framework embedded on the vehicles and on the perception boxes, the system generates instantaneous spatial occupancy grids, by interpreting the point clouds generated by the sensors (sensor model). With planar sensors, placed at the level of the wanted occupancy grid, such as the IBEO Lidar on the vehicles or the Hokuyo Lidar on the first developed perception box, a classic sensor model can be used: before the laser impact the space is considered as empty, occupied at the impact point and undefined after the impact. In our previous approach, the angular differences between the 4 laser layers of our IBEO Lidars was taken into account by introducing a *confidence factor* in the data, reducing in this way the effect of the impacts too close to the ground. In this approach the ground is assumed to be flat and the confidence factor is calculated geometrically. Then, given the orientation of these sensors and the environments traversed, such a model was quite satisfactory.

However, this traditional sensor model has to be adapted when using Velodyne or Quanergy sensors mounted on the top of the vehicle and providing dense 3D data with a high horizontal and vertical resolution. Indeed, in this case the laser layers are capable of depicting an obstacle from above, and consequently an impact at a given distance does not certify any more a free area until the impact. Moreover, many impact points are located on the ground and have to be appropriately modeled in order to systematically avoid deceptive obstacle detection. Then, the previous flat-ground assumption doesn't hold anymore, since the actual ground shape is integrated into the data and the correct segmentation of obstacle becomes critical in the process. This is why we have developed the new *Ground Estimator* approach.

The aim of the method is, upstream from the Bayesian filtering step of our current perception system (CMCDOT), to first dynamically *estimate the ground elevation*, to exploit this information for making a *relevant data classification* between actual obstacle impacts and ground impacts, and finally to generate the *relevant occupancy grid using this classified 3D point cloud* (sensor model). The developed method is based on a recursive spatial and temporal filtering of a Bayesian network of elevation nodes, constantly re-estimated and re-evaluated with respect to data and spatial continuity. The construction of the occupancy grid is based, on the one hand, on the location of the laser impacts, and on the other hand on the shape of the ground and the height at which the lasers pass through the different portions of the space.

The approach has been first successfully tested and validated with dense Lidar sensors (Velodyne and Quanergy). The use of the enhanced sensor model is also currently tested with sparser sensors, with the objective to increase their robustness. The obtained results show promising perspectives, offering a robust and efficient ground representation, data segmentation and relevant occupancy grid, and also offering quality inputs for the next steps of the perception framework. A journal paper and a patent are under preparation.

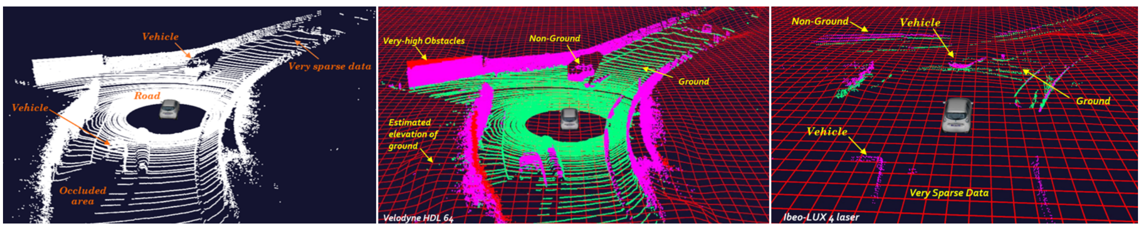

Figure 7. (a) Typical 3D point cloud generated by Velodyne LiDAR, (b) Point cloud segmentation between ground (green points) and non-ground (purple points), and estimated average elevation of the terrain (red grid) (c) Point Cloud Segmentation on 4-Ibeo Lux LiDAR data and estimated elevation of terrain.

7.1.3. Dense & Robust outdoor perception for autonomous vehicles

Participants: Victor Romero-Cano, Christian Laugier.

Robust perception plays a crucial role in the development of autonomous vehicles. While perception in normal and constant environmental conditions has reached a plateau, robust perception in changing and challenging environments has become an active research topic, particularly due to the safety concerns raised by the introduction of self-driving cars to public streets. In collaboration with Toyota Motors Europe and starting in April 2016 we have developed techniques that tackle the robust-perception problem by combining multiple complementary sensor modalities.

Our techniques, similar to those presented in [78], [91] explore the complementary relationships between passive and active sensors at the pixel level. Low-level sensor fusion allows for an effective use of raw data in the fusion process and encourages the development of recognition systems that work directly on multi-modal data rather than higher level estimates. During the last nine months we have developed low-level sensor fusion approaches that, differently from most of the related literature, do not have fixed requirements regarding coverage or density of the active sensors. This provides a competitive advantage due to the elevated costs of dense range sensors such as Velodyne LIDARs.

Our framework outputs a new image-like data representation where each pixel contains not only colour but also other low level features such as depth and regions of interest where generic objects are likely to be. Our approach is generic so it allows for the integration of data coming from any active sensor into the image space. Additionally, it does not aim at tackling the object detection problem directly but it proposes a multi-modal-data representation from which object detection methods may benefit. For evaluation purposes we have tackled the concrete problem of fusing color images and sparse lidar returns, however, as explained before, the framework is amenable for the inclusion of any other range-sensor modality. The framework creates *XDimages* by extrapolating range measurements across the image space in a two-stage procedure. The first stage considers locally homogeneous areas given by a super-pixel segmentation while the second one further expands depth values by performing self-supervised segmentation of areas seeded by the range sensor. The framework's pipeline is illustrated in Figure 8.

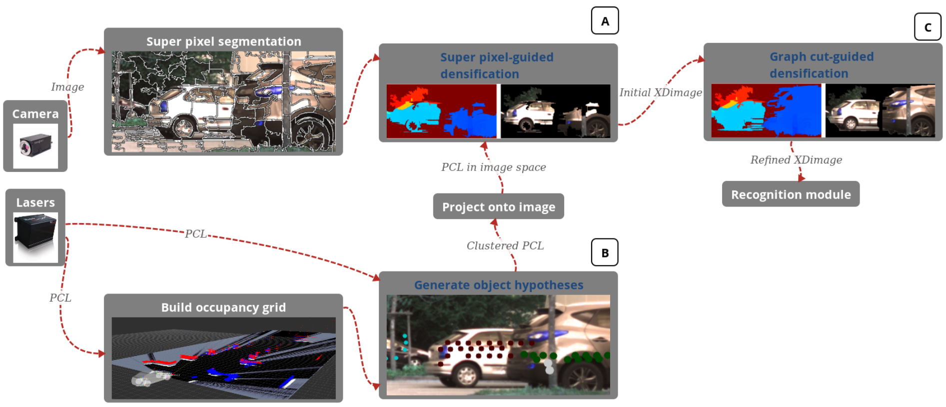

Figure 8. The XDvision framework.

We have named an instance of our data structure an *XDimage*. It corresponds to an augmented camera image where individual pixels contain both appearance and geometric information. The first and more challenging problem to be solved in order to build XDimages is that of densifying sparse point cloud data provided by active range sensors. In our approach we extrapolated depth information using a two-steps procedure as follows:

1. Extend depth values projected onto individual pixels to neighbouring pixels that have similar appearance.
2. Obtain geometry-based object hypothesis.
3. For each geometry-based object hypothesis, extrapolate range measurements in order to account for entire objects.

The results of this work have resulted in a patent application [82] and a paper submission to ICRA 2017 [83].

7.1.4. Integration of Bayesian Perception System on Embedded Platforms

Participants: Tiana Rakotovao, Christian Laugier, Diego Puschini [CEA DACLE], Julien Mottin [CEA DACLE].

Perception is a primary task for an autonomous car where safety is of utmost importance. A perception system builds a model of the driving environment by fusing measurements from multiple perceptual sensors including LIDARs, radars, vision sensors, etc. The fusion based on occupancy grids builds a probabilistic environment model by taking into account sensor uncertainties. Our objective is to integrate the computation of occupancy grids into embedded low-cost and low-power platforms. Occupancy Grids perform though intensive probability calculus that can be hardly processed in real-time on embedded hardware.

As a solution, we introduced a new sensor fusion framework called *Integer Occupancy Grid* [80]. Integer Occupancy Grids rely on a proven mathematical foundation that enables to process probabilistic fusion through simple addition of integers. The hardware/software integration of integer occupancy grids is safe and reliable. The involved numerical errors are bounded and parameterized by the user. Integer Occupancy Grids enable a real-time computation of multi-sensor fusion on embedded low-cost and low-power processing platforms dedicated for automotive applications. This research work has been conducted in the scope of the PhD thesis of Tiana Rakotovao, which will be defended in February 2017.

Figure 9. Fusion of three front LIDARs and one rear LIDAR on the ZOE platform

Experiences showed that Integer Occupancy Grids enable the real-time fusion of the four ibeo LUX LIDARs mounted on the ZOE experimental platform of IRT Nano-Elec [79]. The LIDARs produces about 80,000 points at 25Hz. These points are fused in real-time through a hardware/software integration of the Integer Occupancy Grid framework on an embedded CPU based on ARM A9@1GHz. The platform respects the low-cost and low-power constraints of processing hardware used for automotive. The fusion produces an occupancy grid at more than 25 Hz as illustrated on figure 9.

7.1.5. Embedded and Distributed Perception

Participants: Christian Laugier, Julia Chartes, Amaury Nègre, Lukas Rummelhard, Jean-Alix David, Jerome Lussereau, Nicolas Turro [SED], Jean-Francçois Cuniberto [SED].

7.1.5.1. Embedded Perception in an Experimental Vehicle Renault ZOE

In the scope of the *Perfect* project of the IRT nanoelec, we have started to build an experimental platform using a Renault Zoe equipped with several types of sensors (see 2014 and 2015 annual activity reports). The platform includes multiple sensors, an embedded perception system based on the CMCDOT, and a collision risk component, figure 10(a) illustrates.

Figure 10. (a) Display of the HMI (b) Collision simulation with a mannequin (c) On left: picture of the smartbox, on right: picture of the cone.

In 2016, we have continued to develop and to improve the platform using the latest version of the CMCDOT, some optimized perception and localization components, and new V2X communication functions for distributed perception.

In particular, we have developed an improved the localization function using maps and V2X communication devices. We also developed a new embedded component for sharing data between the infrastructure perception boxes and the vehicle; this component is based on the use of V2X communication and GPS time synchronization. This is a first step towards a fully distributed perception system. The development of this system will be continued in 2017 (see next section).

During the year 2016, experiments have been pushed forward on testing the perception algorithms, the collision risk alert and the localization components using a fabric mannequin as shown on figure 10(b). The mannequin has been motorized for easier and more realistic tests and demos. More details are given in the team publications at MCG 2016 [29] and at GTC Europe 2016. The work of the team is also explained on youtube videos "Irt Nanoelec Perfect Project" [55] and for the technical side "Bayesian Embedded Perception" [54].

New experiments have also been performed on some road intersections and highways, in order to collect new data on driver's behaviors. These experiments have been conducted on mountain roads with changing slopes and on highway (to study the lane changing behaviors). They have been performed in the scope of our cooperation with Renault and with Toyota. The way these experimental data have been used is described in the section “Situation Awareness”. More recently, we have also started to work on the development of the automatic driving controls on the Zoe vehicle. For that purpose, we have recently signed a cooperation agreement with Ecole Centrale de Nantes. The basic functions for automatic driving will be implemented on the Zoe at the beginning of 2017. For that purpose, a physical model of the Zoe is currently in construction under ROS Gazebo simulator. This should allow us to implement and to test the required control laws.

7.1.5.2. Distributed Perception

In 2015, we have developed a first *Connected Perception Box* including a GPS, a V2X communication device, a cheap Lidar sensor, and an Nvidia Tegra K1 board. The box was powered using a battery, and the objective was to reduce as far as possible the required energy consumption. Within the box, the perception process is performed using the CMCDOT algorithm. In 2016, we have continued to develop this concept of distributed perception. We have developed a second generation of the perception box, using a Quanergy M8 360° Lidar, a TX1 Nvidia Tegra board, an ITRI V2X communication device and the last version of the CMCDOT system. This new box is more efficient and powerful than the previous one. It allows the real-time exchange of objects positions and velocities, through a V2X communication between the perception box and the connected vehicle.

This leads to the extension of the vehicle perception area to some hidden areas, and to generate some alerts in case of a high collision risk, cf. fig. 11. In this approach, time synchronization has been performed using GPS time and NTP protocol.

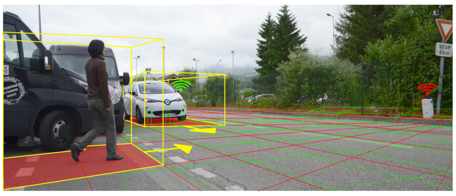

Figure 11. (a) Shared perception between car and perception box

7.1.5.3. Public demonstrations and Technological Transfer

2016 has been a year with many scientific events and public demos. Several public demonstrations of our experimental vehicle have performed, some of them in presence of local government officials during a GIANT show at CEA.

The collaboration with Nvidia on Embedded Perception for autonomous driving has been extended to 2017, and the "GPU research center" label has been renewed.

Toyota Motor Europe (TME) is strongly interested in the CMCDOT technology, and Inria is currently negotiating with them the conditions of a first licence for R&D purpose. A first implementation of the executable code of CMCDOT has successfully been implemented on the TME experimental vehicle in Brussels. We are currently discussing with TME an extension of the license to several other experimental vehicles located in some other places in the world.

At the end of 2016, we also started to transfer the CMCDOT technology to two industrial companies in the fields of industrial mobile robots and automatic shuttles. Confidential contracts for the joint development of proofs of concepts are under signing. The work will be performed at the beginning of 2017.

7.2. Situation Awareness

Participants: Christian Laugier, Olivier Simonin, Jilles Dibangoye, Alejandro Dizan Vasquez Govea [Apple since January 2016], Stephanie Lefevre [Mercedes-Benz North America], David Sierra-Gonzalez, Mathieu Barbier, Victor Romero-Cano.

7.2.1. Framework for Motion Prediction and Collision Risk Assessment

Participants: Christian Laugier, Alejandro Dizan Vasquez Govea [Apple since January 2016], Stephanie Lefevre [Mercedes-Benz North America], Lukas Rummelhard.

For several years, the challenging scientific problem of Motion Prediction, Risk Assessment and Decision-Making in open and dynamic environments has been one of our main research topics (see activity reports of the former e-Motion Inria team-project and Chroma team 2015 activity report).

Throughout 2016, we have continued this line of work by developing and experimentally testing new frameworks for Motion Prediction and Collision Risk Assessment in complex dynamic scenes involving multiple moving agents having various behaviors. This work has been conducted in the scope of three main scenarios: Short-term prediction in crowded urban environments (see approach and results in sections 7.1.1 and 7.1.5), Autonomous driving in highway environments (see section 7.2.2), and Safe Intersection crossing.

The main underlying concepts of the developed framework have recently been published in the second edition of the Handbook of Robotics [31]. They have also been presented into a Mooc course on “Autonomous Mobiles Robots and Vehicles”, dedicated to graduate and undergraduate students and to engineers in Robotics [57]. This Mooc has been published twice in 2015 and in 2016.

The recent results have been published at ICRA 2016 [27] and also presented by C. Laugier in several invited talks : Asprom2016 [16], ICIT2016 [14], CUHK2016 [15], GTC-Europe2016 [24] and ARSO2016 [17].

Another contribution relies in the implementation of some the proposed models on two experimental vehicles (Lexus and Zoe experimental platforms). As it has been mentioned in the section 7.1.5, several experiments on short-term collision risk assessment have successfully been conducted with these platforms in 2015 and 2016 (c.f. [84], [67]).

This work will be continued in 2017, in the scope of our ongoing collaborative projects with Toyota, Renault and IRT nanoelec. It will also be used as a support for the planned technological transfers with two industrial companies in the fields of industrial mobile robots and automatic shuttles (see section 7.1.5).

7.2.2. Planning-based motion prediction for collision risk estimation in autonomous driving scenarios

Participants: David Sierra-Gonzalez, Christian Laugier, Jilles Dibangoye, Alejandro Dizan Vasquez Govea [Apple since January 2016].

The objective is to develop a collision risk estimation system capable of reliably finding the risk of collision associated to the different feasible trajectories of the ego-vehicle. This research work is done in the scope of the Inria-Toyota long-term cooperation and of the PhD thesis work of David Sierra-Gonzáles.

One key factor, and probably the biggest challenge in order to produce robust collision risk estimation in traffic scenes, is the motion prediction of the dynamic obstacles (i.e. the other drivers for highway scenarios). The difficulty stems from the fact that human behavior is determined by a complex set of interdependent factors, which are very hard to model (e.g. intentions, perception, emotions). As a consequence, most existing systems are based on simple short-term motion models assuming constant velocity or acceleration.

We opt here for a planning-based approach, which assumes that drivers instinctively act as to minimize a cost (or equivalently, maximize a reward). This cost function encodes the preferences of the driver to, for instance, keep a minimum distance with the vehicle in front, drive in the right lane in the highway, or respect the speed limits. By using Inverse Reinforcement Learning (IRL) algorithms, we can obtain such cost function directly from expert demonstrations (i.e. simply observing how people drive).

Two well-known IRL algorithms [35], [101] have been implemented and used to obtain driver models from human demonstrations. The algorithms have been adapted to work with simulated demonstrations obtained on a highway simulator, and with real-world data from the Lexus and Renault Zoe platforms. Figure 12.a shows a slice of one such cost function in the context of a real highway scene.

A novel framework has been developed in order to exploit the predictive potential of these models for the task of highway scene prediction [26]. The ability of these dynamic models to capture the risk-aversive behavior of drivers leads to an interaction-aware prediction. In contrast to other state-of-the-art interaction-aware approaches [59], the complexity of our prediction framework does not grow exponentially in the number of vehicles in the scene, but only quadratically. Figure 12.b shows the prediction produced by our framework in two prototypical simulated highway scenarios. The figure shows the result of summing up across the occupancy distributions over a discretization of the road for all the vehicles in the scene, at different timesteps (note that the result is no longer a probability distribution, but it is convenient to visualize the prediction).

This framework has been patented by Inria and Toyota Motor Europe in October 2016.

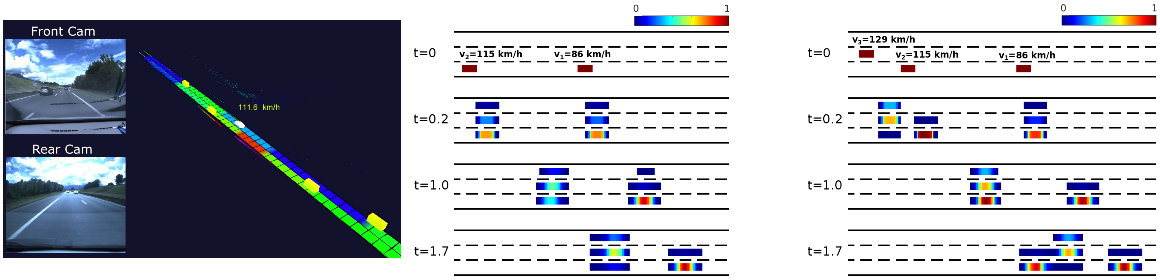

Figure 12. a) Slice of a cost function obtained from real demonstrated data superimposed on the road on a highway scene. Red indicates high cost, green intermediate, and blue low. b) and c) Prediction of two prototypical simulated traffic scenes with the framework from [26]. We show the predicted occupancy probabilities over a discretization of the road for different timesteps.

7.2.3. Functional space representation for automated road intersection crossing

Participants: Mathieu Barbier, Christian Laugier, Olivier Simonin.

The objective is to develop a framework for modeling road intersections using relevant functional areas, which can be exploited by an autonomous vehicle for safely crossing the intersection. These functional areas try to capture various characteristics such as crossing, merging or approaching areas, the car dynamics when moving in such areas, or the related uncertainty. We made the assumption that such a functional space representation can be stored in a map and can be constructed using observed trajectories. This work is performed in the scope of the PhD thesis of Mathieu Barbier, which is supported by a CIFRE fellowship with Renault.

In a preliminary work done with map by Renault, it has been observed that the information stored in a map does not fully match with the real motions executed by cars within a given intersection. The differences between the stored and the real path might be important. This difference is not due to error during the map creation, but rather to other constraints related to the driving action (e.g. visibility, dynamics). Such a difference leads to serious difficulties at the level of the autonomous driving decision-making process.

Constructing a functional model, requires to first analyze the topological and dynamics structure of an intersection, and in a second step to imagine how it would be possible to extract such type of information from maps and observed trajectories. Two main structures seem to emerge from this study:

- Merging and Crossing points, areas where two cars are the most likely to collide.
- Approaching areas, areas where drivers are most likely to show constant driving behaviors.

In order to learn motions patterns of multiple cars, we have chosen to train Gaussian processes [81] [93] using simulated data set generated using the SCANER™system. The resulting distribution is segmented using different threshold, in order to find approaching areas and to combine pairs of such areas for constructing overlapping areas. The correlation between this discretization and both real and simulated velocity profiles has been shown by the experimental results, see Fig. 13. The approach has been published at IEEE ITSC 2016 [18].

We recently started to make use of a Random Forest classifier to connect features of trajectories with an intended maneuver (stop, pass, yield) and to take advantage of the discretization. This research work will be continued in 2017.

7.3. Robust state estimation (Sensor fusion)

7.3.1. Visual-inertial structure from motion: observability properties and state estimation

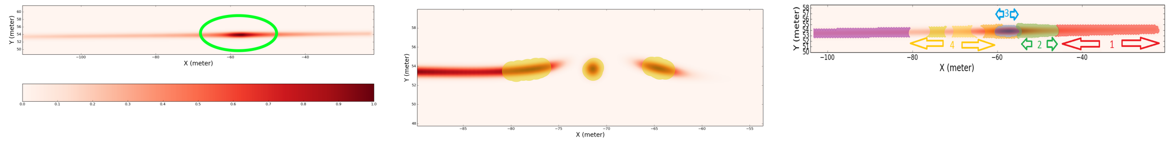

Figure 13. Different step of the framework to discretize the space : a) Map created with prediction from set of GPs, the highlighted area has a high mean probability b) Segmentation of crossing and merging areas, in red the probability of two cars being in the same position and in yellow where this probability is higher than the threshold c) Discretization of approaching area

Participant: Agostino Martinelli.

This research is the follow up of our investigations carried out during the last three years. The main results obtained this year regard the following three topics:

1. Exploitation of the closed form solution introduced in [70] in the framework of Micro Aerial Vehicle (MAV) navigation;
2. Introduction of a new method for simultaneous localization and Gyroscope calibration;
3. Analytic solution of the Unknown Input Observability problem (UIO problem) in the nonlinear case.

Regarding the first two topics, we successfully implemented a new method for MAV localization and mapping, on the aerial vehicles available at the Vision and Perception lab at the university of Zurich [0]. This method is based on our previous closed form solution recently introduced in [70]. The practical advantage of this solution is that it is able to determine several physical quantities (e.g, speed, orientation, absolute scale) by only using the measurements provided by a monocular camera and an Inertial Measurement Unit (IMU) during a short interval of time (about 3 seconds). In other words, an initialization is not requested to determine the aforementioned physical quantities. This fact has a fundamental importance in robotics and it is novel with respect to all the state of the art approaches for visual-inertial sensor fusion, which use filter-based or optimization-based algorithms. Due to the nonlinearity of the system, a poor initialization can have a dramatic impact on the performance of these estimation methods.

Finally, by further studying the impact of noisy sensors on the performance of the closed-form solution introduced in [70], we found that this performance is very sensitive to the gyroscope bias. For, we developed a powerful and simple optimization approach to remove this bias. This method has been tested in collaboration with the vision and perception team in Zurich (in the framework of the ANR-VIMAD) and published on the IEEE Robotics and Automation Letters [12]. Additionally, these results have been presented at the International Conference on Robotics and Automation [21].

Regarding the third topic, we still considered the problem of deriving the observability properties of the visual-inertial structure from motion problem when the number of inertial sensors is reduced. This case corresponds to solve a problem that in control theory is known as the Unknown Input Observability (UIO). This problem was still unsolved in the nonlinear case. In [71] we introduced a new method able to provide sufficient conditions for the state observability. On the other hand, this method is based on a state augmentation. Specifically, the new extended state includes the original state together with the unknown inputs and their time-derivatives up to a given order. Then, the method introduced in [71] is based on the computation of a codistribution defined in the augmented space. This makes the computation necessary to derive the observability properties dependent on the dimension of the augmented state. Our effort to deal with this fundamental issue, was devoted to separate the information on the original state from the information on its extension. Last year, we fully solved this problem in the case of a single unknown input [73], [72]. This year we solved the problem for any number

[0] This is the partner of the ANR project VIMAD, in charge of the experiments

of unknown inputs. We presented this solution at the university of Pisa in June and at the university of Rome, Tor Vergata, in December.

7.4. Motion-planning in human-populated environment

We explore motion planning algorithms to allow robots/vehicles to navigate in human populated environment, and to predict human motions.

We have proposed a novel planning-based motion prediction approach [27] which addresses the weaknesses of the previous state-of-the-art motion prediction technique [56], namely *High computational complexity* and *Limited ability to model the temporal evolution along the predicted path*. In 2016, this work has evolved in two new directions, which are prediction of pedestrian behaviors in urban environments and mapping of human flows. We also started to investigate the navigation of a telepresence robot in collaboration with the GIPSA Lab. These work are presented here after.

7.4.1. Urban Behavioral Modeling

Participants: Pavan Vasishta, Raphael Frisch, Anne Spalanzani.

The objective of modeling urban behavior is to predict the trajectories of pedestrians in towns and around car or platoons. We aim to integrate various entities of urban environments such as crosswalks, sidwalks, points of interest, but also characteristics of mobile obstacles (such cars and platoons) and proxemics in order to build a costmap that will show how pedestrians are driven around the ego-vehicle. This work is in the scope of the VALET project and the PhD of Pavan Vasishta (in collaboration with the Inria team Pervasive Interaction). It started in february 2016. Furthermore, a collaboration with the Laboratory of Psychology and NeuroCognition of Grenoble has been initiated to ground interaction and personal space models in experimental data from psychology.

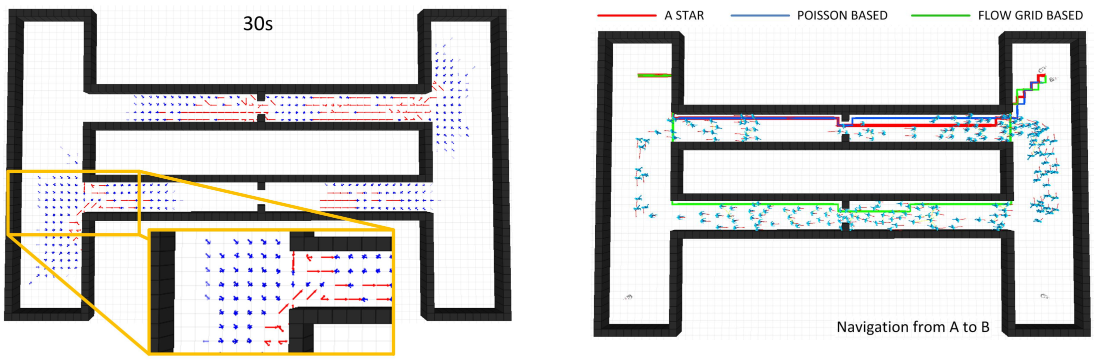

Figure 14. Illustration of (a) Flow-grid mapping in a two-corridor environment where 200 moving pedestrians turns (b) A path-planning computed with different cost functions in this populated environment*

7.4.2. Modeling human-flows from robot(s) perception

Participants: Olivier Simonin, Jacques Saraydaryan, Fabrice Jumel.

In order to deal with robot navigation in dense human populated environments, eg. in flows of humans, we started to investigate the problem of mapping these flows. The challenge is to build such a map from robot perceptions while robots move autonomously to perform some tasks. We developped a counting-based grid model which computes likelihoods of human presence and motion direction in each cell, see red vectors in Fig. 14.a (this is a statistical learning of repetitive human motions). We extended the flow grid model with a human motion predictive model based on the Von Misses motion patern, allowing to "accelerate" the flow grid mapping, see blue vectors in Fig. 14.a.

Then we explored how path-planning can benefit of such a flow grid, that is taking into account the risk for a robot to encounter humans in opposite direction. We first implement the Flow-Grid model in a simulator built upon PedSim and ROS tools, allowing to simulate mobile robots, crowd of pedestrians and sensors to detect their motion. Then, we compared three A*-based path-planning models using different levels of information about human presence: non-informed, a grid of human presence likelihood proposed by Tiplaldi [95] and our grid of human motion likelihood. Simulations involving 200 moving persons and 4 collaborative robots allowed to test simultaneously the mapping of human motions and the related path-planning. The different kind of paths obtained are illustrated in Fig. 14.b, showing the ability of the flow-grid based A* to avoid to cross areas with a possible opposite human flow. These results have been presented at RSS workshop DEMUR [30].

We also started some experiments with our mobile indoor robots (incl. the Pepper) in human populated environments, see [30]. We plan to demonstrate the efficiency of the approach by participating to the new Pepper-league of the Robocup@Home competition, over the future period 2017-2020.

7.4.3. Navigation of telepresence robots

Participants: Olivier Simonin, Anne Spalanzani, Gerard Bailly [GIPSA, CNRS, Grenoble], Rémi Cambuzat.

In 2016 we obtained with the team of Gérard Bailly, from GIPSA/CNRS Grenoble, a regional support for the TENSIVE project. It funds the PhD thesis of Remi Cambuzat on immersive teleoperation of telepresence robots for verbal interaction and social navigation, started in October 2016. Chroma is focusing on the problem of social navigation, and more paricularly on the balance between human commands and autonomous navigation. Two issues are adressed : how to understand the expected direction given by the pilot to the teleprence robot, in order to ease the workload of the pilot ? how to assist the navigation, from embedded processes and sensors on the robot, while following the expected behavior given by the remote pilot ?

First months of the thesis concerned the building of a specific state-of-the-art, the formalization of some experimental scenarios, and the study of the Pepper robot capabilities in this scientific challenge.

7.5. Decision Making in Multi-Robot Systems

7.5.1. Multi-robot path-planning and patrolling

7.5.1.1. Patrolling under connectivity constraints

Participants: Olivier Simonin, Anne Spalanzani, Mihai Popescu, Fabrice Valois [Inria, Agora (ex Urbanet) team].

Patrolling is mainly used in situations where the need of repeatedly visiting certain places is critical. In this work, we consider a deployment of fixed targets, eg. wireless sensors, that several robots are in charge of patrolling while they have to maintain their (periodic) connectivity in order to collect and bring data up to a sink node. We have shown that this is fundamentally a problem of vertex coverage with bounded simple cycles (CBSC). We offered a formalization of the CBSC problem and proved it is NP-hard and at least as hard as the Traveling Salesman Problem (TSP). Then, we provided and analyzed heuristics relying on clusterings and geometric techniques. The proposed approach relies on two steps: the first one partitions the vertices, the second one computes hamiltonian cycles on each partition. We implemented two classic hamiltonian cycle heuristics, one is based on Minimum Spanning Trees computations and the other on Christofides algorithm. Comparisons on randomly-generated graphs showed that the Christofides algorithm computes shorter cycles. This work, started in the Master internship of Mihai-Ioan Popescu, now continuing as PhD student in Chroma, has been published in 2016 in [25]. Work is now focusing on the problem of synchronizing robots to meet at intersection nodes between the cycles.

Another important element of this work is the construction of a new collaboration with the team of Gabriela Czibula in Babes-Bolyai University at Cluj-Napoca (Romania). It will focus on optimization and online adaptation of the multi-cycle patrolling with machine learning (RL) techniques in order to deal with the arrival of new targets in the environment. We obtained, in the end of 2016, a french-romanian PHC [0] bilateral project, called DRONEM, funding students and researchers exchanges during two years.

[0] Hubert Curien Partnership

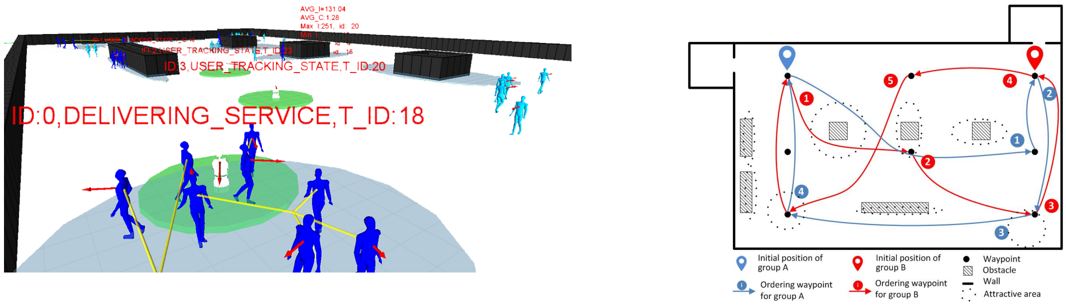

Figure 15. a) Simulator for dynamic patroling of people based on PedSim. b) Scenario of the 200 pedestrians moving along two predefined paths plus local attractors and randoms moves.

7.5.1.2. Patrolling moving people (dynamic patrolling)

Participants: Jacques Saraydaryan, Fabrice Jumel, Olivier Simonin.

In the context of service robotics, we address the problem of serving people by a set of collaborating robots, that is to delever regularly services to moving people. We showed that the problem can be formally expressed as a dynamic patrolling task. We call it the robot-waiters problem, where robots have to regularly visit all the moving persons (to deliver objects/information). In the publication [87], we proposed different criteria and metrics suitable to this problem, by considering not only the time to patrol all the people but also the equity of the delivery. We proposed and compared four algorithms, two are based on standard solutions to the static patrolling problem and two are defined according the specificity of patrolling moving entities, in particular greedy-based solutions on distance and idleness people information. In order to limit robot traveled distances, the last approach introduces a clustering heuristic to identify groups among people. To compare algorithms and to prepare real experiments we evaluated performances by using our simulator (combining PedSim and ROS). The simulator and the scenrio test - paths followed by humans - are illustrated in figure 15.a and 15.b. Experimental results show the efficiency of the specific new approaches over standard (static patrolling) approaches. We also analysed the influence of the number of robots on the performances, showing a convergence of performances when it grows. See [87] and extensions in 2016 [28].

We are currently developping new algorithms using the mapping and prediction of human flows based on the work presented in section 7.4.2 to allow robots to predict where human (groups) will move (under hypothesis of repetitive behaviors).

7.5.1.3. Global-local optimization in autonomous multi-vehicles systems

Participants: Olivier Simonin, Jilles Dibangoye, Laetitia Matignon, Florian Peyreron [VOLVO Group, Lyon], Guillaume Bono, Olivier Buffet [Inria Nancy Grand Est], Mohamed Tlig [IRT-Systemx, Paris].

We address transport and traffic management problems with driverless vehicles. We mainly study how local decisions can improve complexity of global (planning) solutions.

A previous work carried in the PhD of M. Tlig [96] concerned stop-free crossing roads with driverless vehicles. We explored distributed algorithms to optimize the global traffic in the road network (time and energy), based on Hill-Climbing techniques, so as to go from a synchronization within each intersection to the synchronization of a network. Experiments in simulation showed that proposed algorithms can efficiently optimize the initial decentralized solution, while keeping its properties (only the temporal phase for crossing in each intersection is modified). In 2016 we extended the experimental study, which was published in the RIA revue [13] and submited to an international journal.

In 2016, we started a new cooperation with the VOLVO Group, in the context of the INSA-VOLVO Chair. It funds the PhD thesis of G. Bono which deals with global-local optimization under uncertainty for goods distribution using a fleet of autonomous vehicles. First months of the thesis focused on building i) a state of the art about online pick-up and delivery solutions with a fleet of autonomous vehicles and ii) defining formally the scenario and hypothesis of the considered problem.

7.5.2. Anytime algorithms for multi-robot cooperation

7.5.2.1. Complex scenes observation

Participants: Olivier Simonin, Laetitia Matignon, Christian Wolf [LIRIS, INSA Lyon], Simon Bultmann [internship], Stefan Chitic.

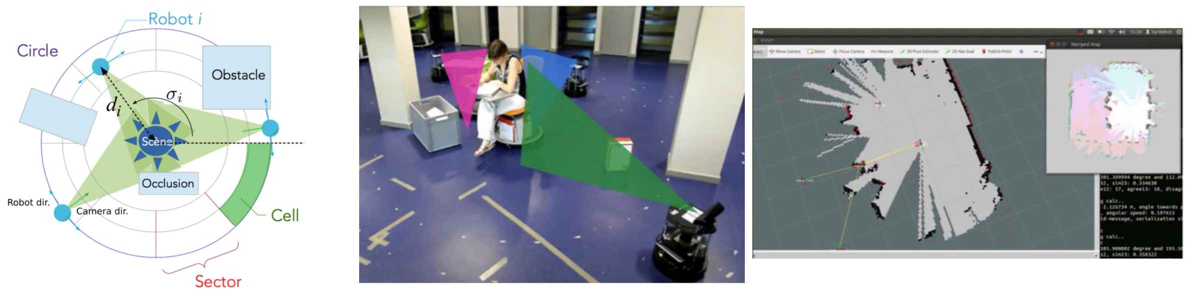

Figure 16. Illustrations (a) Concentric navigation model. (b) Experimental setup and multi-robot mapping with Turtlebot 2.

Solving complex tasks with a fleet of robots requires to develop general strategies that can decide in real time (or time-bounded) efficient and cooperative actions. This is particularly challenging in complex real environments. To this end, we explore anytime algorihms and adaptive/learning techniques.

The "Crome" [0] project [0] is motivated by the exploration of the joint-observation of complex (dynamic) scenes by a fleet of mobile robots. In our current work, the considered scenes are defined as a sequence of activities, performed by a person in a same place. Then, mobile robots have to cooperate to find a spatial configuration around the scene that maximizes the joint observation of the human pose skeleton. It is assumed that the robots can communicate but have no map of the environment and no external localization.

To attack the problem, in cooperation with colleagues from vision (C. Wolf, Liris), we proposed an original concentric navigation model allowing to keep easily each robot camera towards the scene (see fig. 16.a). This model is combined with an incremental mapping of the environment and exploration guided by meta-heuristics in order to limit the complexity of the exploration state space. We developped a simulator that uses real data from real human pose captures to simulate dynamic scene and noise in sensor information. A video presenting the simulator interface and showing the incremental exploration and mapping can be found at . Results have been published in 2016 in [20] (ICTAI). It compares the variants of the approach and shows its features such as adaptation to the dynamic of the scene and robustness to the noise in the observations.

We have also developped an experimental framework for the circular navigation of several Turtlebot2 robots around a scene, presented in figure 16.b. Especially, given that we assume in our work that robots have no map of the environment, we implemented a cooperative multi-robot mapping based on the merging of occupancy grid maps. Robots are individually building and communicating to other robots their local maps. Each robot tries to align these local maps to compute a joint, global representation of the environment. We carried out

[0] Coordination d'une flottille de robots mobiles pour l'analyse multi-vue de scènes complexes

[0] Funded by an INSA BQR in 2014-2015 (led by O. Simonin) and a LIRIS transversal project in 2016-2017 (led by L. Matignon)

the map-merging by adapting several methods known in literature [86] to our specific topology, i.e. the single hypothesis of a common center point (the scene) shared by robots. We compared the methods in real-world multi-robot scenarios (see Simon Bultmann's internship report).

7.5.2.2. Middleware for open multi-robot systems

Participants: Stefan Chitic, Julien Ponge [CITI, Dynamid], Olivier Simonin.

Multi-robots systems (MRS) require dedicated tools and models to face the complexity of their design and deployment (there is no or very limited tools/middleware for MRS). In the context of the PhD work of S. Chitic, we address the problem of neighbors and service discovery in an ad-hoc network formed by a fleet of robots. Robots needs a protocol that is able to constantly discover new robots in their coverage area. This led us to propose a robotic middleware, SDfR, that is able to provide service discovery. This protocol is an extension of the Simple Service Discovery Protocol (SSDP) used in Universal Plug and Play (UPnP) to dynamic networks generated by the mobility of the robots. Even if SDfR is platform independent, we proposed a ROS integration in order to facilitate the usage. We evaluated a series of overhead benchmarking across static and dynamic scenarios. Eventualy, we experimented some use-cases where our proposal was successfully tested with Turtlebot 2 robots. Results have been pubished in [19]. In 2016, the work continued by the definition of a timed automata based design and validation tool-set, that offers a framewok to formalize and implement multi-robot behaviors and to check some (temporal) properties.

7.5.3. Sequential decision-making under uncertainty

The holy grail of Artificial Intelligence (AI)—creating an agent (e.g., software, robot or machine) that comes close to mimicking and (possibly) exceeding human intelligence—remains far off. But past years have seen breakthroughs in agents that can gain abilities from experience with the environment, providing significant advances in the society and the industries including: health care, autonomous driving, recommender systems, etc. These advances are partly due to single-agent planning and (deep) reinforcement learning, that is, AI research subfields in which the agent can describe its world as a Markov decision process. Some stand-alone planning and reinforcement learning (RL) algorithms (e.g., Policy and Value Iteration, Q-learning) are guaranteed to converge to the optimal behavior, as long as the environment the agent is experiencing is Markovian. Although Markov decision processes provide a solid mathematical framework for single-agent planning and RL, they do not offer the same theoretical grounding in multi-agent systems, that is, groups of autonomous, interacting agents sharing a common environment, which they perceive through sensors and upon which they act with actuators. Multi-agent systems are finding applications everywhere today. At home, in cities, and almost everywhere, we are surrounded by a growing number of sensing and acting machines, sometimes visibly (e.g., robots, drones, cars, power generators) but often imperceptibly (e.g., smartphones, televisions, vacuum cleaners, wash- ing machines). Before long, through the emergence of a new generation of communication networks, most of these machines will be interacting with one another through the internet of things. In contrast to single-agent systems, when multiple agents interact with one another, how the environment evolves depends not only upon the action of one agent but also on the actions taken by the other agents, rendering the Markov property invalid since the environment is no longer stationary. In addition, a centralized (single-agent) control authority is often inadequate, because agents cannot (e.g., due to communication cost, latency or noise) or do not want (e.g., in competitive or strategic settings) to share all their information all the time. This raises a simple fundamental question: how to design a general algorithm for efficiently computing rational policies for a group of cooperating or competing agents in spite of stochasticity, limited information and computational resources? The remainder of this section points out some of the main results of the year to this question as well as ongoing projects.

7.5.3.1. Optimally solving cooperative games as continuous Markov decision processes

Participants: Jilles S. Dibangoye, Olivier Buffet [Inria Nancy], Christopher Amato [Univ. New Hampshire], François Charpillet [Inria Nancy, Larsen team].

Decentralized partially observable Markov decision processes (Dec-POMDPs) provide a general model for decision-making under uncertainty in decentralized settings, but are difficult to solve optimally (NEXP-Complete). As a new way of solving these problems, we introduce the idea of transforming a Dec-POMDP into a continuous-state deterministic MDP with a piecewise-linear and convex value function. This approach makes use of the fact that planning can be accomplished in a centralized offline manner, while execution can still be decentralized. This new Dec-POMDP formulation, which we call an occupancy MDP, allows powerful POMDP and continuous-state MDP methods to be used for the first time. To provide scalability, we refine this approach by combining heuristic search and compact representations that exploit the structure present in multi-agent domains, without losing the ability to converge to an optimal solution. In particular, we introduce a feature-based heuristic search value iteration (FB-HSVI) algorithm that relies on feature-based compact representations, point-based updates and efficient action selection. A theoretical analysis demonstrates that FB-HSVI terminates in finite time with an optimal solution. We include an extensive empirical analysis using well-known benchmarks, thereby demonstrating that our approach provides significant scalability improvements compared to the state of the art. This work has been published in JAIR journal [11].

7.5.3.2. Optimally solving two-person zero-sum partially observable stochastic games: a convex optimization approach

Participants: Jilles S. Dibangoye, Olivier Buffet [Inria Nancy], Mihai Indricean [INSA Lyon internship].

This work proposes a novel theory and algorithms to optimally solving a two-person zero-sum POSGs (zs-POSGs). That is a general framework for modeling and solving two-person zero-sum games (zs-Games) with imperfect information. Our theory builds upon the result demonstrating that the original problem is reducible to a zs-Game—but now with perfect information. In this form, we show that the dynamic programming theory applies. In particular, we extended Bellman equations [39] for zs-POSGs, and coined them maximin (resp. minimax) equations. Even more importantly, we demonstrated Von Neumann & Morgenstern's minimax theorem [99] [100] holds in zs-POSGs. We further proved that value functions—solutions of maximin (resp. minimax) equations—yield special structures. More specifically, the maximin value functions are convex whereas the minimax value functions are concave. We also showed how our results apply to more restrictive settings, essentially leading to more concise information. Together these findings allow us to introduce a key algorithm avoiding exhaustive enumeration of doubly exponentially many pure strategies, as suggested so far. We further illustrate the use of our algorithm through numerical examples.

7.5.3.3. Decentralized Markov decision processes in open systems: models and first algorithms

Participants: Jilles S. Dibangoye, Abdel-Illah Mouaddib [Univ. Caen Basse-Normandie], Jonathan Cohen [Univ. Caen Basse-Normandie].

Many real-world multiagent applications, e.g., rescue operations, require to dynamically assemble or disassemble teams needed to provide a service based on agents entering or quitting the system. While Decentralized Partially Observable Markov Decision Processes (Dec-POMDPs) formalize decision-making by multiple agents, they fail to exploit the team flexibility. Queueing models can formalize birth-death processes by which agents enter or exit a team, but they fail to capture multiagent planning under uncertainty. This work, in the context of the PhD work of J. Cohen, introduces a new model synthesized from Dec-POMDPs and birth-death processes, called open Dec-POMDPs. The primary result is the proof that the latter is NEXP-Complete. Exploiting the team flexibility, enables us to present a best-response dynamics' algorithm, which can dynamically adapt to agents entering or quitting a team and computes local optimum solutions.

7.5.3.4. Does randomization makes cooperative multi-agent planning easier?

Participant: Jilles S. Dibangoye.

These recent years have seen significant progress in multi-agent planning problems formulated as decentralized partially observable Markov decision processes (Dec-POMDPs). In state-of-the-art algorithms, agents use policies that do not employ random devices, i.e., deterministic policies, which are simple to handle and to implement, and yet are good candidates to be optimal. Integer linear programming (ILP) or constraint optimization programming (COP) can formalize the search for deterministic policies, unfortunately their worst case complexity (NP-Complete) suggest to be little hope for optimally solving real-world instances. In this paper, we show—for the first time—that the randomization allows us to use linear programming (LP) instead of ILP while preserving optimality, which drops the worst-case complexity from NP to P. Specifically, we introduce the first linear programs for incrementally approaching the optimal value function starting from upper-and lower-bound functions. We further extends state-of-the-art algorithm for Dec-POMDPs to use randomized policies. Finally, empirical results demonstrate significant improvements in time needed to find an ε-optimal solution on all tested benchmarks.

7.5.3.5. Reinforcement learning approach for active perception using multiple robots

Participants: Jilles S. Dibangoye, Jacques Saradaryan, Laëtitia Matignon, Trad Ahmed Yahia [Master Internship], Lorcan Charonnat [Internship INSA], Yuting Zhang [Internship INSA], Yifan Xiong [Internship INSA].

We consider cooperative, decentralized stochastic control problems represented as a decentralized partially observable Markov decision process. A critical issue that limits the applicability of that setting to realistic domains is how agents can learn to act optimally by interacting with the environment and with one another, given only an incomplete knowledge about the model. Reinforcement learning has previously been applied to decentralized decision making with a focus on distributed methods, which often results in suboptimal solutions. On the contrary, we build upon the idea that plans that are to be executed in a decentralized fashion can nonetheless be formulated in a centralized manner using a generative model of the environment. Following this line of thought, we propose the first (centralized) reinforcement learning algorithm for computing the optimal Q-value functions for cooperative, decentralized stochastic control problems. Experiments show our approach can learn to act optimally in many domains from the literature. We currently investigate robotic applications of this approach, including unknown scene reconstruction by a fleet of mobile robots.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Toyota Motors Europe

[2006 - 2017]

The contract with Toyota Motors Europe is a joint collaboration involving Toyota Motors Europe, Inria and ProBayes. It follows a first successful short term collaboration with Toyota in 2005.

This contract aims at developing innovative technologies in the context of automotive safety. The idea is to improve road safety in driving situations by equipping vehicles with the technology to model on the fly the dynamic environment, to sense and identify potentially dangerous traffic participants or road obstacles, and to evaluate the collision risk. The sensing is performed using sensors commonly used in automotive applications such as cameras and lidar.

This collaboration has been extended for 4 years and Toyota provides us with an experimental vehicle Lexus equipped with various sensing and control capabilities. Several additional connected technical contracts have been signed also.

8.1.2. Renault

[2010 - 2017]

This contract was linked to the PhD Thesis of Stephanie Lefèvre. The objective is to develop technologies for collaborative driving as part of a Driving Assistance Systems for improving car safety. Both vehicle perception and communications are considered in the scope of this study. An additional short-term contract (3 months) has also been signed in november 2012.

8.1.3. IRT-Nano Perfect (2012-2014, and 2015-2017)

Perfect is a project supported by ANR in the scope of the IRT (Technological Research Institute) Nano-electronic driven by the CEA (Nuclear Energy Agency). The partners of the project are the CEA-LETI LIALP laboratory, ST-Microelectronics and Inria. The goal of this project is to propose integrated solutions for “Embeeded Bayesian Perception for dynamic environments” and to develop integrated open platforms. During the first phase of the project (2012-2014), the focus is on the domain of transportation (both vehicle and infrastructure); health and smart home sectors will also be considered in the second phase (2015-2017).

8.2. Bilateral Grants with Industry

8.2.1. INSA-VOLVO Chair PhD grant

[Oct 2016 - Oct 2019]

This grant is linked to the PhD Thesis of Guillaume Bono, funded by the INSA-VOLVO Chair. The objective is to deal with Global-local Optimization Under Uncertainty for Goods Distribution Using a Fleet of Autonomous Vehicles.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. Projet AAP ARC6 (2015-18)

Participants: Olivier Simonin, Anne Spalanzani, Fabrice Valois [Insa de Lyon, Inria Urbanet].

Regional project (Rhône-Alpes) "Mobilité au sein de flottes de robots sous contrainte de maintien de la connectivité" ARC6, 2015-2018. Leader : O. Simonin.

This project funds the PhD thesis of Mihai-Ioan Popescu, who started on november 2015, and co-advized by O. Simonin, A. Spalanzani and F. Valois. The project involves also the Pole de compétitivité "Via Meca".

9.1.2. Projet AAP ARC6 (2016-19)

Participants: Gérard Bailly [CNRS, GIPSA Lab. Grenoble], Olivier Simonin, Anne Spalanzani.

Regional project (Rhône-Alpes) "TENSIVE Robots de TEléprésence : Navigation Sociale et Interaction VErbale immersives" ARC6, 2016-2019. Leader : G. Bailly.

This project funds the PhD thesis of Remi Cambuzat who started on october 2016, and co-advized by G. Bailly (Dir.), O. Simonin and A. Spalanzani.

9.2. National Initiatives

9.2.1. ANR

9.2.1.1. ANR "VIMAD" (2015-17)

The VIMAD project aims at developing a robust and reliable perception system, only based on visual and inertial measurements, to enhance the navigation capabilities of fully autonomous micro aerial drones. It also aims at acquiring a deep theoretical comprehension of the problem of fusing visual and inertial measurements, by investigating its observability properties in challenging scenarios.

The activities related to this project, followed the work-plan (first year). They regarded the usage of our closed-form solution (recently published on the journal of computer vision, [70]) in the framework of micro aerial navigation in order to:

1. automatically perform state initialization;
2. improve the data matching process.

Additionally, the activities of VIMAD regarded the investigation of an unsolved problem in control theory, which is the unknown input observability problem in the nonlinear case, and its applications to the visual-inertial structure from motion problem.

See section 7.3.1 for a description of the results obtained during this first year of the project.

9.2.1.2. ANR "Valet" (2016-18)

The ANR VALET project proposes a novel approach for solving car-sharing vehicles redistribution problem using vehicle platoons guided by professional drivers. An optimal routing algorithm is in charge of defining platoons drivers' routes to the parking areas where the followers are parked in a complete automated mode. The consortium is made of 2 academic partners : Inria (RITS, Chroma, Prima) and Ircyyn Ecole Centrale de Nantes and the AKKA company.

In the VALET project we will propose a novel approach for solving car-sharing vehicles redistribution problem using vehicle platoons guided by professional drivers, retrieving vehicles parked randomly on the urban parking network by users. The phD student (Pavan Vashista) recruited in this project will focus on integrating models of human behaviors (pedestrian and/or drivers), proxemics (human management of space) and traffic rules to evaluate and communicate a risk to pedestrians that may encounter the trajectory of the VALET vehicle. His PhD thesis has started on february 2016 and is co-supervized by D. Vaufreydaz (Inria/PervasiveInteraction).

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. "ENABLE" Ecsel Project

ENABLE-S3 means "European Initiative to Enable Validation for Highly Automated Safe and Secure Systems". It is a H2020 Ecsel project.

ENABLE-S3 is *industry-driven* and therefore aims to foster the leading role of the European industry. This is also reflected in its *use case driven approach*. The main technical objectives are extracted from the use cases defined by the industrial partners, in order to validate the success of the developed methods and tools.

Recent scientific publications from the automotive domain predict that more than 100 Mio km of road driving is required for the thorough validation of a fully automated vehicle. Only if this extensive test is done, it is statistically proven that the automated vehicle is as safe as a manually driven car. Taking further into account the high number of vehicle variants and software versions, one can easily understand that *new validation approaches* are required to validate new Electronics, Components and Systems (ECS) for automated vehicles within a reasonable time period at reasonable costs. The same characteristic hold for other transportation domains such as aeronautics, maritime or rail.

The ENABLE-S3 project will provide European industry with leading-edge technologies that *support the development of reliable, safe and secure functions for highly automated and/or autonomously operating systems* by enabling the *validation and verification at reduced time and costs*.

Enables-S3 is a large European consortium, involving a French consortium leaded by Valeo, and including Thales, Renault and Inria. The project will start in March-April 2016 and will have a duration of 3 years.

9.3.2. Collaborations with Major European Organizations

- Autonomous System laboratory: ETHZ, Zurich (Switzerland)

  Subject: Vision and IMU data Fusion for 3D navigation in GPS denied environment.
- Robotics and Perception Group: University of Zurich (Switzerland)

  Subject: Vision and IMU data Fusion for 3D navigation in GPS denied environment.
- Karlsruhe Institut fur Technologie (KIT, Germany)

  Subject: Autonomous Driving (student exchanges and common project).
- Vislab Parma (Italy)

  Subject: Embedded Perception & Autonomous Driving (visits, projects submissions, and book chapter in the new edition of the Handbook of Robotics).
- University of Babes-Bolyai, Cluj-Napoca, Romania.

Subject: Multi-robot patrolling and Machine Learning (Visit and PHC "DRONEM" 2017-18 obtained in December 2016).

- Department of Electrical & Computer Engineering: University of Thrace, Xanthi (GREECE)

  Subject: 3D coverage based on Stochastic Optimization algorithms
- Universidade de Aveiro (Portugal)

  Subject: Leader following. co-direction of P. Stein phD.
- Centro De Automatica y Robotica, UPM-CSIC, Madrid (Spain)

  Subject: Target interception.
- Bonn-Rhein-Sieg University of Applied Sciences (Germany)

  Subject: Using Semantic Information for Robot Navigation.
- Social Robotics Laboratory, Freiburg (Germany)

  Subject: Human behavior understanding.
- BlueBotics: BlueBotics Company, Lausanne (Switzerland)

  Subject: Implementation of self-calibration strategies for wheeled robots and SLAM algorithms for industrial purposes.

9.4. International Initiatives

9.4.1. Inria International Labs

- iCeiRA [0] international robotics laboratory led by Prof Ren Luo from NTU (Taiwan). Christian Laugier (Inria) and Raja Chatila (UPMC & CNRS) have actively participated to the starting of this laboratory in 2012 and are external Principal Investigators.

  Subject: Human centered robotics.

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

9.4.2.1. SAMPEN

Title: self adaptive mobile perception and navigation

International Partner (Institution - Laboratory - Researcher):

Start year: 2014

See also: http://emotion.inrialpes.fr/people/spalanzani/HomeSAMPEN.html

The associate team project is a Robotic project. The aim of the project is to propose a self-adaptive system of perception combined with a system of autonomous navigation. Usually, systems of perception rely on a set of specific sensors and a calibration is done in a specific environment. We propose to develop some methods to make perception systems adaptive to the environmental context and to the set of sensors used. This perception, that can be embedded on the mobile robot as well as on home structures (wall, ceiling, floor), will be helpful to localize agents (people, robot) present in the scene. Moreover, it will give information to better understand social scenes. All information will be used by the navigation system to move with a behavior that fit the context.

9.4.3. Inria International Partners

9.4.3.1. Informal International Partners

- UC Berkeley & Stanford University (CA, USA)

  Subject: Autonomous Driving (postdoc in the scope of Inria@SV, common publications and patent).
- Massachussetts Institute of Technology (MIT), Cambridge, MA (USA)

  Subject: Decentralized Control of Markov Decision Processes.

[0] International Center of Excellence in Intelligent Robotics and Automation Research.

9.4.4. Participation in Other International Programs

- IEEE Robotics and Automation. Christian Laugier is member of several IEEE committees, in particular: IROS Steering committee, co-chair of Technical Committee on Autonomous Ground vehicles and Intelligent Transport Systems, Steering committee and Senior Editor of IEEE Transactions on Intelligent Vehicles. Olivier Simonin is member of the TC on Multi-Robot Systems (MRS).

  Subject: International Robotics Research Supporting.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

- O. Simonin was co-chair of the Workshop DEMUR "On-line decision-making in multi-robot coordination" at International Conf. RSS, Ann Arbor, University of Michigan, June 2016.
- O. Simonin was General chair of the 2eme Journée nationale Robotique & IA., Clermont-Ferrand, RFIA 2016, 27 juin 2016.
- C. Laugier, Ph. Martinet, C. Stiller and U. Nunes, organized a workshop entitled "8th Workshop on Planning, Perception and Navigation for Intelligent Vehicles - A bridge between Robotics and ITS technologies" at IEEE ITSC 2016, Rio de Janeiro, November 1st 2016 (about 90 attendees).
- C. Laugier has been appointed as Program co-chair for IEEE/RSJ IROS 2018 (Madrid) and General co-Chair of IEEE/RSJ IROS 2019 (Hong Kong).

10.1.1.2. Member of the Organizing Committees

- C. Laugier was Associate Editor for IEEE/RSJ IROS 2016, for IEEE ICRA 2016, and for IEEE ITSC 2016.

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

- Jilles S. Dibangoye was Program Committee member of the following conferences:
  - International Joint Conference on Artificial Intelligence (IJCAI)
  - Autonomous Agent and Multi-agent Systems International Conference (AAMAS)
- O. Simonin is Program Committee member for Autonomous Agent and Multi-agent Systems International Conference (AAMAS) Special Track Robotics.
- O. Simonin is Program Committee member of the JFSMA conference since 2008 (Journées Francophones sur les Systèmes Multi-Agents).

10.1.2.2. Reviewer

- A. Martinelli served, in quality of reviewer, at the following international conferences: ICRA 2016, IROS 2016, ACC 2016.
- O. Simonin served, in quality of reviewer, at the following international conferences : IROS 2016, ICRA 2016.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- C. Laugier is Member of the Steering Committee of the journal IEEE Transaction on Intelligent Vehicles.
- C. Laugier Senior Editor of the journal IEEE Transaction on Intelligent Vehicles.

- C. Laugier is member of the Editorial Board of the journal IEEE ROBOMECH
- O. Simonin is a member of the editorial board of RIA Revue d'Intelligence Artificielle.

10.1.3.2. Reviewer - Reviewing Activities

- A. Martinelli served, in quality of reviewer, for the following journals: Transaction on Automation Science and Engineering, IEEE Robotics and Automation Letters.
- Jilles S. Dibangoye served as a reviewer for the following journals: Journal on Artificial Intelligence Research (JAIR), Artificial Intelligence Journal (AIJ), IEEE Transactions on Robotics (TRO).
- O. Simonin serves, in quality of reviewer, for Autonomous Robots Journal (AURO) and the Revue d'Intelligence Artificielle (RIA).

10.1.4. Invited Talks

Anne Spalanzani was invited to give a talk at

- Xerox (Meylan), september 2016.
- the conference RFIA (Clermont Ferrand), June 2016.
- the journées scientifique d'Inria (Rennes), June 2016.

Agostino Martinelli was invited to give a talk at

- Centro Piaggio, University of Pisa, June 2016, “Nonlinear Unknown Input Observability: the General Analytic Solution”.
- Automation Lab, University of Tor Vergata, Rome, December 2016, “Nonlinear Unknown Input Observability: the General Analytic Solution”.
- Vision and Perception lab., University of Zurich, December 2016, “Visual-Inertial Sensor Fusion”.

Christian Laugier was invited to give a talk at

- IEEE ICIT 2016, Session on Cognitive Systems and Automation for Service Robotics and Intelligent Mobility, Taipei, March 2016, "Bayesian Perception & Decision for Autonomous Vehicles and Mobile Robots”.
- Mediatek International Company, Hsinchu, Taiwan, March 15th 2016, “Bayesian Perception Technologies and Industrial Applications”.
- City-U Seminar, Hong Kong, April 22nd 2016, “Bayesian Perception & Decision for Autonomous vehicles and Mobile Robots”.
- Robotics Symposium, CUHK, T-Stone Robotics Institute, Hong Kong, April 21-22 2016, “Embedded Bayesian Perception & Decision-making for Autonomous Mobility in Dynamic Human Environments”.
- IEEE ARSO 2016, Plenary talk, Shanghai, July 2016, “Towards Fully Autonomous Driving ? The Perception & Decision-Making Bottleneck”.

Olivier Simonin was invited to give a talk at

- Université de Babes-Bolyai, Cluj-Napoca, Romania, July 2016.
- Workshop SAMPEN, Lyon, Januray 27, 2016.
- Robotics Times Connect, Lyon, December 7, 2016.

10.1.5. Leadership within the Scientific Community

- C. Laugier is co-chair with Philippe Martinet and Christoph Stiller, of the IEEE RAS Technical Committee on "Autonomous Ground Vehicles and Intelligent Transportation Systems (AGVITS)".
- C. Laugier is member of the Committee "safety of autonomous vehicles" (committee leaded by ARDI in the scope of the Innovation Regional Strategy).

10.1.6. Scientific Expertise

- C. Laugier has been invited as a panel member of the evaluation committee of "Beijing Institute of Technology (BIT)". A three days evaluation seminar has been held in Beijing on November 9-11, 2016.
- C. Laugier is Scientific Consultant for the Probayes company.
- O. Simonin is member of the 2017 ANR scientific committee.

10.1.7. Research Administration

- C. Laugier is a member of several Ministerial and Regional French Committees on Robotics and Autonomous Cars.
- O. Simonin is member of the Rhone-Alpes Robotics cluster (Coboteam), for Inria and INSA de Lyon entities.
- A. Martinelli carried out the activity of leader for the ANR project VIMAD
- A. Martinelli carried out the activity of leader for the CARNOT project SEDIA

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

INSA Lyon 5th year : O. Simonin, resp. of the Robotics option : AI for Robotics, Software and Hardware for robotics, Robotics projects, 50h, M2, Dept. Telecom INSA de Lyon, France.

INSA Lyon 3rd year : O. Simonin, Algorithmique et programmation, 20h, L3, Dept. Telecom INSA de Lyon, France.

M2R MoSIG: A. Martinelli, Autonomous Robotics, 12h, ENSIMAG Grenoble

INSA Lyon 5th year : A. Spalanzani, Navigation en environnement humain, 2h, M2, INSA de Lyon, France.

E-learning

10.2.2. Supervision

PhD in progress: Tiana Rakotovao Andriamahefa, Embedded Bayesian Perception on a Multi-core Architecture, 2013, C. Laugier and D. Ruspini (CEA LETI).

PhD in progress: David Sierra Gonzalez, Autonomous Driving, 2014, E. Mazer (Inria Prima), J. Dibangoye, C. Laugier (cooperation Toyota).

PhD in progress: Mathieu Barbier, Decision making for Intelligent Vehicles, 2015, E. Mazer (Inria Prima), O. Simonin, C. Laugier (cooperation Renault)

PhD in progress: Vishnu K. Narayanan, semi-autonomous navigation of a electric wheelchair using visual servoing and user intention analysis, 2013, M. Babel (Lagadic Team) and A. Spalanzani.

PhD in progress: Stefan Chitic, Middleware for multi-robot systems, 2013, O. Simonin, J. Ponge (CITI-Dynamid), Ministry funding.

PhD in progress: Pavan Vasishta, behavioral modeling in urban environments. A. Spalanzani and D. Vaudreydaz (Pervasive Interaction), started in Feb. 2016.

PhD in progress: Mihai Popescu, Robot fleet mobility under communication constraints, 2015, O. Simonin, A. Spalanzani, F. Valois (Agora), Regional funding.

Starting PhD: Guillaume Bono, Global-local Optimization Under Uncertainty for Goods Distribution Using a Fleet of Autonomous Vehicles, O. Simonin, J. Dibangoye, L. Matignon, INSA-Volvo Chair funding.

Starting PhD: Remi Cambuzat, Robots de TEléprésence : Navigation Sociale et Interaction VErbale immersives, G. Bailly (CNRS GIPSA lab), A. Spalanzani, O. Simonin, Regional funding.

10.2.3. Juries

- O. Simonin was a member (president) of the defense committee of the PhD thesis of Emmanuel Hermellin, Univ. de Montpellier, LIRMM, November 18, 2016.
- O. Simonin was a member of the defense committee of the PhD thesis of Arnaud Paris, Université d'Orléan, Labo PRISME, Bourges, October 17, 2016.
- O. Simonin was a member of the defense committee of the PhD thesis of Patrick Bechon, Université de Toulouse, ISAE Supaero, May 26, 2016.
- O. Simonin was a member (president) of the defense committee of the PhD thesis of Osamah Saif, Université de Technologie de Compiègne UTC, March 23, 2016.
- O. Simonin was a member (president) of the defense committee of the PhD thesis of Zhicheng Hou, Université de Technologie de Compiègne UTC, February 10, 2016.
- A. Spalanzani was a reviewer and a member of the defense committee of the PhD thesis of Omar Adair Islas Ramìrez, Université Pierre et Marie Curie, November 28th, 2016.
- A. Spalanzani was a member of the defense committee of the PhD thesis of Suman Raj Bista, Université de Rennes 1, December 20th, 2016.
- C. Laugier was reviewer and member of the defense committee of the PhD thesis of Alexandre Armand (ENSTA ParisTech, May 31 2016).

11. Bibliography

Major publications by the team in recent years

[1] M. ANDRIES, O. SIMONIN, F. CHARPILLET.*Localisation of humans, objects and robots interacting on load-sensing floors*, in "IEEE Sensors Journal", 2015, vol. PP, n^o^ 99, 12 [*DOI :* 10.1109/JSEN.2015.2493122], https://hal.inria.fr/hal-01196042.

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[3] J. S. DIBANGOYE, O. BUFFET, O. SIMONIN.*Structural Results for Cooperative Decentralized Control Models*, in "24th International Joint Conference on Artificial Intelligence (IJCAI)", 2015, p. 46–52.

[4] J. KAISER, A. MARTINELLI, F. FONTANA, D. SCARAMUZZA.*Simultaneous State Initialization and Gyroscope Bias Calibration in Visual Inertial aided Navigation*, in "IEEE Robotics and Automation Letters", January 2016, https://hal.archives-ouvertes.fr/hal-01423550.

[5] A. MARTINELLI.*Closed-form solution of visual-inertial structure from motion*, in "International Journal of Computer Vision", August 2013, online, https://hal.archives-ouvertes.fr/hal-00905881.

[6] P. PAPADAKIS, A. SPALANZANI, C. LAUGIER.*Social Mapping of Human-Populated Environments by Implicit Function Learning*, in "IEEE International Conference on Intelligent Robots and Systems", Tokyo, Japan, 2013, https://hal.inria.fr/hal-00860618.

[7] M.-I. POPESCU, H. RIVANO, O. SIMONIN.*Multi-robot Patrolling in Wireless Sensor Networks using Bounded Cycle Coverage*, in "ICTAI 2016 28th International Conference on Tools with Artificial Intelligence", San Jose, United States, IEEE, November 2016, https://hal.archives-ouvertes.fr/hal-01357866.

[8] T. RAKOTOVAO, J. MOTTIN, D. PUSCHINI, C. LAUGIER.*Multi-sensor fusion of occupancy grids based on integer arithmetic*, in "In 2016 IEEE International Conference on Robotics and Automation (ICRA)", 2016.

[9] A. SPALANZANI, J. RIOS-MARTINEZ, C. LAUGIER, S. LEE.*Risk Based Navigation Decisions*, in "Handbook of Intelligent Vehicles", A. ESKANDARIAN (editor), Springer Verlag, February 2012, vol. 1, http://hal.inria.fr/hal-00743336.

[10] D. VASQUEZ.*Novel Planning-based Algorithms for Human Motion Prediction*, in "IEEE Conference on Robotics and Automation", Stockholm, Sweden, May 2016, https://hal.inria.fr/hal-01256516.

Publications of the year

Articles in International Peer-Reviewed Journal

[11] J. S. DIBANGOYE, C. AMATO, O. BUFFET, F. CHARPILLET.*Optimally Solving Dec-POMDPs as Continuous-State MDPs*, in "Journal of Artificial Intelligence Research", February 2016, vol. 55, p. 443-497 [*DOI :* 10.1613/JAIR.4623], https://hal.inria.fr/hal-01279444.

[12] J. KAISER, A. MARTINELLI, F. FONTANA, D. SCARAMUZZA.*Simultaneous State Initialization and Gyroscope Bias Calibration in Visual Inertial aided Navigation*, in "IEEE Robotics and Automation Letters", January 2016, https://hal.archives-ouvertes.fr/hal-01423550.

Articles in National Peer-Reviewed Journal

[13] M. TLIG, O. BUFFET, O. SIMONIN.*Intersections intelligentes pour le contrôle de véhicules sans pilote : coordination locale et optimisation globale*, in "Revue des Sciences et Technologies de l'Information - Série RIA : Revue d'Intelligence Artificielle", 2016, https://hal.inria.fr/hal-01330354.

Invited Conferences

[14] C. LAUGIER.*Bayesian Perception & Decision for Autonomous Vehicles and Mobile Robots (Invited Talk)*, in "IEEE ICIT 2016", Taipei, Taiwan, Prof Ren Luo, March 2016, https://hal.inria.fr/hal-01435868.

[15] C. LAUGIER.*Embedded Bayesian Perception & Decision-making for Autonomous Mobility in Dynamic Human Environments (Invited Talk)*, in "Robotics Symposium, CUHK Robotics Institute", Hong Kong, Hong Kong SAR China, April 2016, https://hal.inria.fr/hal-01428627.

[16] C. LAUGIER.*Embedded Perception & Risk Assessment for next Cars Generation (Invited Talk)*, in "Asprom-Cap'Tronic-UIMM seminar: “De la voiture connectée à la voiture Autonome : Technologies, Enjeux et Applications »", Paris, France, Asprom-Cap'Tronic-UIMM, February 2016, https://hal.inria.fr/hal-01428211.

[17] C. LAUGIER.*Towards Fully Autonomous Driving ? The Perception & Decision-making bottleneck (Plenary Talk)*, in "IEEE ARSO 2016", Shanghai, China, Proceedings of IEEE ARSO 2016, July 2016, vol. 2016, https://hal.inria.fr/hal-01435861.

International Conferences with Proceedings

[18] M. BARBIER, C. LAUGIER, O. SIMONIN, J. IBANEZ-GUZMAN.*Functional Discretization of Space Using Gaussian Processes for Road Intersection*, in "2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC 2016)", Rio de Janeiro, Brazil, proceedings of the 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC 2016, IEEE Intelligent Transportation Systems Society, November 2016, 7, https://hal.inria.fr/hal-01362223.

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[24] C. LAUGIER, J. CHARTRE.*Intelligent Perception and Situation Awareness for Automated vehicles*, in "Conference GTC Europe 2016", Amsterdam, Netherlands, September 2016, https://hal.inria.fr/hal-01428547.

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[26] D. SIERRA GONZÁLEZ, J. S. DIBANGOYE, C. LAUGIER.*High-Speed Highway Scene Prediction Based on Driver Models Learned From Demonstrations*, in "Proceedings of the 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC 2016)", Rio de Janeiro, Brazil, November 2016, https://hal.inria.fr/hal-01396047.

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[28] J. SARAYDARYAN, F. JUMEL, O. SIMONIN.*Patrouille Multi-Agent Dynamique, application en Robotique au Service de Personnes Mobiles*, in "Journées Francophones sur les Systèmes Multi-Agents (JFSMA) 2016", Rouen, France, October 2016, https://hal.archives-ouvertes.fr/hal-01357609.

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[29] J. CHARTRE, L. RUMMELHARD, A. NÈGRE, J.-A. DAVID, J. LUSSEREAU, C. LAUGIER.*Situation Awareness for Intelligent Mobility in Dynamic Environments IRT Nanoelec Perfect Platform*, in "5th International conference on Machine Control & Guidance", Vichy, France, October 2016, https://hal.inria.fr/hal-01393287.

[30] J. SARAYDARYAN, F. JUMEL, O. SIMONIN.*Modeling human flows from robots perception : application to navigation in dynamic environment*, in "RSS Workshop On-line decision-making in multi-robot coordination", Ann Arbor, United States, June 2016, https://hal.archives-ouvertes.fr/hal-01357791.

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[32] C. LAUGIER.*Autnonomous Vehicles: Societal and Technological Evolution (Invited Contribution)*, December 2016, Table ronde "Vehicule Autonome et Ville de Demain - Technologie, Business et Société: Quels enjeux ?" Issy-les-Moulineaux, https://hal.inria.fr/hal-01437003.

[33] C. LAUGIER.*Bayesian Perception & Decision for Autonomous Vehicles and Mobile Robots: From Research to Industrial Applications*, March 2016, Invited talk at MediaTek, Taipei, https://hal.inria.fr/hal-01436967.

[34] C. LAUGIER.*Bayesian Perception & Decision-making for Robot Navigation in Dynamic Environments (Invited Talk)*, April 2016, Invited talk at CityU Hong Kong, https://hal.inria.fr/hal-01436976.

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[43] J. S. DIBANGOYE, C. AMATO, O. BUFFET, F. CHARPILLET.*Exploiting Separability in Multiagent Planning with Continuous-State MDPs (Extended Abstract)*, in "24th International Joint Conference on Artificial Intelligence (IJCAI)", 2015, p. 4254–4260.

[44] G. FERRER, A. SANFELIU.*Bayesian Human Motion Intentionality Prediction in urban environments*, in "Pattern Recognition Letters", 2014, vol. 44, n^o 0, p. 134 - 140, Pattern Recognition and Crowd Analysis [*DOI :* 10.1016/J.PATREC.2013.08.013], http://www.sciencedirect.com/science/article/pii/S0167865513003176.

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Team COMPSYS

Compilation and Embedded Computing Systems

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Architecture, Languages and Compilation

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Team COMPSYS

Creation of the Project-Team: 2004 January 01, updated into Team: 2016 January 01, end of the Team: 2016 December 31

Keywords:

Computer Science and Digital Science:
2.1.1. - Semantics of programming languages
2.1.6. - Concurrent programming
2.1.10. - Domain-specific languages
2.2.1. - Static analysis
2.2.5. - GPGPU, FPGA, etc.
2.4.1. - Analysis
6.2.6. - Optimization
6.2.7. - High performance computing
7.2. - Discrete mathematics, combinatorics

Other Research Topics and Application Domains:
6.6. - Embedded systems
9.4.1. - Computer science

Compsys is located at Ecole Normale Supérieure de Lyon.

1. Members

Research Scientists
Alain Darte [Team leader, CNRS, Senior Researcher, HDR]
Tomofumi Yuki [Inria, Researcher]

Faculty Member
Paul Feautrier [ENS Lyon, Emeritus Professor, HDR]

PhD Students
Alexandre Isoard [ENS Lyon, until May 2016]
Guillaume Iooss [ENS Lyon/Colorado State University, until July 2016]

Visiting Scientists
Hammami Emna [PhD student, Tunis University, April-June 2016]
Julien Versaci [Master 2 internship, Claude Bernard University, April-June 2016]
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Chiraz Benamor [ENS]

2. Overall Objectives

2.1. Introduction

Keywords: Compilation, code analysis, code optimization, memory optimization, combinatorial optimization, algorithmics, polyhedral optimization, hardware accelerators, high-level synthesis, high-performance computing, multicore, GPU, FPGA, DSP.

Compsys has been developing compilation techniques, more precisely code analysis and code optimization techniques, to help programming or designing "embedded computing systems" and platforms for "small" HPC (High-Performance Computing). The team focused first on both low-level (back-end) optimizations and high-level (front-end, mainly source-to-source) transformations, for specialized embedded processors (DSP) and high-level synthesis of hardware accelerators (FPGA). More recent activities included a shift towards abstract interpretation and program termination, the compilation for GPUs and multicores, and the analysis of parallel languages. The main characteristic of Compsys is its use of algorithmic and formal methods (with graph algorithms, linear programming, polyhedral optimizations) to address code analysis and optimization problems (e.g., termination, register allocation, memory optimizations, scheduling, automatic generation of interfaces) and the validation of these techniques through the development of compilation tools.

Compsys started as an Inria project in 2004, after 2 years of maturation. This first period of Compsys, Compsys I, was positively evaluated in Spring 2007 after its first 4 years period (2004-2007). It was again evaluated by AERES in 2009, as part of the general evaluation of LIP, and got the best possible mark, A+. The second period (2007-2012), Compsys II, was again evaluated positively by Inria in Spring 2012 and formally prolonged into Compsys III at the very end of 2012. In 2013, Fabrice Rastello moved to Grenoble first to expand the activities of Compsys in the context of Giant, a R&D technology center with several industrial and academic actors. He left officially the team in 2014 to work on his own. The research directions of Compsys III then followed the lines presented in the synthesis report provided for the 2012 evaluation, including a shift towards the compilation of streaming programming, the analysis and optimizations of parallel languages, and an even stronger focus on polyhedral optimizations and their extensions. While Christophe Alias was mostly involved in his developments of the Zettice/XTREMLOGIC start-up, the hiring of Laure Gonnord (in 2013) and Tomofumi Yuki (in 2014) added new forces on the code analysis research aspects and on HPC polyhedral-related topics. However, Christophe Alias and Laure Gonnord left the team in Sep. 2015. Reaching the limit of 12 years, the project-team ended officially in Dec. 2015, but with no possible future as a new project, because it was below critical mass. Compsys was nevertheless extended as an Inria team until Dec. 2016, in particular to allow the (positive) final Inria evaluation in Spring 2016 and to let the last participants think about their future. At the end of 2016, Tomofumi Yuki moved back to Rennes in the Cairn Inria team, Paul Feautrier is still a member of LIP as an emeritus professor at ENS-Lyon but is now a long term visitor to the Parkas Inria team in Paris, and Alain Darte remains CNRS researcher at LIP, ENS-Lyon, but is not affiliated to Inria anymore.

Section 2.2 defines the general context of the team's activities. Section 2.3 presents the research objectives and main achievements in Compsys I, i.e., until 2007. Section 2.4 shows how the research directions of the team were modified for Compsys II and outlines the main results we obtained in this period (until 2012). Finally, Section 2.5 summarizes the goals and achievements of Compsys III. More details can be found in the annual Inria reports. As for the highlights of the past year, i.e., 2016, they are given in Section 5.1.

2.2. General Presentation

Classically, an embedded computer is a digital system that is part of a larger system and that is not directly accessible to the user. Examples are appliances like phones, TV sets, washing machines, game platforms, or even larger systems like radars and sonars. In particular, this computer is not programmable in the usual way. Its program, if it exists, is supplied as part of the manufacturing process and is seldom (or ever) modified thereafter. As the embedded systems market grows and evolves, this view of embedded systems is becoming obsolete and tends to be too restrictive. Many aspects of general-purpose computers apply to modern embedded platforms. Nevertheless, embedded systems remain characterized by a set of specialized application domains, rigid constraints (cost, power, efficiency, heterogeneity), and its market structure. The term *embedded system* has been used for naming a wide variety of objects. More precisely, there are two categories of so-called *embedded systems*: a) control-oriented and hard real-time embedded systems (automotive, plant control, airplanes, etc.); b) compute-intensive embedded systems (signal processing, multi-media, stream processing) processing large data sets with parallel and/or pipelined execution. Compsys is primarily concerned with this second type of embedded systems, referred to as *embedded computing systems*.

Today, the industry sells many more embedded processors than general-purpose processors; the field of embedded systems is one of the few segments of the computer market where the European industry still has a substantial share, hence the importance of embedded system research in the European research initiatives. Our priority towards embedded software was motivated by the following observations: a) the embedded system market was expanding, among many factors, one can quote pervasive digitalization, low-cost products, appliances, etc.; b) research on software for embedded systems was poorly developed in France, especially if one considers the importance of actors like Alcatel, STMicroelectronics, Matra, Thales, etc.; c) since embedded systems increase in complexity, new problems are emerging: computer-aided design, shorter time-to-market, better reliability, modular design, component reuse, etc.

A specific aspect of embedded computing systems is the use of various kinds of processors, with many particularities (instruction sets, registers, data and instruction caches, now multiple cores) and constraints (code size, performance, storage, power). The development of *compilers* is crucial for this industry, as selling a platform without its programming environment and compiler would not be acceptable. To cope with such a range of different processors, the development of robust, generic (retargetable), though efficient compilers is mandatory. Unlike standard compilers for general-purpose processors, compilers for embedded processors and hardware accelerators can be more aggressive (i.e., take more time to optimize) for optimizing some important parts of applications. This opens a new range of optimizations. Another interesting aspect is the introduction of platform-independent intermediate languages, such as Java bytecode, that is compiled dynamically at runtime (aka just-in-time). Extreme lightweight compilation mechanisms that run faster and consume less memory have to be developed. The introduction of intermediate languages such as OpenCL was also a sign of the need for portability (as well as productivity) across diverse (if not heterogeneous) platforms. One of the initial objectives of Compsys was thus to revisit existing compilation techniques in the context of such embedded computing systems, to deconstruct some of these techniques, to improve them, and to develop new techniques taking constraints of embedded processors and platforms into account.

As for *high-level synthesis* (HLS), several compilers/systems have appeared, after some first unsuccessful industrial attempts in the past. These tools are mostly based on C or C++ as for example SystemC, VCC, CatapultC, Altera C2H, Pico-Express, Vivado HLS. Academic projects also exist (or existed) such as Flex and Raw at MIT, Piperench at Carnegie-Mellon University, Compaan at the University of Leiden, Ugh/Disydent at LIP6 (Paris), Gaut at Lester (Bretagne), MMAlpha (Insa-Lyon), and others. In general, the support for parallelism in HLS tools is minimal, especially in industrial tools. Also, the basic problem that these projects have to face is that the definition of performance is more complex than in classical systems. In fact, it is a multi-criteria optimization problem and one has to take into account the execution time, the size of the program, the size of the data structures, the power consumption, the manufacturing cost, etc. The impact of the compiler on these costs is difficult to assess and control. Success will be the consequence of a detailed knowledge of all steps of the design process, from a high-level specification to the chip layout. A strong cooperation of the compilation and chip design communities was needed. The main expertise in Compsys for this aspect was in the *parallelization* and optimization of *regular computations*. Hence, we targeted applications with a large potential parallelism, but we attempted to integrate our solutions into the big picture of CAD environments.

More generally, the aims of Compsys were to develop new compilation and optimization techniques for the field of embedded computing system design. This field is large, and Compsys did not intend to cover it in its entirety. As previously mentioned, we were mostly interested in the automatic design of accelerators, for example designing a VLSI or FPGA circuit for a digital filter, or later GPUs and multicores, and in the development of new back-end compilation strategies for embedded processors. We studied code transformations that optimize features such as execution time, power consumption, code and die size, memory constraints, and compiler reliability. These features are related to embedded systems but some are not specific to them. The code transformations we developed were both at source level and at assembly level. A specificity of Compsys has always been to mix a solid theoretical basis for all code optimizations we introduced with algorithmic/software developments. Within Inria, our project was related to the "architecture and compilation" theme, more precisely code optimization, as some of the research conducted in Parkas (previously known as Alchemy), Alf (previously known as Caps), Camus, and to high-level architectural synthesis, as some of the research in Cairn.

At the end of the 90s, most french researchers working on high-performance computing (automatic parallelization, languages, operating systems, networks) moved to grid computing. We thought that applications, industrial needs, and research problems were more interesting in the design of embedded platforms. Furthermore, we were convinced that our expertise on high-level code transformations could be more useful in this field. This is the reason why Tanguy Risset came to Lyon in 2002 to create the Compsys team with Anne Mignotte and Alain Darte, before Paul Feautrier, Antoine Fraboulet, and Fabrice Rastello joined the group. Before integrating the team, all Compsys members had a background in automatic parallelization, and high-level program analyses and transformations. Paul Feautrier was the initiator of the polyhedral model for program transformations around 1990 and, before coming to Lyon, started to be more interested in programming models and optimizations for embedded applications, in particular through collaborations with Philips. Alain Darte worked on mathematical tools and algorithmic issues for parallelism extraction in programs. He became interested in the automatic generation of hardware accelerators, thanks to his stay at HP Labs in the Pico project in 2001. Antoine Fraboulet did a PhD with Anne Mignotte – who was working on high-level synthesis (HLS) – on code and memory optimizations for embedded applications. Fabrice Rastello did a PhD on tiling transformations for parallel machines, then was hired by STMicroelectronics where he worked on assembly code optimizations for embedded processors. Tanguy Risset worked for a long time on the synthesis of systolic arrays, being the main architect of the HLS tool MMAlpha. Christophe Alias did a PhD on algorithm recognition for program optimizations and parallelization, and two post-docs, one in Compsys on array contraction, one in Ohio State University with Prof. P. Sadayappan on memory optimizations. Laure Gonnord did a PhD on invariant generation and program analysis and became interested on compilation and code generation since her postdoc in the team. Finally, Tomofumi Yuki did a PhD on polyhedral programming environments and optimizations (in Colorado State University, with Prof. S. Rajopadhye) before a post-doc on polyhedral HLS in the Cairn team (Rennes).

To understand why we think automation in our field is highly important, it may be worth to quote Bob Rau and his colleagues (IEEE Computer, Sep. 2002):

"Engineering disciplines tend to go through fairly predictable phases: ad hoc, formal and rigorous, and automation. When the discipline is in its infancy and designers do not yet fully understand its potential problems and solutions, a rich diversity of poorly understood design techniques tends to flourish. As understanding grows, designers sacrifice the flexibility of wild and woolly design for more stylized and restrictive methodologies that have underpinnings in formalism and rigorous theory. Once the formalism and theory mature, the designers can automate the design process. This life cycle has played itself out in disciplines as diverse as PC board and chip layout and routing, machine language parsing, and logic synthesis.

We believe that the computer architecture discipline is ready to enter the automation phase. Although the gratification of inventing brave new architectures will always tempt us, for the most part the focus will shift to the automatic and speedy design of highly customized computer systems using well-understood architecture and compiler technologies."

We share this view of the future of architecture and compilation. Without targeting too ambitious objectives, we were convinced of two complementary facts: a) the mathematical tools developed in the past for manipulating programs in automatic parallelization were lacking in high-level synthesis and embedded computing optimizations and, even more, they started to be rediscovered frequently in less mature forms, b) before being able to really use these techniques in HLS and embedded program optimizations, we needed to learn a lot from the application side, from the electrical engineering side, and from the embedded architecture side. Our primary goal was thus twofold: to increase our knowledge of embedded computing systems and to adapt/extend code optimization techniques, primarily designed for high performance computing, to the special case of embedded computing systems. In the initial Compsys proposal, we proposed four research directions, centered on compilation methods for embedded applications, both for software and accelerators design:

- Code optimization for specific processors (mainly DSP and VLIW processors);
- Platform-independent loop transformations (including memory optimization);
- Silicon compilation and hardware/software codesign;
- Development of polyhedral (but not only) optimization tools.

These research activities were primarily supported by a marked investment in polyhedra manipulation tools and, more generally, solid mathematical and algorithmic studies, with the aim of constructing operational software tools, not just theoretical results. Hence the fourth research theme was centered on the development of these tools.

2.3. Summary of Compsys I Achievements

The main achievements of Compsys I were the following:

- The development of a strong collaboration with the compilation group at STMicroelectronics, with important results in aggressive optimizations for instruction cache and register allocation.
- New results on the foundation of high-level program transformations, including scheduling techniques for process networks and a general technique for array contraction (memory reuse) based on the theory of lattices.
- Many original contributions with partners closer to hardware constraints, including CEA, related to SoC simulation, hardware/software interfaces, power models, and simulators.

The Compsys team has been evaluated by Inria for the first time in April 2007. The evaluation, conducted by Erik Hagersted (Uppsala University), Vinod Kathail (Synfora, inc), J. (Ram) Ramanujam (Baton Rouge University) was positive. Compsys I thus continued into Compsys II for 4-5 years but in a new configuration as Tanguy Risset (who was hired professor at Insa-Lyon) and Antoine Fraboulet (assistant professor at Insa-Lyon) left the project to follow research directions closer to their host laboratory at Insa-Lyon.

2.4. Summary of Compsys II Achievements

Due to Compsys size reduction (from 5 permanent researchers to 3 in 2008, then 4 again in 2009), the team then focused, in Compsys II, on two research directions only:

- Code generation for embedded processors, on the two opposite, though connected, aspects: aggressive compilation and just-in-time compilation.
- High-level program analysis and transformations for high-level synthesis tools.

The main achievements of Compsys II were:

- the great success of the collaboration with STMicroelectronics with many deep results on SSA (Static Single Assignment), register allocation, liveness scalar analysis, and intermediate program representations;
- the design of high-level program analysis, optimizations, and tools, mainly related to high-level synthesis (some leading to the development of the Zettice start-up), including liveness array analysis, memory folding, as well as program (while loops) termination.

For more details on the past years of Compsys II, see the previous annual reports from 2008 to 2012. Compsys II was positively evaluated in Spring 2012 by Inria. The evaluation committee members were Walid Najjar (University of California Riverside), Paolo Faraboschi (HP Labs), Scott Mahlke (University of Michigan), Pedro Diniz (University of Southern California), Peter Marwedel (TU Dortmund), and Pierre Paulin (STMicroelectronics, Canada), the last three assigned specifically to Compsys.

2.5. Summary of Compsys III Achievements

For Compsys III, the changes in the permanent members (departure of Fabrice Rastello and arrival of Laure Gonnord, while she was only external collaborator of Compsys until Sep. 2013) reduced the forces on back-end code optimizations, and in particular dynamic compilation, but increased (for a short period only) the forces on program analysis. In this context, Compsys III has continued to develop fundamental concepts or techniques whose applicability should go beyond a particular architectural or language trend, as well as stand-alone tools (either as proofs of concepts or to be used as basic blocks in larger tools/compilers developed by others) and our own experimental prototypes. One of the main objectives of Compsys III has been to try to push the polyhedral model beyond its present limits both in terms of analysis techniques (possibly integrating approximation and runtime support) and of applicability (e.g., analysis of parallel or streaming languages, program verification, compilation towards accelerators such as GPU or multicores). The hiring of Tomofumi Yuki supported this new direction. The achievements of Compsys III include work on:

- Back-end code analysis including fast scalar liveness analysis, register spilling analysis, pointer and array analysis.
- Polyhedral code analysis and optimizations, including communication analysis for kernel offloading to FPGA and GPU, analysis of while loops, analysis of parallel and streaming languages (liveness, memory folding, race detection), parametric tiling, polynomial extensions.

Compsys III was positively evaluated in Spring 2016 (with regrets with respect to its undesired stop) in Spring 2016. This evaluation also served as the final evaluation of Compsys after 12 years. The evaluation committee members were Krzystof Czarnecki (University of Waterloo), Benoît Dupont de Dinechin (Kalray), Nikil Dutt (UC Irvine), Walid Najjar (UC Riverside), Kristoffer Rose (Two Sigma Investments, NYW), Christian Schulte (KTH Royal Institute of Technology), Tulika Mitra (NUS), J. (Ram) Ramanujam (Lousiana State Univ.), Kathryn S. McKinley (chair, Microsoft), the last three being directly responsible for Compsys evaluation.

More details on the 2013, 2014, 2015 activities are given in the corresponding annual reports (see also the synthesis report provided for the 2016 evaluation). The new results for this year (2016) are given in Section 5.1 (highlights) and from Section 7.1 to 7.7 (new results).

3. Research Program

3.1. Architecture and Compilation Trends

The embedded system design community is facing two challenges:

- The complexity of embedded applications is increasing at a rapid rate.
- The needed increase in processing power is no longer obtained by increases in the clock frequency, but by increased parallelism.

While, in the past, each type of embedded application was implemented in a separate appliance, the present tendency is toward a universal hand-held object, which must serve as a cell-phone, as a personal digital assistant, as a game console, as a camera, as a Web access point, and much more. One may say that embedded applications are of the same level of complexity as those running on a PC, but they must use a more constrained platform in terms of processing power, memory size, and energy consumption. Furthermore, most of them depend on international standards (e.g., in the field of radio digital communication), which are evolving rapidly. Lastly, since ease of use is at a premium for portable devices, these applications must be integrated seamlessly to a degree that is unheard of in standard computers.

All of this dictates that modern embedded systems retain some form of programmability. For increased designer productivity and reduced time-to-market, programming must be done in some high-level language, with appropriate tools for compilation, run-time support, and debugging. This does not mean however that all embedded systems (or all of an embedded system) must be processor based. Another solution is the use of field programmable gate arrays (FPGA), which may be programmed at a much finer grain than a processor, although the process of FPGA "programming" is less well understood than software generation. Processors are better than application-specific circuits at handling complicated control and unexpected events. On the other hand, FPGAs may be tailored to just meet the needs of their application, resulting in better energy and silicon area usage. It is expected that most embedded systems will use a combination of general-purpose processors, specific processors like DSPs, and FPGA accelerators (or even low-power GPUs). Such a combination DSP+FPGA is already present in recent versions of the Atom Intel processor.

As a consequence, parallel programming, which has long been confined to the high-performance community, must become the common place rather than the exception. In the same way that sequential programming moved from assembly code to high-level languages at the price of a slight loss in performance, parallel programming must move from low-level tools, like OpenMP or even MPI, to higher-level programming environments. While fully-automatic parallelization is a Holy Grail that will probably never be reached in our lifetimes, it will remain as a component in a comprehensive environment, including general-purpose parallel programming languages, domain-specific parallelizers, parallel libraries and run-time systems, back-end compilation, dynamic parallelization. The landscape of embedded systems is indeed very diverse and many design flows and code optimization techniques must be considered. For example, embedded processors (micro-controllers, DSP, VLIW) require powerful back-end optimizations that can take into account hardware specificities, such as special instructions and particular organizations of registers and memories. FPGA and hardware accelerators, to be used as small components in a larger embedded platform, require "hardware compilation", i.e., design flows and code generation mechanisms to generate non-programmable circuits. For the design of a complete system-on-chip platform, architecture models, simulators, debuggers are required. The same is true for multicores of any kind, GPGPU ("general-purpose" graphical processing units), CGRA (coarse-grain reconfigurable architectures), which require specific methodologies and optimizations, although all these techniques converge or have connections. In other words, embedded systems need all usual aspects of the process that transforms some specification down to an executable, software or hardware. In this wide range of topics, Compsys concentrated on the code optimizations aspects (and the associated analysis) in this transformation chain, restricting to compilation (transforming a program to a program) for embedded processors and programmable accelerators, and to high-level synthesis (transforming a program into a circuit description) for FPGAs.

Actually, it is not a surprise to see compilation and high-level synthesis getting closer (in the last 10 years now). Now that high-level synthesis has grown up sufficiently to be able to rely on place-and-route tools, or even to synthesize C-like languages, standard techniques for back-end code generation (register allocation, instruction selection, instruction scheduling, software pipelining) are used in HLS tools. At the higher level, programming languages for programmable parallel platforms share many aspects with high-level specification languages for HLS, for example the description and manipulations of nested loops, or the model of computation/communication (e.g., Kahn process networks and its many "streaming" variants). In all aspects, the frontier between software and hardware is vanishing. For example, in terms of architecture, customized processors (with processor extensions as first proposed by Tensilica) share features with both general-purpose processors and hardware accelerators. FPGAs are both hardware and software as they are fed with "programs" representing their hardware configurations.

In other words, this convergence in code optimizations explains why Compsys studied both program compilation and high-level synthesis, and at both front-end and back-end levels, the first one acting more at the granularity of memories, transfers, and multiple cores, the second one more at the granularity of registers, system calls, and single core. Both levels must be considered as they interact with each other. Front-end optimizations must be aware of what back-end optimizations will do, as single core performance remain the basis for good parallel performances. Some front-end optimizations even act directly on back-end features, for example register tiling considered as a source-level transformation. Also, from a conceptual point of view, the polyhedral techniques developed by Compsys are actually the symbolic front-end counterpart, for structured loops, of back-end analysis and optimizations of unstructured programs (through control-flow graphs), such as dependence analysis, scheduling, lifetime analysis, register allocation, etc. A strength of Compsys was to juggle with both aspects, the first one based on graph theory with SSA-type optimizations, the other on polyhedra representing loops, and to exploit the correspondence between both. This has still to be exploited, for applying polyhedral techniques to more irregular programs. Besides, Compsys had a tradition of building free software tools for linear programming and optimization in general, as needed for our research.

3.1.1. Compilation and Languages Issues in the Context of Embedded Processors, "Embedded Systems", and Programmable Accelerators

Compilation is an old activity, in particular back-end code optimizations. The development of embedded systems was one of the reasons for the revival of compilation activities as a research topic. Applications for embedded computing systems generate complex programs and need more and more processing power. This evolution is driven, among others, by the increasing impact of digital television, the first instances of UMTS networks, and the increasing size of digital supports, like recordable DVD, and even Internet applications. Furthermore, standards are evolving very rapidly (see for instance the successive versions of MPEG). As a consequence, the industry has focused on programmable structures, whose flexibility more than compensates for their larger size and power consumption. The appliance provider has a choice between hard-wired structures (Asic), special-purpose processors (Asip), (quasi) general-purpose processors (DSP for multimedia applications), and now hardware accelerators (dedicated platforms – such as those developed by Thales or the CEA –, or more general-purpose accelerators such as GPUs or even multicores, even if these are closer to small HPC platforms than truly embedded systems). Our cooperation with STMicroelectronics, until 2012, focused on investigating the compilation for specialized processors, such as the ST100 (DSP processor) and the ST200 (VLIW DSP processor) family. Even for this restricted class of processors, the diversity is large, and the potential for instruction level parallelism (SIMD, MMX), the limited number of registers and the small size of the memory, the use of direct-mapped instruction caches, of predication, generated many open problems. Our goal was to contribute to their understanding and their solutions.

An important concept to cope with the diversity of platforms is the concept of *virtualization*, which is a key for more portability, more simplicity, more reliability, and of course more security. This concept – implemented at low level through binary translation and just-in-time (JIT) compilation [0] – consists in hiding the architecture-dependent features as long as possible during the compilation process. It has been used for a while for servers such as HotSpot, a bit more recently for workstations, and now for embedded computing. The same needs drive the development of intermediate languages such as OpenCL to, not necessarily hide, but at least make more uniform, the different facets of the underlying architectures. The challenge is then to design and compile high-productivity and high-performance languages [0] (coping with parallelism and heterogeneity) that can be ported to such intermediate languages, or to architecture-dependent runtime systems. The offloading of computation kernels, through source-to-source compilation, targeting back-end C dialects, has the same goals: to automate application porting to the variety of accelerators.

For JIT compilation, the compactness of the information representation, and thus its pertinence, is an important criterion for such late compilation phases. Indeed, the intermediate representation (IR) is evolving not only from a target-independent description to a target-dependent one, but also from a situation where the compilation time is almost unlimited (cross-compilation) to one where any type of resource is limited. This is one of the reasons why static single assignment (SSA), a sparse compact representation of liveness information, became popular in embedded compilation. If time constraints are common to all JIT compilers (not only for

[0] *Aggressive compilation* consists in allowing more time to implement more complete and costly solutions: compilation time is less relevant than execution time, size, and energy consumption of the produced code, which can have a critical impact on the cost and quality of the final product. The application is usually cross-compiled, i.e., compiled on a powerful platform distinct from the target processor. *Just-in-time compilation*, on the other hand, corresponds to compiling applets on demand on the target processor. The code can be uploaded or sold separately on a flash memory. Compilation is performed at load time and even dynamically during execution. The optimization heuristics, constrained by time and limited resources, are far from being aggressive. They must be fast but smart enough.

[0] For examples of such languages, see the keynotes event we organized in 2013: http://labexcompilation.ens-lyon.fr/hpc-languages.

embedded computing), the benefit of using SSA is also in terms of its good ratio pertinence/storage of information. It also enables to simplify algorithms, which is also important for increasing the reliability of the compiler. In this context, our aim has been, in particular, to develop exact or heuristic solutions to *combinatorial* problems that arise in compilation for VLIW and DSP processors, and to integrate these methods into industrial compilers for DSP processors (mainly ST100, ST200, Strong ARM). Such combinatorial problems can be found in register allocation, opcode selection, code placement, when removing the SSA multiplexer functions (known as ϕ functions). These optimizations are usually done in the last phases of the compiler, using an assembly-level intermediate representation. As mentioned in Sections 2.3 and 2.4, we made a lot of progress in this area in our past collaborations with STMicroelectronics (see also previous activity reports). Through the Sceptre and Mediacom projects, we first revisited, in the light of SSA, some code optimizations in an aggressive context, to develop better strategies, without eliminating too quickly solutions that may have been considered as too expensive in the past. Then we exploited the new concepts introduced in the aggressive context to design better algorithms in a JIT context, focusing on the speed of algorithms and their memory footprint, without compromising too much on the quality of the generated code.

Our recent research directions were more focused on programmable accelerators, such as GPU and multicores, but still considering *static* compilation and without forgetting the link between high-level (in general at source-code level) and low-level (i.e., at assembly-code level) optimizations. They concerned program analysis (of both sequential and parallel specifications), program optimizations (for memory hierarchies, parallelism, streaming, etc.), and also the link with applications, and between compilers and users (programmers). Polyhedral techniques play an important role in these directions, even if control-flow-based techniques remain in the background and may come back at any time in the foreground. This is also the case for high-level synthesis, as exposed in the next section.

3.1.2. Context of High-Level Synthesis and FPGA Platforms

High-level synthesis has become a necessity, mainly because the exponential increase in the number of gates per chip far outstrips the productivity of human designers. Besides, applications that need hardware accelerators usually belong to domains, like telecommunications and game platforms, where fast turn-around and time-to-market minimization are paramount. When Compsys started, we were convinced that our expertise in compilation and automatic parallelization could contribute to the development of the needed tools.

Today, synthesis tools for FPGAs or ASICs come in many shapes. At the lowest level, there are proprietary Boolean, layout, and place-and-route tools, whose input is a VHDL or Verilog specification at the structural or register-transfer level (RTL). Direct use of these tools is difficult, for several reasons:

- A structural description is completely different from an usual algorithmic language description, as it is written in term of interconnected basic operators. One may say that it has a spatial orientation, in place of the familiar temporal orientation of algorithmic languages.
- The basic operators are extracted from a library, which poses problems of selection, similar to the instruction selection problem in ordinary compilation.
- Since there is no accepted standard for VHDL synthesis, each tool has its own idiosyncrasies and reports its results in a different format. This makes it difficult to build portable HLS tools.
- HLS tools have trouble handling loops. This is particularly true for logic synthesis systems, where loops are systematically unrolled (or considered as sequential) before synthesis. An efficient treatment of loops needs the polyhedral model. This is where past results from the automatic parallelization community are useful.
- More generally, a VHDL specification is too low level to allow the designer to perform, easily, higher-level code optimizations, especially on multi-dimensional loops and arrays, which are of paramount importance to exploit parallelism, pipelining, and perform communication and memory optimizations.

Some intermediate tools were proposed that generate VHDL from a specification in restricted C, both in academia (such as SPARK, Gaut, UGH, CloogVHDL), and in industry (such as C2H, CatapultC, Pico-Express, Vivado HLS). All these tools use only the most elementary form of parallelization, equivalent to instruction-level parallelism in ordinary compilers, with some limited form of block pipelining, and communication through FIFOs. Targeting one of these tools for low-level code generation, while we concentrate on exploiting loop parallelism, might be a more fruitful approach than directly generating VHDL. However, it may be that the restrictions they impose preclude efficient use of the underlying hardware. Our first experiments with these HLS tools reveal two important issues. First, they are, of course, limited to certain types of input programs so as to make their design flows successful, even if, over the years, they become more and more mature. But it remains a painful and tricky task for the user to transform the program so that it fits these constraints and to tune it to get good results. Automatic or semi-automatic program transformations can help the user achieve this task. Second, users, even expert users, have only a very limited understanding of what back-end compilers do and why they do not lead to the expected results. An effort must be done to analyze the different design flows of HLS tools, to explain what to expect from them, and how to use them to get a good quality of results. Our first goal was thus to develop high-level techniques that, used in front of existing HLS tools, improve their utilization. This should also give us directions on how to modify them or to design new tools from scratch.

More generally, HLS has to be considered as a more global parallelization process. So far, no HLS tools is capable of generating designs with communicating *parallel* accelerators, even if, in theory, at least for the scheduling part, a tool such as Pico-Express could have such capabilities. The reason is that it is, for example, very hard to automatically design parallel memories and to decide the distribution of array elements in memory banks to get the desired performances with parallel accesses. Also, how to express communicating processes at the language level? How to express constraints, pipeline behavior, communication media, etc.? To better exploit parallelism, a first solution is to extend the source language with parallel constructs, as in all derivations of the Kahn process networks model, including communicating regular processes (CRP). The other solution is a form of automatic parallelization. However, classical methods, which are mostly based on scheduling, need to be revisited, to pay more attention to locality, process streaming, and low-level pipelining, which are of paramount importance in hardware. Besides, classical methods mostly rely on the runtime system to tailor the parallelism degree to the available resources. Obviously, there is no runtime system in hardware. The real challenge is thus to invent new scheduling algorithms that take resource, locality, and pipelining into account, and then to infer the necessary hardware from the schedule. This is probably possible only for programs that fit into the polyhedral model, or in an incrementally-extended model.

Our research activities on polyhedral code analysis and optimizations directly targeted these HLS challenges. But they are not limited to the automatic generation of hardware as can be seen from our different contributions on X10, OpenStream, parametric tiling, etc. The same underlying concepts also arise when optimizing codes for GPUs and multicores. In this context of polyhedral analysis and optimizations, we focused on three aspects:

- developing high-level transformations, especially for loops and memory/communication optimizations, that can be used in front of HLS tools so as to improve their use, as well as for hardware accelerators;
- developing concepts and techniques in a more global view of high-level synthesis and high-level parallel programming, starting from specification languages down to hardware implementation;
- developing more general code analysis so as to extract more information from codes as well as to extend the programs that can be handled.

3.2. Code Analysis, Code Transformations, Code Optimizations

Embedded systems, as we recalled earlier, generated new problems in code analysis and optimization both for optimizing embedded software (compilation) and hardware (HLS). We now give a bit more details on some general challenges for program analysis, optimizations, and transformations, induced by this context, and on our methodology, in particular our development and use of polyhedral optimizations and its extensions.

3.2.1. Processes, Scheduling, Mapping, Communications, etc.

Before mapping an application to an architecture, one has to decide which execution model is targeted and where to intervene in the design flow. Then one has to solve scheduling, placement, and memory management problems. These three aspects should be handled as a whole, but present state of the art dictates that they be treated separately. One of our aims was to develop more comprehensive solutions. The last task is code generation, both for the processing elements and the interfaces processors/accelerators.

There are basically two execution models for embedded systems: one is the classical accelerator model, in which data is deposited in the memory of the accelerator, which then does its job, and returns the results. In the streaming model, computations are done on the fly, as data items flow from an input channel to the output. Here, the data are never stored in (addressable) memory. Other models are special cases, or sometimes compositions of the basic models. For instance, a systolic array follows the streaming model, and sometimes extends it to higher dimensions. Software radio modems follow the streaming model in the large, and the accelerator model in detail. The use of first-in first-out queues (FIFO) in hardware design is an application of the streaming model. Experience shows that designs based on the streaming model are more efficient that those based on memory, for such applications. One of the point to be investigated is whether it is general enough to handle arbitrary (regular) programs. The answer is probably negative. One possible implementation of the streaming model is as a network of communicating processes either as Kahn process networks (FIFO based) or as our more recent model of communicating regular processes (memory based, such as CRP mentioned hereafter). It is an interesting fact that several researchers have investigated the translation from process networks [12] and to process networks [20], [21]. Streaming languages such as StreamIt and OpenStream are also interesting solutions to explore.

Kahn process networks (KPN) were introduced 30 years ago as a notation for representing parallel programs. Such a network is built from processes that communicate via perfect FIFO channels. Because the channel histories are deterministic, one can define a semantics and talk meaningfully about the equivalence of two implementations. As a bonus, the dataflow diagrams used by signal processing specialists can be translated on-the-fly into process networks. The problem with KPNs is that they rely on an asynchronous execution model, while VLIW processors and FPGAs are synchronous or partially synchronous. Thus, there is a need for a tool for synchronizing KPNs. This can be done by computing a schedule that has to satisfy data dependences within each process, a causality condition for each channel (a message cannot be received before it is sent), and real-time constraints. However, there is a difficulty in writing the channel constraints because one has to count messages in order to establish the send/receive correspondence and, in multi-dimensional loop nests, the counting functions may not be affine. The same situation arises for the OpenStream language (see Section 7.2. Recent developments on the theory of polynomials (see Section 7.1) may offer a solution to this problem. One can also define another model, *communicating regular processes* (CRP), in which channels are represented as write-once/read-many arrays. One can then dispense with counting functions and prove that the determinacy property still holds. As an added benefit, a communication system in which the receive operation is not destructive is closer to the expectations of system designers.

The main difficulty with this approach is that ordinary programs are usually not constructed as process networks. One needs automatic or semi-automatic tools for converting sequential programs into process networks. One possibility is to start from array dataflow analysis [15] or variants. Another approach attempts to construct threads, i.e., pieces of sequential code with the smallest possible interactions. In favorable cases, one may even find outermost parallelism, i.e., threads with no interactions whatsoever. Tiling mechanisms can also be used to define atomic processes that can be pipelined as we proposed initially for FPGA [9].

Whatever the chosen solution (FIFO or addressable memory) for communicating between two accelerators or between the host processor and an accelerator, the problems of optimizing communication between processes and of optimizing buffers have to be addressed. Many local memory optimization problems have already been solved theoretically. Some examples are loop fusion and loop alignment for array contraction, techniques for data allocation in scratch-pad memory, or techniques for folding multi-dimensional arrays [11]. Nevertheless, the problem is still largely open. Some questions are: how to schedule a loop sequence (or even a process network) for minimal scratch-pad memory size? How is the problem modified when one introduces unlimited and/or bounded parallelism (same questions for analyzing explicitly-parallel programs)? How does one take into account latency or throughput constraints, bandwidth constraints for input and output channels, memory hierarchies? All loop transformations are useful in this context, in particular loop tiling, and may be applied either as source-to-source transformations (when used in front of HLS or C-level compilers) or to generate directly VHDL or lower-level C-dialects such as OpenCL. One should keep in mind that theory will not be sufficient to solve these problems. Experiments are required to check the relevance of the various models (computation model, memory model, power consumption model) and to select the most important factors according to the architecture. Besides, optimizations do interact: for instance, reducing memory size and increasing parallelism are often antagonistic. Experiments will be needed to find a global compromise between local optimizations. In particular, the design of cost models remain a fundamental challenge.

Finally, there remains the problem of code generation for accelerators. It is a well-known fact that methods for program optimization and parallelization do not generate a new program, but just deliver blueprints for program generation, in the form, e.g., of schedules, placement functions, or new array subscripting functions. A separate code generation phase must be crafted with care, as a too naive implementation may destroy the benefits of high-level optimization. There are two possibilities here as suggested before; one may target another high-level synthesis or compilation tool, or one may target directly VHDL or low-level code. Each approach has its advantages and drawbacks. However, both situations require that the input program respects some strong constraints on the code shape, array accesses, memory accesses, communication protocols, etc. Furthermore, to get the compilers do what the user wants requires a lot of program tuning, i.e., of program rewriting or of program annotations. What can be automated in this rewriting process? Semi-automated?

In other words, we still need to address scheduling, memory, communication, and code generation issues, in the light of the developments of new languages and architectures, pushing the limits of such an automation of program analysis, program optimizations, and code generation.

3.2.2. Beyond Static Control Programs

With the advent of parallelism in supercomputers, the bulk of research in code transformation resulted in (semi-)automatic parallelization, with many techniques (analysis, scheduling, code generation, etc.) based on the description and manipulation of nested loops with polyhedra. Compsys has always taken an active part in the development of these so-called "polyhedral techniques". Historically, these analysis were (wrongly) understood to be limited to static control programs.

Actually, the polyhedral model is neither a programming language nor an execution model, rather an intermediate representation. As such, it can be generated from imperative sequential languages like C or Fortran, streaming languages like CRP, or equational languages like Alpha. While the structure of the model is the same in all three cases, it may enjoy different properties, e.g., a schedule always exists in the first case, not in the two others. The import of the polyhedral model is that many questions relative to the analysis of a program and the applicability of transformations can be answered precisely and efficiently by applying well-known mathematical results to the model.

For irregular programs, the basic idea is to construct a polyhedral over-approximation, i.e., a program which has more operations, a larger memory footprint, and more dependences than the original. One can then parallelize the approximated program using polyhedral tools, and then return to the original, either by introducing guards, or by insuring that approximations are harmless. This technique is the standard way of dealing with approximated dependences. We already started to study the impact of approximations in our kernel offloading technique, for optimizing remote communications [10]. It is clear however that this extension method based on over-approximation will apply only to mildly non-polyhedral programs. The restriction to arrays as the only data structure is still present. Its advantage is that it will be able to subsume in a coherent framework many disparate tricks: the extraction of SCoPs, induction variable detection, the omission of non-affine subscripts, or the conversion of control dependences into data dependences. The link with the techniques developed in the PIPS compiler (based on array region analysis) is strong and will have to be explored.

Such over-approximations can be found by mean of abstract interpretation, a general framework to develop static analysis on real-life programs. However, they were designed mainly for verification purposes, thus precision was the main issue before scalability. Although many efforts were made in designing specialized analyses (pointers, data structures, arrays), these approaches still suffer from a lack of experimental evidence concerning their applicability for code optimization. Following our experience and work on termination analysis (that connects the work on back-end CFG-like and front-end polyhedral-like optimizations), and our work on range analysis of numerical variables and on the memory footprint on real-world C programs [18], one of our objectives for the future was to bridge the gap between abstract interpretation and compilation, by designing cheaper analyses that scale well, mainly based on compact representations derived from variants of static single assignment (SSA), with a special focus on complex control, and complex data structures (pointers, lists) that still suffer from complexity issues in the area of optimization.

Another possibility is to rely on application specific knowledge to guide compiler decisions, as it is impossible for a compiler alone to fully exploit such pieces of information. A possible approach to better utilize such knowledge is to put the programmers "in the loop". Expert parallel programmers often have a good idea about coarse-grain parallelism and locality that they want to use for an application. On the other hand, fine-grain parallelism (e.g., ILP, SIMD) is tedious and specific to each underlying architecture, and is best left to the compiler. Furthermore, approximations will have opportunities to be refined using programmer knowledge. The key challenge is to create a programming environment where compiler techniques and programmer knowledge can be combined effectively. One of the difficulties is to design a common language between the compiler and the programmer. The first step towards this objective is to establish inter-disciplinary collaborations with users, and take the time to analyze and optimize their applications together.M

3.3. Mathematical Tools

All compilers have to deal with *sets* and relations. In classical compilers, these sets are finite: the set of statements of a program, the set of its variables, its abstract syntax tree (AST), its control-flow graph (CFG), and many others. It is only in the first phase of compilation, parsing, that one has to deal with infinite objects, regular and context-free languages, and those are represented by finite grammars, and are processed by a symbolic algorithm, `yacc` or one of its clones.

When tackling parallel programs and parallel compilation, it was soon realized that this position was no longer tenable. Since it makes no sense to ask whether a statement can be executed in parallel with itself, one has to consider sets of operations, which may be so large as to forbid an extensive representation, or even be infinite. The same is true for dependence sets, for memory cells, for communication sets, and for many other objects a parallel compiler has to consider. The representation is to be *symbolic*, and all necessary algorithms have to be promoted to symbolic versions.

Such symbolic representations have to be efficient – the formula representing a set has to be much smaller than the set itself – and effective – the operations one needs, union, intersection, emptiness tests and many others – have to be feasible and fast. As an aside, note that progress in algorithm design has blurred the distinction between polynomially-solvable and NP-complete problems, and between decidable and undecidable questions. For instance SAT, SMT, and ILP software tools solve efficiently many NP-complete problems, and the Z3 tool is able to "solve" many instances of the undecidable Hilbert's 10th problem.

Since the times of Pip and of the Polylib, Compsys has been active in the implementation of basic mathematical tools for program analysis and synthesis. Pip is still developed by Paul Feautrier and Cédric Bastoul, while the Polylib is now taken care of by the Inria Camus project, which introduced Ehrhart polynomials. These tools are still in use world-wide and they also have been reimplemented many times with (sometimes slight) improvements, e.g., as part of the Parma Polylib, of Sven Verdoolaege's Isl and Barvinok libraries, or of the Jollylib of Reservoir Labs. Other groups also made a lot of efforts towards the democratization of the use of polyhedral techniques, in particular the Alchemy Inria project, with Cloog and the development of Graphite in GCC, and Sadayappan's group in the USA, with the development of U. Bondhugula's Pluto prototype compiler. The same effort is made through the PPCG prototype compiler (for GPU) and Pencil (directives-based language on top of PPCG).

After 2009, Compsys continued to focus on the introduction of concepts and techniques to extend the polytope model, with a shift toward tools that may prepare the future. For instance, PoCo and C2fsm are able to parse general programs, not just SCoPs (static control programs), while the efficient handling of Boolean affine formulas [13] is a prerequisite for the construction of non-convex approximations. Euclidean lattices provide an efficient abstraction for the representation of spatial phenomena, and the construction of *critical lattices* as embedded in the tool Cl@k is a first step towards memory optimization in stream languages and may be useful in other situations. Our work on Chuba introduced a new element-wise array reuse analysis and the possibility of handling approximations. Our work on the analysis of while loops is both an extension of the polytope model itself (i.e., beyond SCoPs) and of its applications, here links with program termination and worst-case execution time (WCET) tools.

A recent example of this extension idea is the proposal by Paul Feautrier to use polynomials for program analysis and optimization [14]. The associated tools are based on Handelman and Schweighofer theorems, the polynomial analogue of Farkas lemma. While this is definitely work in progress, with many unsolved questions, it has the potential of greatly enlarging the set of tractable programs.

As a last remark, observe that a common motif of these developments is the transformation of finite algorithms into symbolic algorithms, able to solve very large or even infinite instances. For instance, PIP is a symbolic extension of the Simplex; our work on memory allocation is a symbolic extension of the familiar register allocation problem; loop scheduling extends DAG scheduling. Many other algorithms await their symbolic transformation: a case in point is resource-constrained scheduling.

4. Application Domains

4.1. Compilers for Embedded Computing Systems

The previous sections described our main activities in terms of research directions, but also placed Compsys within the embedded computing systems domain, especially in Europe. We will therefore not come back here to the importance, for industry, of compilation and embedded computing systems design.

In terms of application domain, the embedded computing systems we considered are mostly used for multimedia: phones, TV sets, game platforms, etc. But, more than the final applications developed as programs, our main application has always been the computer itself: how the system is organized (architecture) and designed, how it is programmed (software), how programs are mapped to it (compilation and high-level synthesis).

The industry that can be impacted by our research is thus all the companies that develop embedded processors, hardware accelerators (programmable or not), embedded systems, and those (the same plus other) that need software tools to map applications to these platforms, i.e., that need to use or even develop programming languages, program optimization techniques, compilers, operating systems. Compsys did not focus on all these critical parts, but our activities were connected to them.

4.2. Users of HPC Platforms and Scientific Computing

The convergence between embedded computing systems and high-performance computing (HPC) technologies offers new computing platforms and tools for the users of scientific computing (e.g., people working in numerical analysis, in simulation, modeling, etc.). The proliferation of “cheap” hardware accelerators and multicores makes the “small HPC” (as opposed to computing centers with more powerful computers, grid computing, and exascale computing) accessible to a larger number of users, even though it is still difficult to exploit, due to the complexity of parallel programming, code tuning, interaction with compilers, which result from the multiple levels of parallelism and of memories in the recent architectures. The link between compiler and code optimization research (as in Compsys) and such users are still to be reinforced, both to guarantee the relevance of compiler research efforts with respect to application needs, and to help users better interact with compiler choices and understand performance issues.

The support of Labex MILYON (through its thematic quarters, such as the thematic quarter on compilation we organized in 2013 [0], or the 2016 thematic quarter on high-performance computing, with a dedicated inter-disciplinary spring school between numerical simulation and polyhedral compilation, see hereafter) and the activities of the LyonCalcul initiative [0] are means to get closer to users of scientific computing, even if it is too early to know if Compsys will indeed be directly helpful to them.

5. Highlights of the Year

5.1. Highlights of the Year

Scientific Results and Dissemination

Despite the approaching end of Compsys, we continued the objectives we fixed for Compsys III, i.e., pushing static compilation beyond its present limits, both in terms of techniques and applications. Our most important efforts in 2016 were to extend static analysis from sequential codes to parallel specifications and languages, to develop polynomial techniques, and to increase inter-disciplinary collaborations and dissemination towards HPC users and their applications. The most important results in 2016 are the following:

- **Publications** Well recognized in the polyhedral community, we got three papers at IMPACT'16, the central event of this community, one paper at the main compiler conference (CC'16), and a last one in the field of FPGA, which remains an important target for polyhedral optimizations. See Sections 7.1 to 7.7 for more details.
- **Interdisciplinary spring school** With colleagues from HPC numerical simulation, we organized a very successful inter-disciplinary event in May 2016, to bridge the gap between polyhedral compilation and HPC users. See details in Section 10.1.
- **Move towards HPC users** In addition to the spring school we organized, we increased our activity towards HPC users and their applications through the supervision of the internship of J. Versaci (quantum physics), the reviewing of T. Gasc's PhD thesis (fluid dynamics), and the regular contacts with the LMGC lab (mechanics).
- **PhD theses** The end of Compsys coincided also with the end of two PhD theses, the PhD thesis of Guillaume Iooss [16] and the PhD thesis of Alexandre Isoard [17], see Section 10.2.2.
- **Final evaluation** The team was evaluated in March 2016, this was also its final evaluation.

Final Evaluation and End of Compsys

Compsys has been created in 2002 as an Inria team, then in 2004 as an Inria project-team, and evaluated by Inria first in 2007, then in 2012. It was evaluated again in March 2016, which was its final evaluation because an Inria project-team is limited to 12 years. The construction of a new project was planned in early 2015, following the shift in the research directions that started in the second half of Compsys III. A few tentative research directions were:

- Shift the application domain from embedded systems to high performance computing (HPC) but at small scale (desktop HPC: FPGA, GPU, multicores). In fact, the two ecosystems are nowadays slowly converging.
- A stronger attention to real HPC users and real HPC applications may lead to better programming models ("putting the programmer in the loop").
- Design new models of programs. The polynomial model is but an example.
- Explore the synergy between parallel programming and program verification and certification; in particular, import approximation methods from one field to the other. Abstract interpretation is a case in point.

[0] Thematic quarter on compilation: http://labexcompilation.ens-lyon.fr/
[0] Lyon Calcul federation: http://lyoncalcul.univ-lyon1.fr

However, while its field of expertise, compilation for parallel and heterogeneous systems, is still of crucial importance, the unexpected departure in Sep. 2015 of two of its staff members made this future impossible. We nevertheless continued in 2016, in particular to present our activities in this last evaluation, until the three last members had to split in three different cities (Lyon, Paris, Rennes). We report here some of the comments made by the external reviewers that, we think, summarize well some aspects of our efforts, successes, and difficulties during 15 years:

- *Compsys established and matured the polyhedral optimization approach, which is the state of the art for locality and parallelism optimization in optimizing compilers. The project has had world-wide impact.*
- *We strongly recommend that the members of the team are accommodated in Camus, Cairn, Parkas, or another complementary Inria team, irrespective of the geographical location. Otherwise, Inria will lose one of its peaks of research excellence in Computer Science.*
- *This team is a prime example where Inria requirements on teams are damaging science and collaboration.*
- *This team has produced many impactful results and is considered as the Polyhedral center of excellence. It is globally recognized for its research in both front-end (polyhedral optimizations) and back-end (graph optimizations) compiler optimization techniques integrating elegant foundational theory with real implementation on various architectures (multi-core, FPGAs, DSP, GPU etc.).*
- *In back-end optimizations, the team had developed the state-of-the-art SSA and decoupled register allocation techniques that are important to achieving peak performance.*
- *They have internationally visible and impactful research in compilers, technology transfer to companies through collaborations and through start-ups. They raised the global awareness of polyhedral analysis through creation of workshops, summer schools etc., essentially reviving interest in the topic about a decade ago, and finally educating next-generation of researchers in this area, who are now contributing to both academic and industrial research landscape in France and beyond.*
- *The start-up company (XtremLogic on HLS) is an excellent concrete evidence of technology transfer from the team. [...] In the future, a more careful analysis of the trade-off between technology transfer and academic research is necessary for small project teams so that a promising research direction does not get jeopardized in Inria.*
- *The Compsys team has truly achieved research excellence in compilation techniques. Unfortunately, the future of the team remains uncertain due to administrative policies. Inria should enable the team to continue with their research strengths in polyhedral analysis and graph-theory based SSA-type optimizations.*

6. New Software and Platforms

6.1. Lattifold

Lattice-based Memory Folding
KEYWORDS: Polyhedral compilation - Euclidean Lattices
FUNCTIONAL DESCRIPTION

Implements advanced lattice-based memory folding techniques. The idea is to reduce memory footprint of multidimensional arrays by reducing the size of each dimension. Given a relation denoting conflicting array cells, it produces a new mapping based on affine functions bounded by moduli. The moduli induces memory reuse and bound memory accesses to a tighter area, allowing to reduce the array size without loss of correctness. Status: proof of concept, see related paper [2].

- Partner: ENS Lyon
- Contact: Alexandre Isoard

6.2. PolyOrdo

Polynomial Scheduler
FUNCTIONAL DESCRIPTION

Computes a polynomial schedule for a sequential polyhedral program having no affine schedule, in lieu of multidimensional schedules. Uses algorithms for finding positive polynomials in semi-algebraic sets. Status: proof of concept software, see related paper [14].

- Contact: Paul Feautrier

6.3. OpenOrdo

OpenStream scheduler
FUNCTIONAL DESCRIPTION

Finds polynomial schedules for the streaming language OpenStream. Main use: detecting deadlocks. The scheduler has been extended to bound the size of stream buffers, either directly or as a side-effect of constructing bounded delay schedules. An effort for bounding the number of in-flight tasks is under way.

Status: proof of concept, see related paper [1].

- Contact: Paul Feautrier

6.4. ppcg-paramtiling

Parametric Tiling Extension for PPCG
KEYWORDS: Source-to-source compiler - Polyhedral compilation
FUNCTIONAL DESCRIPTION

PPCG is a source-to-source compiler, based on polyhedral techniques, targeting GPU architectures. It involves automatic parallelization and tiling using polyhedral techniques. This version replaces the static tiling of PPCG by a fully parametric tiling and code generator. It allows to choose tile sizes at run time when the memory size is known. It also provides a symbolic expression of memory usage depending on the problem size and the tile sizes.

Status: proof of concept, unfinished, see Alexandre Isoard's thesis [17].

- Partner: ENS Lyon
- Contact: Alexandre Isoard

7. New Results

7.1. Handling Polynomials for Program Analysis and Transformation

Participant: Paul Feautrier.

As is well known in natural language processing, the first step in translating a text from one language to another is to understand it. The situation is the same for formal languages. A language processor has to "understand" a program before translating or optimizing or verifying it. Such understanding takes the form of a *model*, usually a mathematical representation whose natural operations mimic the behavior of its program. The polyhedral model is such a representation. However, the set of programs it can represent is too restricted, and the hunt for more powerful models has been under way since the millennium.

An obvious ideas is to replace affine formulas by polynomials, and hence polyhedra by semi-algebraic sets. Polynomials are ubiquitous in HPC and embedded system programming. For instance, the so-called "linearizations" (replacing a multi-dimensional object by a one-dimensional one) generate polynomial access functions. These polynomials then reappear in dependence testing, scheduling, and invariant construction. It may also happen that polynomials are absent from the source program, but are created either by an enabling analysis, as for OpenStream (see Section 7.2), or are imposed by complexity consideration. Lastly, polynomials may be native to the underlying algorithm, as when distances are computed by the usual Euclidean formula. What is needed here is a replacement for the familiar emptiness tests and for Farkas lemma (deciding whether an affine form is positive inside a polyhedron). Recent mathematical results by Handelman and Schweighofer on the *Positivstellensatz* allow one to devise algorithms that are able to solve these problems. The difference is that one gets only sufficient conditions, and that complexity is much higher than in the affine cases.

A paper presenting applications of these ideas to three use cases – dependence testing, scheduling, and transitive closure approximation – was presented at (IMPACT'15) [14]. A tool to manipulate polynomials, polynomial constraints and objective functions, needed for the derivation of polynomial schedules, complements this work (see Section 6.2). It implements Farkas lemma and its generalization with Handelman & Schweighofer formulations, and is in constant development, including improvements on the objective functions, in particular to make schedule selection more stable, independently on the degree of the polynomial schedule.

7.2. Static Analysis of OpenStream Programs

Participants: Albert Cohen [Inria Parkas team], Alain Darte, Paul Feautrier.

In the context of the ManycoreLabs project, we started to study the applicability of polyhedral techniques to the parallel language OpenStream [19]. When applicable, polyhedral techniques are indeed invaluable for compile-time debugging and for generating efficient code well suited to a target architecture. OpenStream is a two-level language in which a control program directs the initialization of parallel task instances that communicate through *streams*, with possibly multiple writers and readers. It has a fairly complex semantics in its most general setting, but we restricted ourselves to the case where the control program is sequential, which is representative of the majority of the OpenStream applications.

In contrast to the language X10, which we studied in previous years, this restriction offers deterministic concurrency by construction, but deadlocks are still possible. We showed that, if the control program is polyhedral, one may statically compute, for each task instance, the read and write indices to each of its streams, and thus reason statically about the dependences among task instances (the only scheduling constraints in this polyhedral subset). If the control program has nested loops, communications use one-dimensional channels in a form of linearization, and these indices may be polynomials of arbitrary degree, thus requiring to extend to polynomials the standard polyhedral techniques for dependence analysis, scheduling, and deadlock detection. Modern SMT allow to solve polynomial problems, albeit with no guarantee of success; the approach previously developed by P. Feautrier [14], and recalled in Section 7.1, offers an alternative solution.

The usual way of disproving deadlocks is by exhibiting a schedule for the program operations, a well-known problem for polyhedral programs where dependences can be described by affine constraints. In the case of OpenStream, we established two important results related to deadlocks: 1) a characterization of deadlocks in terms of dependence paths, which implies that streams can be safely bounded as soon as a schedule exists with such sizes, 2) the proof that deadlock detection is undecidable, even for polyhedral OpenStream. Details of this work have been published at the international workshop IMPACT'16 [1].

Some further developments are in progress for scheduling OpenStream programs using polynomial techniques (with a corresponding prototype scheduling tool, specific to OpenStream, see Section 6.3). In particular, we made some progress for parsing a simplified version of OpenStream, exhibiting the relevant structure, and on the properties and construction of schedules with bounded streams and bounded delays, and on the analysis of the "foot bath", i.e., the pool of tasks that are created (already requiring some resources) but not activated yet (because they need to wait for the termination of other tasks due to dataflow semantics). This work should have interesting connections with the way runtime systems of tasks are managed.

7.3. Liveness Analysis in Explicitly-Parallel Programs

Participants: Alain Darte, Alexandre Isoard, Tomofumi Yuki.

In the light of the parallel specifications encountered in our other work – kernel offloading with pipelined communications [10], automatic parallelization, analysis of X10 [22], [23] and of OpenStream (see Section 7.2), intra-array reuse (see Section 7.4) – we revisited scalar and array element-wise liveness analysis for programs with parallel specifications. In earlier work on memory allocation/contraction (register allocation or intra- and inter-array reuse in the polyhedral model), a notion of "time" or a total order among the iteration points was used to compute the liveness of values. In general, the execution of parallel programs is not a total order, and hence the notion of time is not applicable.

We first revised how conflicts are computed by using ideas from liveness analysis for register allocation, studying the structure of the corresponding conflict/interference graphs. Instead of considering the conflict between two pairs of live ranges, we only consider the conflict between a live range and a write. This simplifies the formulation from having four instances involved in the test down to three, and also improves the precision of the analysis in the general case. Then we extended the liveness analysis to work with partial orders so that it can be applied to many different parallel languages/specifications with different forms of parallelism. An important result is that the complement of the conflict graph with partial orders is directly connected to memory reuse, even in presence of races. However, programs with conditionals do not even have a partial order, and our next step will be to handle such cases with more accuracy. Details of this work have been published at the international workshop IMPACT'16 [3].

Some new developments are in progress to explore even further the properties of such liveness analysis and the construction of conflict sets, in the general case (with connections with the concept of trace monoid) or for some common situations such as series-parallel graphs, appearing in languages such as X10 or OpenMP.

7.4. Extended Lattice-Based Memory Allocation

Participants: Alain Darte, Alexandre Isoard, Tomofumi Yuki.

We extended lattice-based memory allocation [11], an earlier work on memory (array) reuse analysis. The main motivation is to handle in a better way the more general forms of specifications we see today, e.g., with loop tiling, pipelining, and other forms of parallelism available in explicitly parallel languages. Our extension has two complementary aspects. We showed how to handle more general specifications where conflicting constraints (those that describe the array indices that cannot share the same location) are specified as a (non-convex) union of polyhedra. Unlike convex specifications, this also requires to be able to choose suitable directions (or basis) of array reuse. For that, we extended two dual approaches, previously proposed for a fixed basis, into optimization schemes to select suitable basis. Our final approach relies on a combination of the two, also revealing their links with, on one hand, the construction of multi-dimensional schedules for parallelism and tiling (but with a fundamental difference that we identify) and, on the other hand, the construction of universal reuse vectors (UOV), which was only used so far in a specific context, for schedule-independent mapping.

This algorithmic work, connected to our previous work on parametric tiling [10] and the liveness analysis results of Section 7.3, is complemented by a set of prototype scripting tools, see Section 6.1. Details of this work have been published at the 2016 International Conference on Compiler Construction [2].

7.5. Stencil Accelerators

Participants: Steven Derrien [University of Rennes 1, Inria/CAIRN], Sanjay Rajopadhye [Colorado State University], Tomofumi Yuki.

Stencil computations have been known to be an important class of programs for scientific calculations. Recently, various architectures (mostly targeting FPGAs) for stencils are being proposed as hardware accelerators with high throughput and/or high energy efficiency. There are many different challenges for such design: How to maximize compute-I/O ratio? How to partition the problem so that the data fits on the on-chip memory? How to efficiently pipeline? How to control the area usage? We seek to address these challenges by combining techniques from compilers and high-level synthesis tools.

One project in collaboration with the CAIRN team and Colorado State University targets stencils with regular dependence patterns. Although many architectures have been proposed for this type of stencils, most of them use a large number of small processing elements (PE) to achieve high throughput. We are exploring an alternative design that aims for a single, large, deeply-pipelined PE. The hypothesis is that the pipelined parallelism is more area-efficient compared to replicating small PEs. We have published a work-in-progress paper on this topic at IMPACT'16 [4].

7.6. Efficient Mapping of Irregular Memory Accesses on FPGA

Participants: Xinyu Niu [Imperial College London], Tomofumi Yuki.

In a collaboration with Imperial College, we looked at efficiently implementing dynamic dependences on FPGAs. The collaboration is in the context of the EURECA project [0] where the dynamic reconfigurability of modern FPGAs is used to efficiently handle dynamic access patterns. We worked on analyzing data dependent array accesses to identify regularities within irregular memory accesses to reduce the cost of a dynamic memory reconfiguration module.

One part of this work has been published at the 2016 International Conference on Field Programmable Logic and Applications [5].

7.7. PolyApps

Participant: Tomofumi Yuki.

Loop transformation frameworks using the polyhedral model have gained increased attention since the rise of the multi-core era. We now have several research tools that have demonstrated their power on important kernels found in scientific computations. However, there remains a large gap between the typical kernels used to evaluate these tools and the actual applications used by the scientists.

PolyApps is an effort to collect applications from other domains of science to better establish the link between the compiler tools and "real" applications. The applications are modified to bypass some of the front-end issues of research tools, while keeping the ability to produce the original output. The goal is to assess how the state-of-the-art automatic parallelizers perform on full applications, and to identify new opportunities that only arise in larger pieces of code.

We showed that, with a few enhancements, the current tools will be able to reach and/or exceed the performance of existing parallelizations of the applications. One of the most critical element missing in current tools is the ability to modify the memory mappings.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

Since the team was going to be stopped, Compsys did not try to establish any long-term contract with industry.

8.2. Bilateral Grants with Industry

Same situation.

[0] http://www.doc.ic.ac.uk/~nx210/2015/09/01/eureca.html

9. Partnerships and Cooperations

9.1. Regional Initiatives

Compsys followed or participated to the activities of LyonCalcul (http://lyoncalcul.univ-lyon1.fr/), a network to federate activities on high-performance computing in Lyon. In this context, and with the support of the Labex MILYON (http://milyon.universite-lyon.fr/), Compsys had organized in 2013 a thematic quarter on compilation (http://labexcompilation.ens-lyon.fr). A second thematic quarter on high performance computing (HPC) was organized in 2016, initiated by Violaine Louvet (Institute Camille Jordan), with the participation of the LIP teams Aric, Avalon, Compsys, and Roma. Among other events, it included a CNRS inter-disciplinary spring school (https://mathsinfohpc.sciencesconf.org) co-organized by Compsys, connecting mathematics (HPC numerical analysis) and computer science (polyhedral optimizations for HPC) that can be seen as a follow-up of the first polyhedral school organized by Compsys in 2013. See details in Section 10.1.

Alain Darte, Alexandre Isoard, and Tomofumi Yuki had also some exchanges with Violaine Louvet and Thierry Dumont on tiling code optimizations, advising (in an informal way) some of their students during their internships, for implementations on multicore machines and GPUs.

9.2. National Initiatives

9.2.1. French Compiler Community

In 2010, Laure Gonnord and Fabrice Rastello created the french community of compilation, which had no organized venue in the past. All groups with activities related to compilation were contacted and the first “compilation day” was organized in Lyon. This effort has been quickly a success: the community (http://compilfr.ens-lyon.fr/) is now well identified and 3-days workshops now occur at least once a year (the 11th event has been organized in Sep. 2016). The community is animated by Laure Gonnord and Fabrice Rastello since 2010, and now also by Florian Brandner (ex-Compsys too). Alain Darte and Tomofumi Yuki participated to the 11th edition.

Recognized as a sub-group of the CNRS GDR GPL (Software Engineering and Programming), the community is also in charge, since 2014, of organizing one day of the research school “Ecole des jeunes chercheurs en Algorithmique et Programmation” (EJCP). Tomofumi Yuki, in this context, gave a half-day lecture at the 2016 edition (http://ejcp2016.univ-lille1.fr/), following his 2015 course.

9.2.2. Collaboration with Parkas group, in Paris

Alain Darte and Paul Feautrier have regular meetings with Albert Cohen, from the Parkas team at ENS Paris. The current discussions are mostly related to the analysis and compilation of the OpenStream language developed by Parkas, a research topic that started though the ManycoreLabs project (see previous reports). The results of Sections 7.2 and 7.1 are related to this collaboration. Now that Compsys has been stopped, Paul Feautrier is affiliated to Parkas, in addition to his emeritus position at ENS-Lyon.

9.2.3. Collaboration with Cairn group, in Rennes

Tomofumi Yuki continues to work with the Cairn group through regular meetings and occasional visits. The topic of the collaboration is in applying compiler techniques for hardware design using high-level synthesis. Section 7.5 presents the results through this collaboration.

9.2.4. Collaboration with Camus group, in Strasbourg

Paul Feautrier and Tomofumi Yuki have an ongoing cooperation with Alain Ketterlin and Eric Violard (Camus group, Strasbourg). The main result has been the determination of the *happens before* relation of clocked X10, a prerequisite for the detection of races in clocked programs. The resulting formula has been proved correct using the Coq proof assistant. Publishing formal proofs is known to be difficult, but we will give it a try soon.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

After the participation to a (rejected) H2020 proposal in 2015, Compsys did not try any effort in this direction as the team was going to be stopped.

9.3.2. Collaborations in European Programs, Except FP7 & H2020

Same situation.

9.3.3. Collaborations with Major European Organizations

Compsys members participate to the European Network of Excellence on High Performance and Embedded Architecture and Compilation (HiPEAC, http://www.hipeac.net/), either as members or affiliate members. The International Workshop on Polyhedral Compilation Techniques (IMPACT, see Section 9.4.2), co-created by Christophe Alias in 2011, is now an annual event of the HIPEAC conference, as an official workshop. The 5th edition, IMPACT'15, was co-chaired by Alain Darte (see http://impact.gforge.inria.fr/impact2015/), while the 6h edition, IMPACT'16, was co-chaired by Tomofumi Yuki (see http://impact.gforge.inria.fr/impact2016/).

9.4. International Initiatives

9.4.1. Collaboration with Colorado State University

Compsys had always kept strong connections with Colorado State University (CSU):

- In July 2016, Guillaume Iooss defended his joint ENS-Lyon/CSU PhD thesis [16]. He was co-advised by both Sanjay Rajopadhye (CSU) and Christophe Alias (with supplementary support by Alain Darte for administrative reason, as he has no HDR yet).
- Tomofumi Yuki, who did his PhD with Sanjay Rajopadhye, then a post-doc in the Cairn team in Rennes, continued his collaboration with these two groups, as the results described in Section 7.5 illustrate. He also participates regularly, over the net, to the reading group "Melange" of S. Rajodapdhye's group, with CSU students. Due to the stop of Compsys, Tomofumi Yuki has now returned to the Cairn team.
- Waruna Ranasinghe, a PhD student from S. Rajopadhye's team, visited Compsys, to work with Tomofumi Yuki, for 2 months (see Section 9.5).

9.4.2. Polyhedral Community

In 2011, as part of the organization of the workshops at CGO'11, Christophe Alias (with Cédric Bastoul) organized IMPACT'11 (international workshop on polyhedral compilation techniques, http://impact2011.inrialpes.fr/). This workshop in Chamonix was the very first international event on this topic, although it was introduced by Paul Feautrier in the late 80s. Alain Darte gave the introductory keynote talk. After this successful edition (more than 60 people), IMPACT continued as a satellite workshop of the HIPEAC conference, in Paris (2012), Berlin (2013), Vienna (2014). Alain Darte was program co-chair and co-organizer of the 2015 edition in Amsterdam, and Tomofumi Yuki of the 2016 edition in Prague.

The creation of IMPACT, now the annual event of the polyhedral community, helped to identify this community and to make it more visible. This effort was complemented by the organization by Alain Darte of the first school on polyhedral code analysis and optimizations (http://labexcompilation.ens-lyon.fr/polyhedral-school/). A second polyhedral school (https://mathsinfohpc.sciencesconf.org), more open, because involving themes and researchers from numerical analysis (users of HPC), was organized in 2016 by Alain Darte (for the compiler side) and Violaine Louvet (for the HPC side). See details in Section 10.1.

Alain Darte also manages two new mailing lists for news (polyhedral-news@listes.ens-lyon.fr) and discussions (polyhedral-discuss@listes.ens-lyon.fr) on polyhedral code analysis and optimizations. Tomofumi Yuki is involved in the development of PolyBench (http://sourceforge.net/projects/polybench), a suite of kernels used for illustrating polyhedral optimizations. He is also developing PolyApps, a set of larger applications to evaluate the gap between kernels and "real" applications, see more details in Section 7.7.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

9.5.1.1. Visiting PhD students

- Emna Hammami (Tunis University, with Yosr Slama) visited Compsys from April to June 2016 to refine her PhD topic with Compsys members. She also participated to the spring school on numerical simulation and polyhedral compilation.
- Waruna Ranasinghe (Colorado State University, with Sanjay Rajopadhye) visited Compsys from end of June to mid August 2016 to work with Tomofumi Yuki on extending cache oblivious techniques to polyhedral programs.

9.5.1.2. Internships

- Julien Versaci, M2 student from Lyon 1 University, from both physics and computer science departments, worked from April to June 2016 in Compsys, to work on the parallelization of a model of quantum physics. Julien was co-supervised by Jean-Philippe Guillet (physicist) and Tomofumi Yuki, the second part of his internship (until mid August) being done affiliated to Annecy physics laboratory (LAPTH). Julien also participated to the spring school on numerical simulation and polyhedral compilation.

9.5.2. Visits to International Teams

No long (more than one month) stay abroad in 2016.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

Alain Darte is general chair of the steering committee of CPC (International Workshop on Compilers for Parallel Computing), which regroups in Europe, every 18 months, a large community of researchers interested in compilers for HPC. He participated to CPC'16 in Valladolid in July 2016.

10.1.1.2. Member of the Organizing Committees

Tomofumi Yuki was co-organizer of IMPACT'16 (International Workshop on Polyhedral Compilation Techniques, http://impact.gforge.inria.fr/impact2016/) with Michelle Strout (University of Arizona).

10.1.1.3. Spring School on Numerical Simulation and Polyhedral Compilation

Alain Darte (with the help of Tomofumi Yuki for the program) co-organized with Violaine Louvet (Institute Camille Jordan in Lyon, now lead of UMS Gricad in Grenoble) a second polyhedral spring school, May 9-13 2016, targeting both the polyhedral community and HPC users from numerical analysis. This spring school has been labelled (and funded) as a CNRS interdisciplinary spring school (https://mathsinfohpc.sciencesconf.org/), with a total budget of roughly 39 Keuros, including funding from Labex MILYON, CNRS, GDR Calcul, ENS, LIP, and registrations fees, which were kept low to keep the spirit of the first spring school on polyhedral code analysis and optimizations.

This second spring school was motivated by the need for a more global approach for HPC applications, that combines the design of numerical methods with extensive hardware considerations, in interaction with languages and compilers, so as to take into account both the complexity of architectures and the needs of their non-expert users. Research communities in computer science (architecture, compilation) and applied mathematcs (numerical simulation) are not always aware of this need; at least their work do not always spread enough across the other discipline to lead to mutual influence. Automatic code optimizations and tools also require a better evaluation of their applicability. The goal of this research school – or meeting place of two communities – was to make the link between some of the most recent advances on automatic program optimizations (in particular polyhedral techniques and tools) and applied mathematics (schemes for numerical simulation), in relation with application needs. This school was therefore interdisciplinary, with a strong will to bring communities together on the common theme of supercomputing.

We finally opted for a single track instead of parallel sessions, which helped federate the two communities. The school included courses on architectures (M. Haefele, Maison de la simulation), on numerical schemes in connection with stencils (T. Dumont, ICJ), on simulation methods (discontinuous Galerkin) in particular for GPU (P. Helluy, Strasbourg), on polyhedral techniques and tiling (A. Darte, Compsys), on some polyhedral compilers such as Pluto (U. Bondhugula, Bangalore) and PPCG (S. Verdoolaege, ENS), on the roofline model for performance analysis (M. Püschel, ETH Zürich), on stencils and tensors optimizations (Ramanujam, Baton Rouge), on numerical precision (C. Rubio-Gonzalez, UC Davis), plus some additional talks on reproducibility, applications, the ECM model, etc. The school was a success, with 71 participants, roughly half from each community, with 29 coming from abroad (Italy, Algeria, USA, India, Canada, Germany, Croatia, Switzerland, Austria, Belgium), and a majority (37) being PhD students.

The future will tell if our objectives have been reached, i.e., if the two communities will interact more on the long term and rethink their work with an interdisciplinary look, to invent new computing schemes and compilers more suitable for the constraints of today's architectures, in particular their memory hierarchy and locality needs. In Compsys at least, one can already see some moves in this direction, with the interdisciplinary internship of Julien Versaci co-advised by Tomofumi Yuki, the participation of Alain Darte as a referee to the PhD jury of T. Gasc (CEA, Maison de la Simulation, ENS Cachan), a planned seminar by Alain Darte at Maison de la Simulation in early 2017, starting exchanges with the LMGC lab (Montpellier) on their applications, and a planned mini-symposium, following the line of this spring school, at SMAI 2017.

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

In addition to the organization, Tomofumi Yuki was program co-chair of IMPACT'16, with Michelle Strout (University of Arizona).

10.1.2.2. Member of the Conference Program Committees

Alain Darte was a member of the program committee of HPCS'16 (International Conference on High Performance Computing & Simulation) and will be member of the program committee of PACT'17 (International Conference on Parallel Architectures and Compilation Techniques).

Paul Feautrier was a member of the program committees of IMPACT'16 and IMPACT'17.

Tomofumi Yuki was a member of the program committees of SC'16, X10 Workshop'16, IMPACT'16, and IMPACT'17.

10.1.2.3. Reviewer

Alain Darte, Paul Feautrier, and Tomofumi Yuki were reviewers for the different program committees to which they participated.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

No participation to journal editorial boards in 2016.

10.1.3.2. Reviewer - Reviewing Activities

Alain Darte was a reviewer for the “Software, Practice, and Experience” journal.

Paul Feautrier was a reviewer for the “International Journal of Parallel Programming”.

Tomofumi Yuki was a reviewer for the TACO, TOPLAS, JPDC, and TPDS journals.

10.1.4. Invited Talks

Alain Darte was invited to give a talk on “Liveness Analysis in Explicitly-Parallel Programs” at ScalPerf’16 in Bertinoro (Italy), Sep. 2016.

Paul Feautrier was invited to give a talk (in two parts) “Toward A Polynomial Model with Application to the OpenStream Language” at the second and third LCS (Language, Compilation, Semantics) LIP seminars, in June and November 2016.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master:

- Paul Feautrier was invited to give a talk on “New Architectures, New Compilations Problems”, at the student seminar for the IMAG M2 course, Grenoble, December 5, 2016.

Spring/Summer Schools:

- Alain Darte, as part of the spring school on numerical simulation and polyhedral compilation, gave a half-day course on “Introduction to Automated Polyhedral Code Optimizations and Tiling”, see https://mathsinfohpc.sciencesconf.org.
- Tomofumi Yuki, a part of the École Jeunes Chercheurs en Programmation 2016, gave a half-day course on “Research in Compilers and Introduction to Loop Transformations”, see http://ejcp2016.univ-lille1.fr/.

10.2.2. Supervision

PhD: Guillaume Iooss, “Detection of linear algebra operations in polyhedral programs” [16], joint PhD ENS-Lyon/Colorado State University, started Sep. 2011, defended July 1st, 2016, advisors: Christophe Alias and Alain Darte (ENS-Lyon) / Sanjay Rajopadhye (Colorado State University).

PhD: Alexandre Isoard, “Extending Polyhedral Techniques towards Parallel Specifications and Approximations” [17], ENS-Lyon, started in Sep. 2012, defended July 5th, 2016, advisor: Alain Darte.

Guillaume Iooss is now post-doc in the Parkas team, while Alexandre Isoard is R&D engineer at Xilinx (Dublin, Ireland, then San Jose, Ca).

10.2.3. Juries

Alain Darte was one of the two reviewers of the PhD of Thibault Gasc (CEA DAM DIF, Maison de la Simulation, November 2016), entitled “Modèles de performance pour l’adaptation des méthodes numériques aux architectures multi-cœurs vectorielles. Application aux schémas Lagrange-Projection en hydrodynamique compressible”. He was also member of the juries of the PhD of Alexandre Isoard, as adviser, and of Guillaume Iooss as administrative co-adviser.

10.3. Popularization

The interdisciplinary spring school organized in May 2016 (see Section 10.1) is a form of popularization of compiler technology (in particular polyhedral optimizations) towards HPC users from the numerical simulation community.

11. Bibliography

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International Conferences with Proceedings

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[4] G. DEEST, N. ESTIBALS, T. YUKI, S. DERRIEN, S. RAJOPADHYE.*Towards Scalable and Efficient FPGA Stencil Accelerators*, in "6th International Workshop on Polyhedral Compilation Techniques (IMPACT'16), held with HIPEAC'16", Prague, Czech Republic, Proceedings of the IMPACT series, http://impact.gforge.inria.fr/, January 2016, https://hal.inria.fr/hal-01254778.

[5] X. NIU, N. NG, S. WANG, T. YUKI, N. YOSHIDA, W. LUK.*EURECA Compilation: Automatic Optimisation of Cycle-Reconfigurable Circuits*, in "26th International Conference on Field Programmable Logic and Applications", Lausanne, Switzerland, Proceedings of the 26th International Conference on Field Programmable Logic and Applications, August 2016 [*DOI :* 10.1109/FPL.2016.7577359], https://hal.archives-ouvertes.fr/hal-01413307.

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[6] G. DEEST, N. ESTIBALS, T. YUKI, S. DERRIEN, S. RAJOPADHYE.*Towards Scalable and Efficient FPGA Stencil Accelerators*, in "IMPACT'16", Prague, Czech Republic, January 2016, https://hal.inria.fr/hal-01425018.

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Project-Team CONVECS

Construction of verified concurrent systems

IN COLLABORATION WITH: Laboratoire d'Informatique de Grenoble (LIG)

IN PARTNERSHIP WITH:
Institut polytechnique de Grenoble

Université Joseph Fourier (Grenoble)

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Embedded and Real-time Systems

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Project-Team CONVECS

Creation of the Team: 2012 January 01, updated into Project-Team: 2014 January 01

Keywords:

Computer Science and Digital Science:

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1.3. - Distributed Systems
2.1.1. - Semantics of programming languages
2.1.7. - Distributed programming
2.4.1. - Analysis
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Other Research Topics and Application Domains:

6.3.2. - Network protocols
6.4. - Internet of things
6.6. - Embedded systems
8.1. - Smart building/home
9.4.1. - Computer science

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2. Overall Objectives

2.1. Overview

The CONVECS project-team addresses the rigorous design of concurrent asynchronous systems using formal methods and automated analysis. These systems comprise several activities that execute simultaneously and autonomously (i.e., without the assumption about the existence of a global clock), synchronize, and communicate to accomplish a common task. In computer science, asynchronous concurrency arises typically in hardware, software, and telecommunication systems, but also in parallel and distributed programs.

Asynchronous concurrency is becoming ubiquitous, from the micro-scale of embedded systems (asynchronous logic, networks-on-chip, GALS – *Globally Asynchronous, Locally Synchronous* systems, multi-core processors, etc.) to the macro-scale of grids and cloud computing. In the race for improved performance and lower power consumption, computer manufacturers are moving towards asynchrony. This increases the complexity of the design by introducing nondeterminism, thus requiring a rigorous methodology, based on formal methods assisted by analysis and verification tools.

There exist several approaches to formal verification, such as theorem proving, static analysis, and model checking, with various degrees of automation. When dealing with asynchronous systems involving complex data types, verification methods based on state space exploration (reachability analysis, model checking, equivalence checking, etc.) are today the most successful way to detect design errors that could not be found otherwise. However, these verification methods have several limitations: they are not easily accepted by industry engineers, they do not scale well while the complexity of designs is ever increasing, and they require considerable computing power (both storage capacity and execution speed). These are the challenges that CONVECS seeks to address.

To achieve significant impact in the design and analysis of concurrent asynchronous systems, several research topics must be addressed simultaneously. There is a need for user-friendly, intuitive, yet formal specification languages that will be attractive to designers and engineers. These languages should provide for both functional aspects (as needed by formal verification) and quantitative ones (to enable performance evaluation and architecture exploration). These languages and their associated tools should be smoothly integrated into large-scale design flows. Finally, verification tools should be able to exploit the parallel and distributed computing facilities that are now ubiquitous, from desktop to high-performance computers.

3. Research Program

3.1. New Formal Languages and their Concurrent Implementations

We aim at proposing and implementing new formal languages for the specification, implementation, and verification of concurrent systems. In order to provide a complete, coherent methodological framework, two research directions must be addressed:

- *Model-based specifications*: these are operational (i.e., constructive) descriptions of systems, usually expressed in terms of processes that execute concurrently, synchronize together and communicate. Process calculi are typical examples of model-based specification languages. The approach we promote is based on LOTOS NT (LNT for short), a formal specification language that incorporates most constructs stemming from classical programming languages, which eases its acceptance by students and industry engineers. LNT [29] is derived from the ISO standard E-LOTOS (2001), of which it represents the first successful implementation, based on a source-level translation from

LNT to the former ISO standard LOTOS (1989). We are working both on the semantic foundations of LNT (enhancing the language with module interfaces and timed/probabilistic/stochastic features, compiling the m among n synchronization, etc.) and on the generation of efficient parallel and distributed code. Once equipped with these features, LNT will enable formally verified asynchronous concurrent designs to be implemented automatically.

- *Property-based specifications*: these are declarative (i.e., non-constructive) descriptions of systems, which express *what* a system should do rather than *how* the system should do it. Temporal logics and μ-calculi are typical examples of property-based specification languages. The natural models underlying value-passing specification languages, such as LNT, are Labeled Transition Systems (LTSs or simply *graphs*) in which the transitions between states are labeled by actions containing data values exchanged during handshake communications. In order to reason accurately about these LTSs, temporal logics involving data values are necessary. The approach we promote is based on MCL (*Model Checking Language*) [51], which extends the modal μ-calculus with data-handling primitives, fairness operators encoding generalized Büchi automata, and a functional-like language for describing complex transition sequences. We are working both on the semantic foundations of MCL (extending the language with new temporal and hybrid operators, translating these operators into lower-level formalisms, enhancing the type system, etc.) and also on improving the MCL on-the-fly model checking technology (devising new algorithms, enhancing ergonomy by detecting and reporting vacuity, etc.).

We address these two directions simultaneously, yet in a coherent manner, with a particular focus on applicable concurrent code generation and computer-aided verification.

3.2. Parallel and Distributed Verification

Exploiting large-scale high-performance computers is a promising way to augment the capabilities of formal verification. The underlying problems are far from trivial, making the correct design, implementation, fine-tuning, and benchmarking of parallel and distributed verification algorithms long-term and difficult activities. Sequential verification algorithms cannot be reused as such for this task: they are inherently complex, and their existing implementations reflect several years of optimizations and enhancements. To obtain good speedup and scalability, it is necessary to invent new parallel and distributed algorithms rather than to attempt a parallelization of existing sequential ones. We seek to achieve this objective by working along two directions:

- *Rigorous design:* Because of their high complexity, concurrent verification algorithms should themselves be subject to formal modeling and verification, as confirmed by recent trends in the certification of safety-critical applications. To facilitate the development of new parallel and distributed verification algorithms, we promote a rigorous approach based on formal methods and verification. Such algorithms will be first specified formally in LNT, then validated using existing model checking algorithms of the CADP toolbox. Second, parallel or distributed implementations of these algorithms will be generated automatically from the LNT specifications, enabling them to be experimented on large computing infrastructures, such as clusters and grids. As a side-effect, this “bootstrapping” approach would produce new verification tools that can later be used to self-verify their own design.
- *Performance optimization:* In devising parallel and distributed verification algorithms, particular care must be taken to optimize performance. These algorithms will face concurrency issues at several levels: grids of heterogeneous clusters (architecture-independence of data, dynamic load balancing), clusters of homogeneous machines connected by a network (message-passing communication, detection of stable states), and multi-core machines (shared-memory communication, thread synchronization). We will seek to exploit the results achieved in the parallel and distributed computing field to improve performance when using thousands of machines by reducing the number of connections and the messages exchanged between the cooperating processes carrying out the verification task. Another important issue is the generalization of existing LTS representations (explicit, implicit, distributed) in order to make them fully interoperable, such that compilers and verification tools can handle these models transparently.

3.3. Timed, Probabilistic, and Stochastic Extensions

Concurrent systems can be analyzed from a *qualitative* point of view, to check whether certain properties of interest (e.g., safety, liveness, fairness, etc.) are satisfied. This is the role of functional verification, which produces Boolean (yes/no) verdicts. However, it is often useful to analyze such systems from a *quantitative* point of view, to answer non-functional questions regarding performance over the long run, response time, throughput, latency, failure probability, etc. Such questions, which call for numerical (rather than binary) answers, are essential when studying the performance and dependability (e.g., availability, reliability, etc.) of complex systems.

Traditionally, qualitative and quantitative analyzes are performed separately, using different modeling languages and different software tools, often by distinct persons. Unifying these separate processes to form a seamless design flow with common modeling languages and analysis tools is therefore desirable, for both scientific and economic reasons. Technically, the existing modeling languages for concurrent systems need to be enriched with new features for describing quantitative aspects, such as probabilities, weights, and time. Such extensions have been well-studied and, for each of these directions, there exist various kinds of automata, e.g., discrete-time Markov chains for probabilities, weighted automata for weights, timed automata for hard real-time, continuous-time Markov chains for soft real-time with exponential distributions, etc. Nowadays, the next scientific challenge is to combine these individual extensions altogether to provide even more expressive models suitable for advanced applications.

Many such combinations have been proposed in the literature, and there is a large amount of models adding probabilities, weights, and/or time. However, an unfortunate consequence of this diversity is the confuse landscape of software tools supporting such models. Dozens of tools have been developed to implement theoretical ideas about probabilities, weights, and time in concurrent systems. Unfortunately, these tools do not interoperate smoothly, due both to incompatibilities in the underlying semantic models and to the lack of common exchange formats.

To address these issues, CONVECS follows two research directions:

- *Unifying the semantic models*. Firstly, we will perform a systematic survey of the existing semantic models in order to distinguish between their essential and non-essential characteristics, the goal being to propose a unified semantic model that is compatible with process calculi techniques for specifying and verifying concurrent systems. There are already proposals for unification either theoretical (e.g., Markov automata) or practical (e.g., PRISM and MODEST modeling languages), but these languages focus on quantitative aspects and do not provide high-level control structures and data handling features (as LNT does, for instance). Work is therefore needed to unify process calculi and quantitative models, still retaining the benefits of both worlds.
- *Increasing the interoperability of analysis tools*. Secondly, we will seek to enhance the interoperability of existing tools for timed, probabilistic, and stochastic systems. Based on scientific exchanges with developers of advanced tools for quantitative analysis, we plan to evolve the CADP toolbox as follows: extending its perimeter of functional verification with quantitative aspects; enabling deeper connections with external analysis components for probabilistic, stochastic, and timed models; and introducing architectural principles for the design and integration of future tools, our long-term goal being the construction of a European collaborative platform encompassing both functional and non-functional analyzes.

3.4. Component-Based Architectures for On-the-Fly Verification

On-the-fly verification fights against state explosion by enabling an incremental, demand-driven exploration of LTSs, thus avoiding their entire construction prior to verification. In this approach, LTS models are handled implicitly by means of their *post* function, which computes the transitions going out of given states and thus serves as a basis for any forward exploration algorithm. On-the-fly verification tools are complex software artifacts, which must be designed as modularly as possible to enhance their robustness, reduce their development effort, and facilitate their evolution. To achieve such a modular framework, we undertake research in several directions:

- *New interfaces for on-the-fly LTS manipulation*. The current application programming interface (API) for on-the-fly graph manipulation, named OPEN/CAESAR [35], provides an "opaque" representation of states and actions (transitions labels): states are represented as memory areas of fixed size and actions are character strings. Although appropriate to the pure process algebraic setting, this representation must be generalized to provide additional information supporting an efficient construction of advanced verification features, such as: handling of the types, functions, data values, and parallel structure of the source program under verification, independence of transitions in the LTS, quantitative (timed/probabilistic/stochastic) information, etc.
- *Compositional framework for on-the-fly LTS analysis*. On-the-fly model checkers and equivalence checkers usually perform several operations on graph models (LTSs, Boolean graphs, etc.), such as exploration, parallel composition, partial order reduction, encoding of model checking and equivalence checking in terms of Boolean equation systems, resolution and diagnostic generation for Boolean equation systems, etc. To facilitate the design, implementation, and usage of these functionalities, it is necessary to encapsulate them in software components that could be freely combined and replaced. Such components would act as graph transformers, that would execute (on a sequential machine) in a way similar to coroutines and to the composition of lazy functions in functional programming languages. Besides its obvious benefits in modularity, such a component-based architecture will also make it possible to take advantage of multi-core processors.
- *New generic components for on-the-fly verification*. The quest for new on-the-fly components for LTS analysis must be pursued, with the goal of obtaining a rich catalog of interoperable components serving as building blocks for new analysis features. A long-term goal of this approach is to provide an increasingly large catalog of interoperable components covering all verification and analysis functionalities that appear to be useful in practice. It is worth noticing that some components can be very complex pieces of software (e.g., the encapsulation of an on-the-fly model checker for a rich temporal logic). Ideally, it should be possible to build a novel verification or analysis tool by assembling on-the-fly graph manipulation components taken from the catalog. This would provide a flexible means of building new verification and analysis tools by reusing generic, interoperable model manipulation components.

3.5. Real-Life Applications and Case Studies

We believe that theoretical studies and tool developments must be confronted with significant case studies to assess their applicability and to identify new research directions. Therefore, we seek to apply our languages, models, and tools for specifying and verifying formally real-life applications, often in the context of industrial collaborations.

4. Application Domains

4.1. Application Domains

The theoretical framework we use (automata, process algebras, bisimulations, temporal logics, etc.) and the software tools we develop are general enough to fit the needs of many application domains. They are applicable to virtually any system or protocol that consists of distributed agents communicating by asynchronous messages. The list of recent case studies performed with the CADP toolbox (see in particular § 6.5) illustrates the diversity of applications:

- *Bioinformatics:* genetic regulatory networks, nutritional stress response, metabolic pathways,
- *Component-based systems:* Web services, peer-to-peer networks,
- *Databases:* transaction protocols, distributed knowledge bases, stock management,
- *Distributed systems:* virtual shared memory, dynamic reconfiguration algorithms, fault tolerance algorithms, cloud computing,

- *Embedded systems:* air traffic control, avionic systems, medical devices,
- *Hardware architectures:* multiprocessor architectures, systems on chip, cache coherency protocols, hardware/software codesign,
- *Human-machine interaction:* graphical interfaces, biomedical data visualization, plasticity,
- *Security protocols:* authentication, electronic transactions, cryptographic key distribution,
- *Telecommunications:* high-speed networks, network management, mobile telephony, feature interaction detection.

5. New Software and Platforms

5.1. The CADP Toolbox

Participants: Hubert Garavel [correspondent], Frédéric Lang, Radu Mateescu, Wendelin Serwe.

We maintain and enhance CADP (*Construction and Analysis of Distributed Processes* – formerly known as *CAESAR/ALDEBARAN Development Package*) [1], a toolbox for protocols and distributed systems engineering [0]. In this toolbox, we develop and maintain the following tools:

- CAESAR.ADT [34] is a compiler that translates LOTOS abstract data types into C types and C functions. The translation involves pattern-matching compiling techniques and automatic recognition of usual types (integers, enumerations, tuples, etc.), which are implemented optimally.
- CAESAR [40], [39] is a compiler that translates LOTOS processes into either C code (for rapid prototyping and testing purposes) or finite graphs (for verification purposes). The translation is done using several intermediate steps, among which the construction of a Petri net extended with typed variables, data handling features, and atomic transitions.
- OPEN/CAESAR [35] is a generic software environment for developing tools that explore graphs on the fly (for instance, simulation, verification, and test generation tools). Such tools can be developed independently of any particular high level language. In this respect, OPEN/CAESAR plays a central role in CADP by connecting language-oriented tools with model-oriented tools. OPEN/CAESAR consists of a set of 16 code libraries with their programming interfaces, such as:
  - CAESAR_GRAPH, which provides the programming interface for graph exploration,
  - CAESAR_HASH, which contains several hash functions,
  - CAESAR_SOLVE, which resolves Boolean equation systems on the fly,
  - CAESAR_STACK, which implements stacks for depth-first search exploration, and
  - CAESAR_TABLE, which handles tables of states, transitions, labels, etc.

  A number of on-the-fly analysis tools have been developed within the OPEN/CAESAR environment, among which:
  - BISIMULATOR, which checks bisimulation equivalences and preorders,
  - CUNCTATOR, which performs steady-state simulation of continuous-time Markov chains,
  - DETERMINATOR, which eliminates stochastic nondeterminism in normal, probabilistic, or stochastic systems,
  - DISTRIBUTOR, which generates the graph of reachable states using several machines,
  - EVALUATOR, which evaluates MCL formulas,
  - EXECUTOR, which performs random execution,

[0] http://cadp.inria.fr

  - EXHIBITOR, which searches for execution sequences matching a given regular expression,
  - GENERATOR, which constructs the graph of reachable states,
  - PROJECTOR, which computes abstractions of communicating systems,
  - REDUCTOR, which constructs and minimizes the graph of reachable states modulo various equivalence relations,
  - SIMULATOR, XSIMULATOR, and OCIS, which enable interactive simulation, and
  - TERMINATOR, which searches for deadlock states.
- BCG (*Binary Coded Graphs*) is both a file format for storing very large graphs on disk (using efficient compression techniques) and a software environment for handling this format. BCG also plays a key role in CADP as many tools rely on this format for their inputs/outputs. The BCG environment consists of various libraries with their programming interfaces, and of several tools, such as:
  - BCG_CMP, which compares two graphs,
  - BCG_DRAW, which builds a two-dimensional view of a graph,
  - BCG_EDIT, which allows the graph layout produced by BCG_DRAW to be modified interactively,
  - BCG_GRAPH, which generates various forms of practically useful graphs,
  - BCG_INFO, which displays various statistical information about a graph,
  - BCG_IO, which performs conversions between BCG and many other graph formats,
  - BCG_LABELS, which hides and/or renames (using regular expressions) the transition labels of a graph,
  - BCG_MIN, which minimizes a graph modulo strong or branching equivalences (and can also deal with probabilistic and stochastic systems),
  - BCG_STEADY, which performs steady-state numerical analysis of (extended) continuous-time Markov chains,
  - BCG_TRANSIENT, which performs transient numerical analysis of (extended) continuous-time Markov chains, and
  - XTL (*eXecutable Temporal Language*), which is a high level, functional language for programming exploration algorithms on BCG graphs. XTL provides primitives to handle states, transitions, labels, *successor* and *predecessor* functions, etc.

    For instance, one can define recursive functions on sets of states, which allow evaluation and diagnostic generation fixed point algorithms for usual temporal logics (such as HML [42], CTL [30], ACTL [32], etc.) to be defined in XTL.
- PBG (*Partitioned BCG Graph*) is a file format implementing the theoretical concept of *Partitioned LTS* [38] and providing a unified access to a graph partitioned in fragments distributed over a set of remote machines, possibly located in different countries. The PBG format is supported by several tools, such as:
  - PBG_CP, PBG_MV, and PBG_RM, which facilitate standard operations (copying, moving, and removing) on PBG files, maintaining consistency during these operations,
  - PBG_MERGE (formerly known as BCG_MERGE), which transforms a distributed graph into a monolithic one represented in BCG format,
  - PBG_INFO, which displays various statistical information about a distributed graph.
- The connection between explicit models (such as BCG graphs) and implicit models (explored on the fly) is ensured by OPEN/CAESAR-compliant compilers, e.g.:
  - BCG_OPEN, for models represented as BCG graphs,
  - CAESAR.OPEN, for models expressed as LOTOS descriptions,
  - EXP.OPEN, for models expressed as communicating automata,
  - FSP.OPEN, for models expressed as FSP [50] descriptions,
  - LNT.OPEN, for models expressed as LNT descriptions, and
  - SEQ.OPEN, for models represented as sets of execution traces.

The CADP toolbox also includes TGV (*Test Generation based on Verification*), which has been developed by the VERIMAG laboratory (Grenoble) and the VERTECS project-team at Inria Rennes – Bretagne-Atlantique.

The CADP tools are well-integrated and can be accessed easily using either the EUCALYPTUS graphical interface or the SVL [36] scripting language. Both EUCALYPTUS and SVL provide users with an easy and uniform access to the CADP tools by performing file format conversions automatically whenever needed and by supplying appropriate command-line options as the tools are invoked.

5.2. The TRAIAN Compiler

Participants: Hubert Garavel [correspondent], Frédéric Lang, Wendelin Serwe.

We develop a compiler named TRAIAN, see § 5.2), for translating LOTOS NT descriptions into C programs, which will be used for simulation, rapid prototyping, verification, and testing.

The current version of TRAIAN, which handles LOTOS NT types and functions only, has useful applications in compiler construction [37], being used in all recent compilers developed by CONVECS.

The TRAIAN compiler can be freely downloaded from the CONVECS Web site [0].

6. New Results

6.1. New Formal Languages and their Implementations

The ability to compile and verify formal specifications with complex, user-defined operations and data structures is a key feature of the CADP toolbox since its very origins. A long-run effort has been recently undertaken to ensure a uniform treatment of types, values, and functions across all the various CADP tools.

6.1.1. Translation from LNT to LOTOS

Participants: Hubert Garavel, Frédéric Lang, Wendelin Serwe.

LNT is a next generation formal description language for asynchronous concurrent systems, which attempts to combine the best features of imperative programming languages and value-passing process algebras. LNT is increasingly used by CONVECS for industrial case studies and applications (see § 6.5) and serves also in university courses on concurrency, in particular at ENSIMAG (Grenoble) and at Saarland University.

In 2016, the long-term effort to enhance the LNT language and its tools has been pursued. LNT has been enriched with a new statement “use X” that suppresses compiler warnings when a variable X is assigned but not used. The syntax of LNT expressions has been modified so that field selections (“E.X”), field updates (“E1.X = E2”), and array accesses (“E1 [E2]”) can now be freely combined without extra parentheses. LNT programs can now import predefined libraries, and two such libraries (BIT.lnt and OCTET.lnt) have been introduced.

A move towards “safer” LNT exceptions has started. The syntax for exceptions in function declarations has been modified and the semantics of LNT has shifted from “unchecked” to “checked” exceptions: exception parameters, if any, must be explicitly mentioned when a function is called. Such exception parameters can now be passed using either the named style or the positional style.

A few static-semantics constraints have been relaxed; for instance, it is no longer required that actual gate parameters be different when calling a process. Various bugs have been fixed. Several error/warning messages have been made more precise, and the format of LNT error/warning messages has been aligned on that of GCC. Finally, the LNT2LOTOS Reference Manual has been updated and enhanced.

[0] http://convecs.inria.fr/software/traian

6.1.2. Translation from LOTOS NT to C

Participants: Hubert Garavel, Sai Srikar Kasi, Wendelin Serwe.

The TRAIAN compiler is used to build many compilers and translators of the CADP toolbox. This compiler itself is built using the FNC-2 compiler generator that, unfortunately, is no longer available. For this reason, TRAIAN only exists in 32-bit version, and sometimes hits the 3-4 GByte RAM limit when dealing with complex compilers such as LNT2LOTOS.

In 2016 we addressed this issue, in several steps. As a first step, we released a stable version 2.8 of TRAIAN. Then, we gathered all programs written in LOTOS NT, the input language of TRAIAN, and organized them in non-regression test bases. We entirely scrutinized the source code of TRAIAN, which consists in a large collection of attribute grammars, deleting all parts of code corresponding to those features of the LOTOS NT language that were either not fully implemented or seldom used in practice. This reduced the source code of TRAIAN by 40% and divided by two the size of TRAIAN executables. A few other bugs have been fixed and the reference manual of TRAIAN was entirely revised and updated.

In parallel, we undertook a complete rewrite of TRAIAN to get rid of the FNC-2 deprecated attribute grammar tool. We developed lexical and syntactic descriptions of the input language using the SYNTAX compiler-generation system developed at Inria Paris. The syntax tree of LOTOS NT and the library of predefined LOTOS NT types and functions are now themselves defined in LOTOS NT, as we plan to follow a bootstraping approach, using the current version of TRAIAN to build the next one. To this aim, a large fraction of the TRAIAN attribute grammars has been rewritten in LOTOS NT.

6.1.3. Translation from LOTOS to Petri nets and C

Participants: Hubert Garavel, Wendelin Serwe.

The LOTOS compilers CAESAR and CAESAR.ADT, which were once the flagship of CADP, now play a more discrete role since LNT (rather than LOTOS) has become the recommended specification language of CADP. Thus, CAESAR and CAESAR.ADT are mostly used as back-end translators for LOTOS programs automatically generated from LNT or other formalisms such as Fiacre, and are only modified when this appears to be strictly necessary.

In 2016, following the writing of the new CADP manual page for LOTOS, the common front-end of CAESAR and CAESAR.ADT was carefully inspected, which led to various bug fixes regarding type signatures, error messages for overloaded functions, renaming/actualization of sorts and operations, equations for renamed operations, C-language reserved keywords, implementation of numeral sorts, and iterators over these sorts. Another bug was fixed for the "`-external`" option of CAESAR and a new "`-numeral`" option was introduced. Also, the C identifiers automatically generated by CAESAR.ADT for sorts, operations, tester and selector macros have been simplified; as the new conventions are not backward compatible, migration tools were developed to ease transitioning the existing LOTOS and C files.

6.1.4. NUPN

Participant: Hubert Garavel.

Nested-Unit Petri Nets (NUPNs) is an upward-compatible extension of P/T nets, which are enriched with structural information on their concurrent structure. Such additional information can easily be produced when NUPNs are generated from higher-level specifications (e.g., process calculi); quite often, such information allows logarithmic reductions in the number of bits required to represent states, thus enabling verification tools to perform better. The principles of NUPNs are exposed in [33] and its PNML representation is described here [0].

[0] http://mcc.lip6.fr/nupn.php

In 2016, the NUPN principles have been presented in an invited talk at D-CON, the German national conference on concurrency theory. The collection of NUPN models used for experimentation has been enlarged and reorganized; it now contains more than $10,000$ models. A new beta-version of the VLPN (*Very Large Petri Nets*) benchmark suite, which contains 350 large models has been produced. Also, new prototype tools have been developed that try to convert P/T nets into NUPNs, which requires to automatically infer the concurrent structure of flat, unstructured nets.

The CAESAR.BDD tool that analyzes NUPN models and serves to prepare the yearly Model Checking Contest [0] has been enhanced with two new options "`-initial-places`" and "`-initial-tokens`". It now properly handles the case where the initial marking contains more than 2^{31} tokens. The output of the "`-mcc`" option has been made more precise when the NUPN under study is conservative or sub-conservative.

6.1.5. Translation from BPMN to LNT

Participants: Gwen Salaün, Ajay Muroor-Nadumane.

Evolution has become a central concern in software development and in particular in business processes, which support the modeling and the implementation of software as workflows of local and inter-process activities. We advocate that business process evolution can be formally analyzed in order to compare different versions of processes, identify precisely the differences between them, and ensure the desired consistency.

In collaboration with Pascal Poizat (LIP6, Paris), we worked on checking the evolution of BPMN processes. To promote its adoption by business process designers, we have implemented it in a tool, VBPMN, that can be used through a Web application. We have defined different kinds of atomic evolutions that can be combined and formally verified. We have defined a BPMN to LNT model transformation, which, using the LTS operational semantics of LNT, enables us to automate our approach using existing LTS model checking and equivalence checking tools, such as those provided by CADP. We have applied our approach to many examples for evaluation purposes. These results have been published in an international conference [23].

6.1.6. Translation from GRL to LNT

Participants: Hubert Garavel, Fatma Jebali, Jingyan Jourdan-Lu, Frédéric Lang, Eric Léo, Radu Mateescu, Wendelin Serwe.

In the context of the Bluesky project (see § 8.2.2.1), we study the formal modeling of GALS (*Globally Asynchronous, Locally Synchronous*) systems, which are composed of several synchronous subsystems evolving cyclically, each at its own pace, and communicating with each other asynchronously. Designing GALS systems is challenging due to both the high level of (synchronous and asynchronous) concurrency and the heterogeneity of computations (deterministic and nondeterministic). To bring our formal verification techniques and tools closer to the GALS paradigm, we designed a new formal language named GRL (*GALS Representation Language*), as an intermediate format between GALS models and purely asynchronous concurrent models. GRL combines the main features of synchronous dataflow programming and asynchronous process calculi into one unified language, while keeping the syntax homogeneous for better acceptance by industrial GALS designers. GRL allows a modular composition of synchronous systems (blocks), environmental constraints (environments), and asynchronous communication mechanisms (mediums), to be described at a level of abstraction that is appropriate to verification. GRL also supports external C and LNT code. A translator named GRL2LNT has been developed, allowing an LNT program to be generated from a GRL specification automatically. Additionally, an OPEN/CAESAR-compliant compiler named GRL.OPEN (based on GRL2LNT and LNT.OPEN) enables the on-the-fly exploration of the LTS underlying a GRL specification using CADP.

In 2016, a new version 3.3 of the GRL2LNT translator has been released, with an improved LNT code generation exploiting the "`use`" construct newly added to LNT. Also, a non-regression test base containing hundreds of GRL specifications has been set up. This also contributes to the non-regression testing of the compilation chain for LNT by providing new LNT descriptions generated automatically by GRL2LNT.

[0] http://mcc.lip6.fr/

An overview paper about GRL and its translation to LNT was published in an international journal [14]. The complete definition of GRL and its applications to GALS systems are available in F. Jebali's PhD thesis [44].

6.1.7. Translation of Term Rewrite Systems

Participants: Hubert Garavel, Lina Marsso, Mohammad-Ali Tabikh.

In 2016, we pursued the development undertaken in 2015 of a software platform for systematically comparing the performance of rewrite engines and pattern-matching implementations in algebraic specification and functional programming languages. Our platform reuses the benchmarks of the three Rewrite Engine Competitions (2006, 2009, and 2010). Such benchmarks are term-rewrite systems expressed in a simple formalism named REC, for which we developed automated translators that convert REC benchmarks into various languages.

In 2016, we corrected a number of benchmarks and added many new ones, to reach a total of 85 benchmarks in December 2016. Among these new benchmarks, one can mention a formalization of arithmetic operations on signed integers, a collection of (8-bit, 16-bit, and 32-bit) binary adders and multipliers, and a complete model of the MAA ("Message Authenticator Algorithm"), a Message Authentication Code used for financial transactions (ISO 8731-2) between 1987 and 2002.

The existing translators (for Haskell, LOTOS, Maude, mCRL, OCAML, Opal, Rascal, Scala, SML-NJ, and Tom) have been enhanced and new translators (for AProVE, Clean, LNT, MLTON, Stratego/XT) have been developed. Tools for automatically extracting and synthesizing performance statistics have also been developed.

6.2. Parallel and Distributed Verification

6.2.1. Distributed State Space Manipulation

Participants: Hubert Garavel, Hugues Evrard, Wendelin Serwe.

For distributed verification, CADP provides the PBG format, which implements the theoretical concept of *Partitioned LTS* [38] and provides a unified access to an LTS distributed over a set of remote machines.

In 2016, the code of the CAESAR_NETWORK_1 library, which is a building block for the distributed verification tools of CADP, has been carefully scrutinized and split into logically-independent modules. Nine problems have been detected and solved, among which a flaw in the distributed termination algorithm: the entire network could freeze if a worker process crashed too early, before the opening of TCP sockets. From now on, a better distributed termination algorithm is used, which supports the coexistence of several networks, ensures that all connections are closed before terminating, and produces more informative traces indicating which worker has triggered termination. Also, the improved CAESAR_NETWORK_1 library checks that all workers operate in directories that are pairwise distinct, mutually disjoint, and different from the working directory of the coordinator process.

6.2.2. Distributed Code Generation for LNT

Participants: Hugues Evrard, Frédéric Lang, Wendelin Serwe.

Rigorous development and prototyping of a distributed algorithm using LNT involves the automatic generation of a distributed implementation. For the latter, a protocol realizing process synchronization is required. As far as possible, this protocol must itself be distributed, so as to avoid the bottleneck that would inevitably arise if a unique process would have to manage all synchronizations in the system. Using a synchronization protocol that we verified formally in 2013, we developed a prototype distributed code generator, named DLC (*Distributed LNT Compiler*), which takes as input the model of a distributed system described as a parallel composition of LNT processes.

In 2016, we improved the user documentation of the DLC distribution, and added support for structured data types, enabling experiments of DLC on the LNT model of the CAESAR_SOLVE_2 library (see § 6.2.3). An overview paper about DLC has been accepted in an international journal [12].

6.2.3. Distributed Resolution of Boolean Equation Systems

Participant: Wendelin Serwe.

The BES_SOLVE tool of CADP enables to solve BESs (*Boolean Equation Systems*) using the various resolution algorithms provided by the CAESAR_SOLVE library (see 5.1), including a distributed on-the-fly resolution algorithm described in pseudo-code in [45].

In 2016, we modeled the pseudo-code of the distributed resolution algorithm in LNT (about $1,000$ lines). For a set of BES examples (encoded as LNT data types and functions), we experimented the generation of the LTS corresponding to the distributed resolution algorithm applied to each BES. We also experimented with the DLC tool [21] to generate a prototype distributed implementation of the resolution algorithm from its LNT specification. These experiments uncovered some errors in the original pseudo-code.

We also simplified the C implementation included in the BES_SOLVE tool to closer match the corrected LNT model, mainly by removing additional synchronization messages. We started to evaluate the simplified implementation using our non-regression test base (more than $15,000$ BESs), with promising results.

6.2.4. Stability of Communicating Systems

Participant: Gwen Salaün.

Analyzing systems communicating asynchronously via reliable FIFO buffers is an undecidable problem. A typical approach is to check whether the system is bounded, and if not, the corresponding state space can be made finite by limiting the presence of communication cycles in behavioral models or by imposing an upper bound for the size of communication buffers.

In 2016, our focus was on systems that are likely to be unbounded and therefore result in infinite systems. We did not want to restrict the system by imposing any arbitrary bound. We introduced a notion of stability and proved that once the system is stable for a specific buffer bound, it remains stable whatever larger bounds are chosen for buffers. This enables one to check certain properties on the system for that bound and to ensure that the system will preserve them for arbitrarily larger buffer bounds. We also proved that computing this bound is undecidable but we showed how we succeed in computing these bounds for many examples using heuristics and equivalence checking. These results have been published in an international conference [18].

In collaboration with Carlos Canal (University of Málaga, Spain), we have also shown how the stability approach can be used for composition and adaptation of component-based software. This led to a publication in an international conference [20].

6.2.5. Debugging of Concurrent Systems

Participants: Gianluca Barbon, Gwen Salaün.

Model checking is an established technique for automatically verifying that a model satisfies a given temporal property. When the model violates the property, the model checker returns a counterexample, which is a sequence of actions leading to a state where the property is not satisfied. Understanding this counterexample for debugging the specification is a complicated task for several reasons: (i) the counterexample can contain hundreds of actions, (ii) the debugging task is mostly achieved manually, and (iii) the counterexample does not give any clue on the state of the system (e.g., parallelism or data expressions) when the error occurs.

In 2016, we proposed a new approach that improves the usability of model checking by simplifying the comprehension of counterexamples. Our solution aims at keeping only actions in counterexamples that are relevant for debugging purposes. To do so, we first extract in the model all the counterexamples. Second, we define an analysis algorithm that identifies actions that makes the behaviour skip from incorrect to correct behaviours, making these actions relevant from a debugging perspective. Our approach is fully automated by a tool that we implemented and applied on real-world case studies from various application areas for evaluation purposes. A paper presenting these results has been accepted at an international conference.

6.3. Timed, Probabilistic, and Stochastic Extensions

6.3.1. On-the-fly Model Checking for Extended Regular Probabilistic Operators

Participant: Radu Mateescu.

In the context of the SENSATION project (see § 8.3.1.1), we study the specification and verification of quantitative properties of concurrent systems, which requires expressive and user-friendly property languages combining temporal, data-handling, and quantitative aspects.

In 2016, in collaboration with José Ignacio Requeno (Univ. Zaragoza, Spain), we aimed at facilitating the quantitative analysis of systems modeled as PTSs (Probabilistic Transition Systems) labeled by actions containing data values and probabilities. We proposed a new regular probabilistic operator that computes the probability measure of a path specified by a generalized regular formula involving arbitrary computations on data values. This operator, which subsumes the Until operators of PCTL (Probabilistic Computation Tree Logic) [41] and their action-based counterparts, can provide useful quantitative information about paths having certain (e.g., peak) cost values. We integrated the regular probabilistic operator into MCL and we devised an associated on-the-fly model checking method, based on a combined local resolution of linear and Boolean equation systems. We implemented the method in a prototype extension of the EVALUATOR model checker and experimented it on realistic PTSs modeling concurrent systems. This work led to a publication [22].

6.4. Component-Based Architectures for On-the-Fly Verification

6.4.1. Compositional Verification

Participant: Frédéric Lang.

The CADP toolbox contains various tools dedicated to compositional verification, among which EXP.OPEN, BCG_MIN, BCG_CMP, and SVL play a central role. EXP.OPEN explores on the fly the graph corresponding to a network of communicating automata (represented as a set of BCG files). BCG_MIN and BCG_CMP respectively minimize and compare behavior graphs modulo strong or branching bisimulation and their stochastic extensions. SVL (*Script Verification Language*) is both a high-level language for expressing complex verification scenarios and a compiler dedicated to this language.

In 2016, the *n among m* parallel composition operator "`par`" of the EXP language has been extended. Before the extension, the set of m processes among which any subset of size n could be synchronized on a given action was necessarily the set of all parallel processes composed by the "`par`" operator. From now on, by a slight extension of the syntax, this set of m processes can be defined as a subset of the parallel processes. Also, while n had to be strictly greater than 1, it can now also have value 0 (meaning that none of the m processes can perform the corresponding action) or 1 (meaning that each process can perform the corresponding action on its own, without synchronization). A bug in EXP.OPEN has been fixed and better messages are now emitted to warn the user about dubious usage of the "`par`" operator.

The SVL language has been extended to include the extended "`par`" operator. Two bugs have also been corrected.

6.4.2. Other Component Developments

Participants: Hubert Garavel, Frédéric Lang, Radu Mateescu, Wendelin Serwe.

Sustained effort was made to improve the documentation of the CADP toolbox. Various corrections have been brought to the CADP manual pages. A 27-page manual page explaining how the LOTOS language is implemented has been written, and the manual pages of the CAESAR and CAESAR.ADT compilers have been also updated. To make documentation more readable, the EVALUATOR3, and EVALUATOR4 manual pages have been splitted each in two parts, so as to better distinguish between the languages (namely, MCL3 and MCL) and their model checkers. The CADP distribution has been made leaner by keeping only the essential papers, and the "publications" and "tutorial" pages of the CADP Web site have been enriched and reorganized.

The conventions for string notations to represent “raw” values (i.e., values whose type is not a predefined one, but a custom type defined by the user) have been improved, together with the associated conversion algorithms for reading/writing raw values from/to strings. The BCG_WRITE manual page has been updated to more accurately describe how label fields of type "raw" are parsed. The behaviour of the functions `bcg_character_scan()`, `bcg_string_scan()`, `bcg_real_scan()`, and `bcg_raw_scan()` has been carefully revised, and all the BCG libraries and tools (especially BCG_IO) have been modified to follow the new conventions and emit better diagnostics when label fields contain incorrect notations of raw values. Also, BCG_IO has been enhanced so that very long execution sequences can be converted into SEQ or LOTOS files without causing stack overflow.

Finally, enhancements and bug fixes have been brought to other CADP components, including CADP_MEMORY, EUCALYPTUS, INSTALLATOR, OCIS, RFL, TST, and XTL. The style files for the various editors supported by CADP have been updated to take into account the recent features added to LNT. The predefined MCL libraries of the EVALUATOR model checker have been modified to generate more explanatory diagnostics for the inevitability operators.

Although CADP is mostly used on Linux, specific effort has been made to target other execution platforms. Concerning macOS: CADP now supports the recent versions 10.10 (“Yosemite”), 10.11 (“El Capitan”), and 10.12 (“Sierra”). Concerning Windows: changes have been brought to support Windows 10 and the 64-bit version of Cygwin (previously, only the 32-bit version was supported). Other adaptations were required to handle the recent versions of Cygwin packages, MinGW C compiler, and Mintty shell, as well as the case where Cygwin is not installed in “`C:\`”, but in either “`C:\Cygwin`” or “`C:\Cygwin64`”.

6.5. Real-Life Applications and Case Studies

6.5.1. Reconfiguration and Resilience of Distributed Cloud Applications

Participants: Umar Ozeer, Gwen Salaün.

In the context of a collaboration with Orange Labs, an Ensimag student (Bakr Derrazi) supervised by Xavier Etchevers and Gwen Salaün, has made his internship from February 2016 to July 2016 at Orange Labs. As a result, we have proposed a first solution and prototype for detecting and repairing failures of data-centric applications distributed in the cloud. A PhD thesis (Umar Ozeer) has started on this subject in November 2016.

6.5.2. Activity Detection in a Smart Home

Participants: Frédéric Lang, Radu Mateescu.

In collaboration with Paula-Andrea Lago-Martinez and Claudia Roncancio (SIGMA team, LIG) and with Nicolas Bonnefond (PERVASIVE INTERACTION team, Inria and LIG), we study how formal methods can help to analyze logs of events obtained from the many sensors and actuators installed in the Amiqual4Home smart home.

In 2016, we considered using the MCL temporal logic to detect the start and end of activities in a log, such as cooking or taking a shower. We applied our tools on a log containing about $140,000$ events that had been generated over 10 days of living in the smart home. This preliminary study has shown that the MCL temporal logic is sufficiently rich to enable an easy specification of the searched activities, notably thanks to its multiple extensions such as macro definitions, parameterized fixed point operators, and data handling mechanisms. The particularly long length of the analyzed logs also enabled us to improve some of the CADP tools, so that they better scale up. This work led to an article submitted to an international conference.

6.5.3. Other Case Studies

Participant: Hubert Garavel.

The demo examples of CADP, which have been progressively accumulated since the origins of the toolbox, are a showcase for the multiple capabilities of CADP, as well as a test bed to assess the new features of the toolbox. In 2016, the effort to maintain and enhance these demos has been pursued. The demo 12 (Message Authentication Algorithm) and demo 31 (SCSI-2 bus arbitration protocol) have been manually translated from LOTOS to LNT. Additionally, demo 12 has been deeply revised by simplifying its LOTOS, LNT, and C code, by taking advantage of the imperative-programming features of LNT, and by enriching the LNT specification with the test cases contained in the original MAA description. This allowed to detect and correct a mistake in the C code implementing function `HIGH_MUL()`. Other CADP demos (namely demos 05, 16, and 36) have also been simplified and/or enhanced in various ways.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Grants with Industry

Participants: Umar Ozeer, Gwen Salaün.

Umar Ozeer is supported by a PhD grant (from November 2016 to November 2019) from Orange Labs (Grenoble) on detecting and repairing failures of data-centric applications distributed in the cloud and the Internet of Things (see § 6.5.1), under the supervision of Xavier Etchevers (Orange Labs), Gwen Salaün (CONVECS), François Gaël Ottogalli (Orange Labs), and Jean-Marc Vincent (POLARIS project-team).

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. ARC6 Programme

Participants: Lina Marsso, Radu Mateescu, Wendelin Serwe.

ARC6 is an academic research community funded by the Auvergne Rhône-Alpes region, whose objective is to foster the scientific collaborations between different academic institutions of the region working in the domain of information and communication technologies. ARC6 organizes various scientific animations (conferences, working groups, summer schools, etc.) and issues a yearly call for PhD and post-doctorate research project proposals.

Lina Marsso is supported by an ARC6 grant (from October 2016 to October 2019) on formal methods for testing networks of programmable logic controllers, under the supervision of Radu Mateescu and Wendelin Serwe (CONVECS), Ioannis Parissis and Christophe Deleuze (LCIS, Valence).

8.2. National Initiatives

8.2.1. FSN (Fonds national pour la Société Numérique)

8.2.1.1. Connexion

Participants: Hubert Garavel [correspondent], Frédéric Lang.

Connexion [0] (*COntrôle commande Nucléaire Numérique pour l'EXport et la rénovatION*) is a project funded by the FSN, within the second call for projects "*Investissements d'Avenir — Briques génériques du logiciel embarqué*". The project, led by EDF and supported by the *Pôles de compétitivité* Minalogic, Systematic, and *Pôle Nucléaire Bourgogne*, involves many industrial and academic partners, namely All4Tech, Alstom Power, ArevA, Atos Worldgrid, CEA-LIST, CNRS/CRAN, Corys Tess, ENS Cachan, Esterel Technologies, Inria, LIG, Predict, and Rolls-Royce. Connexion aims at proposing and validating an innovative architecture dedicated to the design and implementation of control systems for new nuclear power plants in France and abroad.

[0] http://www.cluster-connexion.fr

Connexion started in April 2012 for four years, and was extended for 6 months until September 2016. In this project, CONVECS assisted another LIG team, IIHM, in specifying human-machine interfaces formally using the LNT language and in verifying them using CADP.

8.2.2. Competitivity Clusters

8.2.2.1. Bluesky for I-Automation

Participants: Hugues Evrard, Hubert Garavel, Fatma Jebali, Jingyan Jourdan-Lu, Frédéric Lang, Eric Léo, Radu Mateescu [correspondent].

Bluesky for I-Automation is a project funded by the FUI (*Fonds Unique Interministériel*) within the *Pôle de Compétitivité* Minalogic. The project, led by Crouzet Automatismes (Valence), involves the SMEs (*Small and Medium Enterprises*) Motwin and VerticalM2M, the LCIS laboratory of Grenoble INP, and CONVECS. Bluesky aims at bringing closer the design of automation applications and the Internet of things by providing an integrated solution consisting of hardware, software, and services enabling a distributed, Internet-based design and development of automation systems. The automation systems targeted by the project are networks of programmable logic controllers, which belong to the class of GALS (*Globally Asynchronous, Locally Synchronous*) systems.

Bluesky started in September 2012 for three years and was extended for nine months until June 2016. The main contributions of CONVECS to Bluesky (see § 6.1.6) are the definition of GRL, the formal pivot language for describing the asynchronous behavior of logic controller networks, and the automated verification of the behavior using compositional model checking and equivalence checking techniques.

8.2.3. Other National Collaborations

We had sustained scientific relations with the following researchers:

- Pierre Boullier (Inria, team ALPAGE),
- Pierre-Etienne Moreau (LORIA, team PAREO),
- Fabrice Kordon and Lom Messan Hillah (LIP6, Paris),
- Noël De Palma and Fabienne Boyer (LIG, Grenoble),
- Xavier Etchevers (Orange Labs, Meylan),
- Christophe Deleuze and Ioannis Parissis (LCIS, Valence),
- Pascal Poizat (LIP6, Paris),
- Lina Ye (LRI, Paris).

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

8.3.1.1. SENSATION

Participants: Hubert Garavel [correspondent], Radu Mateescu, Wendelin Serwe.

SENSATION [0] (*Self ENergy-Supporting Autonomous computaTION*) is a European project no. 318490 funded by the FP7-ICT-11-8 programme. It gathers 9 participants: Inria (ESTASYS and CONVECS project-teams), Aalborg University (Denmark), RWTH Aachen and Saarland University (Germany), University of Twente (The Netherlands), GomSpace (Denmark), and Recore Systems (The Netherlands). The main goal of SENSATION is to increase the scale of systems that are self-supporting by balancing energy harvesting and consumption up to the level of complete products. In order to build such Energy Centric Systems, embedded system designers face the quest for optimal performance within acceptable reliability and tight energy bounds. Programming systems that reconfigure themselves in view of changing tasks, resources, errors, and available energy is a demanding challenge.

[0] http://sensation-project.eu/

SENSATION started on October 1st, 2012 for three years, and has been extended for five months until February 29, 2016. CONVECS contributed to the project regarding the extension of formal languages with quantitative aspects (see § 6.3.1), studying common semantic models for quantitative analysis, and applying formal modeling and analysis to the case studies provided by the industrial partners.

8.3.2. Collaborations with Major European Organizations

The CONVECS project-team is member of the FMICS (*Formal Methods for Industrial Critical Systems*) working group of ERCIM [0]. H. Garavel and R. Mateescu are members of the FMICS board, H. Garavel being in charge of dissemination actions.

8.4. International Initiatives

H. Garavel is a member of IFIP (*International Federation for Information Processing*) Technical Committee 1 (*Foundations of Computer Science*) Working Group 1.8 on Concurrency Theory chaired successively by Luca Aceto and Jos Baeten.

At Saarland University (Germany), H. Garavel is a guest scientist of the DEPEND research group headed by Holger Hermanns, who received an ERC Advanced Grant ("POWVER") in 2016.

In 2016, we had scientific relations with several universities and companies abroad, including:

- SRI International, California, USA (Steven Eker),
- Technical University of Eindhoven, The Netherlands (Jan Friso Groote),
- University of Málaga, Spain (Francisco Durán and Carlos Canal),
- Aalto University, Finland (Hernan Ponce de Leon),
- Technical University of Graz, Austria (Franz Wotawa),
- University of Zaragoza, Spain (José Ignacio Requeno),
- University of Utah, USA (Chris Myers and Zhen Zhang),
- DiffBlue, Oxford, UK (Matthias Güdemann).

8.5. International Research Visitors

8.5.1. Visits of International Scientists

- Hernan Ponce de Leon (Aalto University, Finland) visited us from February 15 to February 19, 2016.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. Member of the Organizing Committees

- H. Garavel is a member of the model board [0] of MCC (*Model Checking Contest*). In 2016, he helped preparing new models (especially those in the NUPN format) and verified, using the CÆSAR.BDD tool of CADP, the forms describing all benchmark models submitted by the contest participants; this revealed a number of inconsistencies. The mission and activities of the model board are described in a journal paper [15].
- Together with Peter Höfner (Data61, CSIRO, Sydney, Australia), H. Garavel set up a model repository (hosted on the Gforge of Inria) to collect and archive formal models of real systems; this infrastructure is used by the series of MARS workshops [0]. The first model deposited in this repository was W. Serwe's description in LOTOS and LNT of an asynchronous circuit implementing the Data Encryption Standard.
- G. Salaün is member of the steering committee of the SEFM (*International Conference on Software Engineering and Formal Methods*) conference series since 2014.

[0] http://fmics.inria.fr
[0] http://mcc.lip6.fr/models.php
[0] http://www.mars-workshop.org/

9.1.2. Scientific Events Selection

9.1.2.1. Chair of Conference Program Committees

- R. Mateescu was the tool chair of TACAS'2016 (*22th International Conference on Tools and Algorithms for the Construction and Analysis of Systems*), Eindhoven, The Netherlands, April 2–8, 2016.
- G. Salaün was co-chair of SVT-SAC'2016 (the *Software Verification and Testing* track of the *31st ACM Symposium on Applied Computing*), Pisa, Italy, April 4–8, 2016.

9.1.2.2. Member of the Conference Program Committees

- H. Garavel was program committee member of the 6th FMF (*Forum Methodes Formelles*), Toulouse-Grenoble-Saclay, France, January 26, 2016.
- F. Lang was program committee member of GaM'2016 (*Graphs as Models*), Eindhoven, The Netherlands, April 2–3, 2016.
- G. Salaün was program committee member of SOAP-SAC'2016 (the *Service-Oriented Architecture and Programming* track) of SAC'2016, Pisa, Italy, April 4–8, 2016.
- R. Mateescu was program committee member of SPIN'2016 (*23rd International SPIN Symposium on Model Checking of Software*), Eindhoven, The Netherlands, April 7–8, 2016.
- G. Salaün was program committee member of CIEL'2016 (*5ème Conférence en IngénieriE du Logiciel*), Besançon, France, June 7, 2016.
- G. Salaün was program committee member of COMPSAC'2016 (*40th IEEE International Conference on Computers, Software and Applications*), Atlanta, Georgia, USA, June 10–14, 2016.
- G. Salaün was program committee member of WWV'2016 (*12th International Workshop on Automated Specification and Verification of Web Systems*), Porto, Portugal, June 26, 2016.
- H. Garavel and G. Salaün were program committee members of SEFM'2016 (*14th International Conference on Software Engineering and Formal Methods*), Vienna, Austria, July 4–8, 2016.
- G. Salaün was program committee member of RV'2016 (*16th International Conference on Runtime Verification*), Madrid, Spain, September 23–30, 2016.
- R. Mateescu was program committee member of FMICS-AVoCS'2016 (*International Workshop on Formal Methods for Industrial Critical Systems and Automated Verification of Critical Systems*), Pisa, Italy, September 26–29, 2016.
- H. Garavel was program committee member of HILT'2016 (*Workshop on High Integrity Language Technology*), Pittsburgh, PA, October 6–7, 2016.
- R. Mateescu was program committee member of ICTSS'2016 (*28th International Conference on Testing Software and Systems*), Graz, Austria, October 17–19, 2016.
- G. Salaün was program committee member of FACS'2016 (*13th International Conference on Formal Aspects of Component Software*), Besançon, France, October 19–21, 2016.

9.1.2.3. Reviewer

- G. Barbon was a reviewer for COMPSAC'2016, SVT-SAC'2017, and FSEN'2017 (*7th IPM International Conference on Fundamentals of Software Engineering*), Tehran, Iran, April 26–28, 2017.
- H. Garavel was a reviewer for SPIN'2016.
- F. Lang was a reviewer for FORTE'2016 (*36th IFIP International Conference on Formal Techniques for Distributed Objects, Components and Systems*), Heraklion, Crete, Greece, June 6–9, 2016.
- R. Mateescu was a reviewer for FACS'2016 and SEFM'2016.
- G. Salaün was a reviewer for DAIS'2016 (*16th IFIP International Conference on Distributed Applications and Interoperable Systems*), Heraklion, Crete, Greece, June 6–9, 2016.

- W. Serwe was a reviewer for SEFM'2016, FMICS-AVoCS'2016, RV'2016, and DATE'2017 (*20th International Conference on Design, Automation and Test in Europe*), Lausanne, Switzerland, March 27–31, 2017.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- H. Garavel is an editorial board member of STTT (*Springer International Journal on Software Tools for Technology Transfer*).

9.1.3.2. Reviewer - Reviewing Activities

- G. Barbon was a reviewer for JSS (*Journal of Systems and Software*).
- H. Garavel was a reviewer for the Mathematical Reviews (MathSciNet) of the American Mathematical Society.
- F. Lang was a reviewer for STTT.
- R. Mateescu was a reviewer for Acta Informatica and STTT.
- G. Salaün was a reviewer for IJCIS (*International Journal of Cooperative Information Systems*), JLAMP (*Journal of Logic and Algebraic Methods in Programming*), IEEE TSE (*Transactions on Software Engineering*), and TSI (*Technique et Science Informatiques*).
- W. Serwe was a reviewer for SPE (*Journal on Software: Practice and Experience*) and STTT.

9.1.4. Software Dissemination and Internet Visibility

The CONVECS project-team distributes several software tools: the CADP toolbox (see § 5.1), the TRAIAN compiler (see § 5.2), the PIC2LNT translator, the PMC model checker, and the DLC compiler.

In 2016, the main facts are the following:

- We prepared and distributed twelve successive versions (2016-a to 2016-l) of CADP.
- A new version 2.8 of TRAIAN was released on February 29, 2016.
- We were requested to grant CADP licenses for 507 different computers in the world.

The CONVECS Web site [0] was updated with scientific contents, announcements, publications, etc.

By the end of December 2016, the CADP forum [0], opened in 2007 for discussions regarding the CADP toolbox, had over 389 registered users and over 1769 messages had been exchanged.

Also, for the 2016 edition of the Model Checking Contest, we provided four families of models (totalling 62 Nested-Unit Petri Nets) derived from our LNT models. A journal article presenting the achievements of the Model Checking Contest since its origins has been published [15].

Other research teams took advantage of the software components provided by CADP (e.g., the BCG and OPEN/CAESAR environments) to build their own research software. We can mention the following developments:

- An approach for specifying formally the composition of Web services [27]
- The Vercors integrated environment for verifying and running distributed components [43], [46]
- The PN2MC tool for modeling and verifying RTCP-nets [53]
- The Alvis tool for designing hierarchical communication diagrams [54]
- The IDCM tool for designing and integrating complex systems [48], [47]
- The Availability Analyzer tool for software architecture decomposition alternatives [55]

[0] http://convecs.inria.fr
[0] http://cadp.inria.fr/forum.html

Other teams also used the CADP toolbox for various case studies:

- Formal specification and verification of TCP extended with the Window Scale Option [49]
- Performance evaluation of concurrent data structures [56]
- Heuristic search for equivalence checking [31]
- Using formal models to cross check an implementation [52]
- Proving linearizability via branching bisimulation [57]
- Computing maximal weak and other bisimulations [28]
- Verification methodologies for fault-tolerant Network-on-Chip systems [58]

9.1.5. Awards and Distinctions

H. Garavel is an invited professor at Saarland University (Germany) as a holder of the Gay-Lussac Humboldt Prize.

9.1.6. Invited Talks

- H. Garavel gave a talk entitled "*Process Calculi: Towards the Great Unification*" on January 12, 2016 at the Formal Methods seminar of Inria Grenoble.
- R. Mateescu gave a talk entitled "*On-the-Fly Verification for Extended Action-Based Temporal Logics*" on March 3rd, 2016 at IST Graz, Austria.
- H. Garavel was a guest speaker at the 9th German national D-CON meeting that took place in Saarbrücken, Germany, on March 7–8, 2016, where he gave a talk entitled "*Nested-Unit Petri Nets*".
- G. Salaün gave a talk entitled "*Automated Verification of Asynchronously Communicating Systems*" on March 15, 2016 at the LORIA laboratory, Nancy, France.
- H. Garavel gave a talk entitled "*On the Simplest Way to Build Integers from Naturals*" on April 28, 2016 at Saarland University, Germany.
- G. Barbon gave a talk entitled "*Debugging Concurrent Programs using Model Checking and Mining Techniques*" at MOVEP'2016 (*12th Summer School on Modelling and Verification of Parallel Processes*) that took place in Genova, Italy, on June 17–July 1, 2016.
- H. Garavel gave a talk entitled "*On the Most Suitable Axiomatization of Signed Integers Using Free Constructors*" during WADT'2016 (*23rd International Workshop on Algebraic Development Techniques*) that took place in Gregynog, Wales, UK, on September 21–24, 2016.
- H. Garavel gave two talks entitled "*Term Rewrite Systems and the Definition of Signed Integers*" and "*Benchmarking Implementations of Conditional Term Rewrite Systems*" on September 30, 2016 at the LSV laboratory, Cachan, France.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

CONVECS is a host team for MOSIG [0] (*Master of Science in Informatics at Grenoble*), the international master programme in computer science, common to Grenoble INP and Université Grenoble Alpes.

[0] http://mosig.imag.fr

In 2016, we carried out the following teaching activities:

- H. Garavel, together with Laurence Pierre (TIMA, Grenoble), created a new curriculum HECS [0] ("*High-confidence Embedded and Cyberphysical Systems*") for 2nd-year MOSIG students. This curriculum opened for the first time in September 2016.
- F. Lang, R. Mateescu, G. Salaün, and W. Serwe gave lectures on models for concurrency, temporal logics, equivalences, formal languages and verification (36 hours) as part of the MOSIG/HECS-2 course ("*Modeling and Analysis of Concurrent Systems*") led by G. Salaün.
- H. Garavel gave lectures on probabilistic models, stochastic models, and static/dynamic fault trees (6 hours) as part of the MOSIG/HECS-3 course ("*Performance and quantitative properties*") led by Goran Frehse (Verimag).
- H. Garavel gave lectures on the synchronous languages Lustre and SCADE, and on model-driven engineering (7.5 hours) as part of the MOSIG/HECS-4 course ("*Industrial processes for high-confidence design*") led by Laurence Pierre (TIMA).
- G. Salaün was co-responsible of the ISI (*Ingéniérie des Systèmes d'Information*) department of ENSIMAG ("*École Nationale Supérieure d'Informatique et de Mathématiques Appliquées*", Grenoble INP) from September 1, 2011 until August 31st, 2016.
- G. Salaün is Professor at Université Grenoble Alpes since September 1st, 2016, and teaches algorithmics, programming, and Web development at the MMI department of IUT1. He is also headmaster of the SMIN professional licence (L3, 3rd year of university), 192 hours.
- W. Serwe supervised a group of six teams in the context of the "*projet Génie Logiciel*" (55 hours "*équivalent TD*", consisting in 16.5 hours of lectures, plus supervision and evaluation).
- F. Lang gave a lecture on formal methods (9 hours "*équivalent TD*") in the framework of the software engineering course given to the first year students of MOSIG.
- F. Lang gave a lecture on "*Modélisation et vérification de systèmes concurrents et temps-réel*" (27 hours "*équivalent TD*") to the third year computer science engineering students of ENSIMAG.
- G. Barbon gave a lecture on "*Théorie des Langages 1*" at ENSIMAG (18 hours "*équivalent TD*").

9.2.2. Supervision

- Fatma Jebali, "*A Formal Framework for Modelling and Verifying Globally Asynchronous Locally Synchronous Systems*", Université Grenoble Alpes, September 12, 2016, F. Lang and R. Mateescu
- PhD in progress: G. Barbon, "*Debugging Concurrent Programs using Model Checking and Mining Techniques*", Université Grenoble Alpes, since October 2015, G. Salaün and V. Leroy
- PhD in progress: L. Marsso, "*Formal Methods for Testing Networks of Controllers*", Université Grenoble Alpes, since October 2016, R. Mateescu, W. Serwe, I. Parissis, and Ch. Deleuze
- PhD in progress: U. Ozeer, "*Autonomous Resilience of Applications in a Largely Distributed Cloud Environment*", Université Grenoble Alpes, since November 2016, X. Etchevers, G. Salaün, F.-G. Ottogalli, and J.-M. Vincent

9.2.3. Juries

- R. Mateescu was reviewer of Oleksandra Kulankhina's PhD thesis, entitled "*A Framework for Rigorous Development of Distributed Components: Formalisation and Tools*", defended at University of Nice Sophia-Antipolis on October 14, 2016.
- G. Salaün was reviewer of Guillaume Verdier's PhD Thesis, entitled "*Variants of Acceptance Specifications for Modular System Design*", defended at University of Toulouse on March 29, 2016.

[0] http://hecs.imag.fr

9.3. Popularization

H. Garavel participates to the program committee and organization committee of FMF (Formal Methods Forum [0]), a series of industrial conferences on formal methods set up by the competitivity clusters Aerospace Valley and Minalogic, with the support of Inria and many other partners. The 6th FMF conference, devoted to safety engineering, was held on January 26, 2016. The 7th FMF conference, devoted to formal methods and cybersecurity, is scheduled on January 31, 2017.

H. Garavel and R. Mateescu co-operated with Gérard Berry to prepare his lecture on explicit-state enumerative verification given at Collège de France on April 22, 2016.

9.4. Miscellaneous Activities

H. Garavel was a member of the 2016 Inria selection committee for hiring research officers (*chargés de recherche*).

In 2016, H. Garavel was appointed to the Executive Commission in charge of International Relations at COMUE University Grenoble Alpes.

F. Lang is chair of the "*Commission du développement technologique*", which is in charge of selecting R&D projects for Inria Grenoble – Rhône-Alpes.

R. Mateescu is the correspondent of the "*Département des Partenariats Européens*" for Inria Grenoble – Rhône-Alpes.

R. Mateescu is a member of the "*Comité d'orientation scientifique*" for Inria Grenoble – Rhône-Alpes.

R. Mateescu is a member of the "*Bureau*" of the LIG laboratory.

G. Salaün was an elected member of the council of the LIG laboratory until August 31, 2016.

G. Salaün is a member of the Scientific Committee of the PCS action of the PERSYVAL Labex.

W. Serwe is "*chargé de mission*" for the scientific axis *Formal Methods, Models, and Languages* of the LIG laboratory.

W. Serwe is (together with Laurent Lefèvre from the AVALON Inria project-team) correspondent in charge of the 2016 Inria activity reports at Inria Grenoble – Rhône-Alpes.

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Project-Team CORSE

Compiler Optimization and Run-time SystEms

IN COLLABORATION WITH: Laboratoire d'Informatique de Grenoble (LIG)

IN PARTNERSHIP WITH:
Institut polytechnique de Grenoble

Université Grenoble Alpes

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Architecture, Languages and Compilation

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7.3. - Optimization
7.6. - Computer Algebra
7.9. - Graph theory

Other Research Topics and Application Domains:

3.2. - Climate and meteorology
3.3.1. - Earth and subsoil
4.5.1. - Green computing
5.3. - Nanotechnology
6.1.2. - Software evolution, maintenance
6.6. - Embedded systems
6.7. - Computer Industry (harware, equipments...)
9.1. - Education
9.6. - Reproducibility

CORSE *is located at Giant/Minatec in Grenoble.*

1. Members

Research Scientists

Fabrice Rastello [Team leader, Inria, Research Scientist, Senior Researcher, HDR]
Frederic Desprez [Inria, Research Scientist, Senior Researcher, HDR]

Faculty Members

Florent Bouchez - Tichadou [Univ. Grenoble Alpes, Associate Professor]
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Kevin Pouget [Univ. Grenoble Alpes, DEMA/Nano2017]
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Fabian Gruber [Univ. Grenoble Alpes]
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Visiting Scientists

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Administrative Assistants

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Others

Léa Albert [Inria, Internship, until Jul 2016]
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2. Overall Objectives

2.1. Overall Objectives

Languages, compilers, and run-time systems are some of the most important components to bridge the gap between applications and hardware. With the continuous increasing power of computers, expectations are evolving, with more and more ambitious, *computational intensive and complex applications*. As desktop PCs are becoming a niche and servers mainstream, three categories of computing impose themselves for the next decade: mobile, cloud, and super-computing. Thus *diversity, heterogeneity* (even on a single chip) and thus also *hardware virtualization* is putting more and more pressure both on compilers and run-time systems. However, because of the energy wall, *architectures* are becoming more and more *complex* and *parallelism ubiquitous* at every level. Unfortunately, the memory-CPU gap continues to increase and energy consumption remains an important issue for future platforms. To address the challenge of *performance and energy consumption* raised by silicon companies, compilers and run-time systems must *evolve* and, in particular, interact, *taking into account the complexity of the target architecture*.

The overall objective of CORSE is to address this challenge by *combining static and dynamic compilation* techniques, with more interactive *embedding of programs and compiler environment in the runtime system*.

3. Research Program

3.1. Scientific Foundations

One of the characteristics of CORSE is to base our researches on diverse advanced mathematical tools. Compiler optimization requires the usage of the several tools around discrete mathematics: combinatorial optimization, algorithmic, and graph theory. The aim of CORSE is to tackle optimization not only for regular but also for irregular applications. We believe that new challenges in compiler technology design and in particular for split compilation should also take advantage of graph labeling techniques. In addition to runtime and compiler techniques for program instrumentation, hybrid analysis and compilation advances will be mainly based on polynomial and linear algebra.

The other specificity of CORSE is to address technical challenges related to compiler technology, runtime systems, and hardware characteristics. This implies mastering the details of each. This is especially important as any optimization is based on a reasonably accurate model. Compiler expertise will be used in modeling applications (e.g. through automatic analysis of memory and computational complexity); Runtime expertise will be used in modeling the concurrent activities and overhead due to contention (including memory management); Hardware expertise will be extensively used in modeling physical resources and hardware mechanisms (including synchronization, pipelines, etc.).

The core foundation of the team is related to the combination of static and dynamic techniques, of compilation, and runtime systems. We believe this to be essential in addressing high-performance and low energy challenges in the context of new important changes shown by current application, software, and architecture trends.

Our project is structured along two main directions. The first direction belongs to the area of runtime systems with the objective of developing strong relations with compilers. The second direction belongs to the area of compiler analysis and optimization with the objective of combining dynamic analysis and optimization with static techniques. The aim of CORSE is to ground those two research activities on the development of the end-to-end optimization of some specific domain applications.

4. Application Domains

4.1. Transfer

The main industrial sector related to the research activities of CORSE is the one of semi-conductor (programmable architectures spanning from embedded systems to servers). Obviously any computing application which has the objective of exploiting as much as possible the resources (in terms of high-performance but also low energy consumption) of the host architecture is intended to take advantage of advances in compiler and runtime technology. These applications are based over numerical kernels (linear algebra, FFT, convolution...) that can be adapted on a large spectrum of architectures. Members of CORSE already maintain fruitful and strong collaborations with several companies such as STMicroelectronics, Bull, Kalray, or Aselta.

Applying our techniques to a specific real application domain is cherished by all members of the team. In particular we believe (multi-scale) computational mechanics (such as fluid mechanics, molecular dynamics) to be a challenging domain that could take advantage both of compiler and run-time technologies that we intend to develop in CORSE. The goal is to provide an end-to-end solution to the automatic optimization (thus targeting portability of optimized code) of a specific application that requires extensive computational power. If we succeed our research should contribute indirectly to advances in that domain. We are still in the process of prospecting for the most appropriate application.

5. New Software and Platforms

5.1. Tirex

TIREX is an extensible, textual intermediate code representation that is intended to be used as an exchange format for compilers and other tools working on low level code. In the scope of the TIREX project we have developed tools for generating TIREX code from higher level languages such as C, as well as a number of static analyses and transformations.

Work on the TIREX project consisted of two main parts, firstly creation of a machine description library for all parts of the TIREX project, secondly, the development of tools for parsing assembly code.

We developed `archinfo`, a LLVM based library that allows programatic access to descriptors for a target CPUs instructions and registers. The focus was to expose information that was not already available from LLVM, such as machine operand types (float or integer, bitwidth, ...) and flags describing the high level behaviour of the instructions.

The, also LLVM based, assembly parser is intended to be used for translating assembly files generated by common compilers to TIREX, but it can also handle a number of idioms usually found in hand written assembly code. It reconstructs some high level information required for the TIREX format, such as the control flow and call graph, from the assembly code. We also started investigating how our existing tools can be extended to directly parse binary code and reconstruct information from them.

5.2. QEMU plugins

We have collaborated with STMicroelectronics on extending the QEMU CPU emulator with a plugin system. These plugins allow users to observe and modify the machine code emitted by QEMUs binary translator.

We have leveraged this to start development on a number of tools for profiling and performance debugging.

- cachesim: A QEMU plugin that feeds memory accesses observed during program execution into the DineroIV cache simulator. This allows estimating the number of a cache misses caused by each instruction of a program. Using this information we can also estimate the amount of memory bandwidth required by a program. This in turn can be used to diagnose if the applications performance is constrained by memory or CPU resources.
- dep-rate: A QEMU plugin that uses a shadow memory to detects data dependencies between instructions and correlates them with cache misses reported by DineroIV to estimate the performance impact of these dependencies.
- cpath: A QEMU plugin that estimates the optimal execution time of a program on an infinitely parallel CPU and compares it to that for a more realistic model of a CPU. This comparison is used to judge the amount of instruction level parallelism existing in a program.

5.3. Givy

Givy is a runtime developed as part of the PhD thesis of François Gindraud. It is designed for architectures with distributed memories, with the Kalray MPPA as the main target. It executes dynamic data-flow task graphs, annotated with memory dependencies. It automatically handles scheduling and placement of tasks (using the memory dependency hints), and generate memory transfers between distributed memory nodes when needed by using a software cache coherence protocol. An important part of the work corresponds on implementing and testing a memory allocator with specific properties that is a building block of the whole run time. This memory allocator is also tuned to work on the MPPA and its constraints, turning with very little memory and being efficient in the context of multith readed calls.

5.4. Dynamic Dependence Graph (DDG)

By instrumenting the memory accesses, at the LLVM IR level, of a hand selected region of a program, the DDG tool builds a graph with all dynamic instructions. Each instruction, i.e. a node in the graph, is identified by a statement identifier, mapping the dynamic instruction to a static statement, and an induction vector, containing the trip counters of loops surrounding the related statement. Edges connecting these nodes represent either data dependence, reuse or anti-dependence among the instructions, obtained by using the shadow memory technique, that labels ownership to a given written memory position to a dynamic instruction, and creating relationship to it to instructions that read the exact same memory position. Instructions that have a statically known formula (SCEVs) are not tracked, allowing our technique to remove, for example, obvious dependencies from a loop iteration to the next, and still track integer instructions. As the number of dynamic instructions, even in very simple applications, grows extremely fast, the generated graph does not to fit in main memory just after a few hundred loop iterations, our tool allows limiting the number of loop iterations that are tracked. Dependencies between iterations outside the observed iteration space can either be ignored or clamped as being generated by a single instruction. The generated graph can be used to guide loop optimizers, that could not extract precise dependencies. It can also be used by performance debugging tools, in order to determine if it is possible to obtain a new instruction schedule that would improve locality.

5.5. Integer polynomial Fourier-Motzkin elimination

Quantifier elimination is the process of removing existential variables of a given formula, obtaining one that is simpler in the number of variables, and that is implied by the original formula. A very well known algorithm is the Fourier-Motzkin elimination process, that given a system (or formula) of inequalities removes variables by combining all upper and lower bounds of such variables. At each step a variable is selected and eliminated. The very first limitation of this algorithm is the fact that it is designed for linear systems, where all coefficients of the variable being eliminated are numeric values, and the inequality can be classified as either a upper or lower bound. When dealing with polynomials, all possible values, positive, negative, or zero, for an coefficient, that is, a symbolic expression, must be explored. To avoid this requirement we use the positiveness algorithm, proposed by Mark Schweighofer, to retrieve symbolic coefficient signs. In fact, this algorithm is of major importance when resolving system over integer variables, instead of reals, as it is used in many other techniques required to preserve the precision of the simplified formula, such as symbolic normalization, convex hull detection, redundancy removing. Our C++ implementation uses GiNaC for symbolic expressions manipulation.

5.6. BOAST: Metaprogramming of Computing Kernels

BOAST aims at providing a framework to metaprogram, benchmark and validate computing kernels. BOAST is a programming framework dedicated to code generation and autotuning. This software allows the transformation from code written in the BOAST DSL to classical HPC targets like FORTRAN, C, OpenMP, OpenCL or CUDA. It also enables the meta-programming of optimization that can be (de)activated when needed. BOAST can also benchmark and do non regression tests on the generated kernels. This approach gives, both, performance gains and improved performance portability.

BOAST can be dowloaded at this address https://forge.imag.fr/projects/boast/.

BOAST was already used to generate and optimize the computing kernels of three scientific applications:

- BigDFT: A massively parallel electronic structure code using wavelet basis set.
- SPECFEM: Computational Infrastructure for Geodynamics.
- Gysela: Fusion plasma simulations.

BOAST is currently used in the context of the European H2020/HPC4E project. The computing kernels of two scientific applications are currently studied with BOAST:

- Alya: Large Scale Computational Mechanics.
- Hou10ni: Solutions to accoustics wave propagation problems. This code is developed by the Magique3D Inria team (Pau, Julien Diaz).

Frédéric Desprez presented BOAST at the CSCD workshop http://www.netlib.org/utk/people/JackDongarra/CCDSC-2016/ in October 2016. After this workshop, a paper was submited at the Internationaj Journal on High Performance Computing Applications (IJHPCA).

BOAST was also used in the Bulldog project during the last CERMACS summer school http://smai.emath.fr/cemracs/cemracs16/ in July 2016. A joint paper with CEA researchers from Cadarache and Maison de la Simulation was also submitted to present the results of the Bulldog project.

5.7. mcGDB: Interactive debugging of OpenMP programs

MCGDB introduced the concept of *programming-model centric* source-level interactive debugging as an extension of the traditional language-level interactive debugging. The idea was to integrate into debuggers the notion of *programming models*, as abstract machines running over the physical ones. These abstract machines, implemented by runtime libraries and programming frameworks, provide the high-level primitives required for the implementation of today's parallel applications.

We developed a proof-of-concept, mcGDB, as a Python extension of GDB, the debugger of the GNU project. mcGDB was initially developed by Kevin Pouget during his thesis with STMicroelectronics. mcGDB is currently extended with the Nano2017/DEMA project.

We proposed the new support of mcGDB for OpenMP task-based programming. This support consists of task-based execution representation and control improvements, in cooperation with Temanejo graphical debugger. We also studied import implementation details of mcGDB, related to the support of multiple OpenMP environments and CPU architectures; the separation of cross-cutting concerns (user interaction and execution representing) through aspect-oriented programming, and the first steps of mcGDB micro-benchmarking.

mcGDB [30] was presented at the second OpenMPCon developpers conference in Nara.

6. New Results

6.1. Simplification and Run-time Resolution of Data Dependence Constraints for Loop Transformations

Participants: Diogo Nunes Sampaio, Alain Ketterlin [Inria CAMUS], Louis-Noël Pouchet [CSU, USA], Fabrice Rastello.

Loop optimizations such as tiling, thread-level parallelization or vectorization are essential transformations to improve performance. It is needed to compute dependence information at compile-time to assess their validity, but in many real situations, static dependence analysis fails to provide precise enough information. Part of the reason for this failure comes from the need to handle polynomial constraints in the dependence computation problem: such polynomial constraints can arise from linearized array accesses, typical in compilers IR such as LLVM-IR. In this scenario, the compiler will often be unable to apply aggressive transformations due to lack of conclusive static dependence analysis. This work tackles the problem of eliminating quantifiers in systems of inequalities using polynomial constraints. In particular, we design a quantifier elimination scheme on integer multivariate-polynomials, which can aid application of off-the-shelf polyhedral transformations on a larger class of programs, that holds polynomial memory access and affine loop bounds. We make a significant leap in accuracy compared to prior approaches, enabling to implement a hybrid optimizing compilation scheme. In this scheme, a test is evaluated at run-time to determine the legality of the program transformation chosen by the compiler, falling back to executing the original code if the test fails. This test integrates all may-dependences, involving polynomial inequalities, and is simplified by quantifier elimination at compile-time using our techniques. The preciseness of the presented scheme and the low run-time overhead of the test are key to make this approach realistic. We experimentally validate our technique on 25 benchmarks using complex loop transformations, achieving negligible overhead. Preciseness is assessed by the observed success of generated test in practical cases. We compare our variable elimination technique to other existing tools and demonstrate we achieve better precision when dealing with polynomial memory accesses.

This work is the fruit of the collaboration 8.4 with OSU.

6.2. A bounded memory allocator for software-defined global address spaces

Participants: François Gindraud, Fabrice Rastello, Albert Cohen [ENS Ulm], Francois Broquedis.

This work is about the design of a memory allocator targeting manycore architectures with distributed memory. Among the family of Multi Processor System on Chip (MPSoC), these devices are composed of multiple nodes linked by an on-chip network; most nodes have multiple processors sharing a small local memory. While MPSoC typically excel on their performance-per-Watt ratio, they remain hard to program due to multilevel parallelism, explicit resource and memory management, and hardware constraints (limited memory, network topology).

Typical programming frameworks for MPSoC leave much target-specific work to the programmer: combining threads or node-local OpenMP, software caching, explicit message passing (and sometimes, routing), with non-standard interfaces. More abstract, automatic frameworks exist, but they target large-scale clusters and do not model the hardware constraints of MPSoC.

This memory allocator is one component of a larger runtime system, called Givy 5.3, to support dynamic task graphs with automatic software caching and data-driven execution on MPSoC. To simplify the programmer's view of memory, both runtime and program data objects live in a Global Address Space (GAS). To avoid address collisions when objects are dynamically allocated, and to manage virtual memory mappings across nodes, a GAS-aware memory allocator is required. This work proposes such an allocator with the following properties: (1) it is free of inter-node synchronizations; (2) its node-local performance match that of state-of-the-art shared-memory allocators; (3) it provides node-local mechanisms to implement inter-node software caching within a GAS; (4) it is well suited for small memory systems (a few MB per node).

This work has been presented at the international conference ISMM 2016 [16].

6.3. On Fusing Recursive Traversals of K-d Trees

Participants: Samyam Rajbhandari [OSU, USA], Jinsung Kim [OSU, USA], Sriram Krishnamoorthy [PNNL, USA], Louis-Noel Pouchet [CSU, USA], Fabrice Rastello, Robert J. Harrison [Stony Brook, USA], P. Sadayappan [OSU, USA].

Loop fusion is a key program transformation for data locality optimization that is implemented in production compilers. But optimizing compilers for imperative languages currently cannot exploit fusion opportunities across a set of recursive tree traversal computations with producer-consumer relationships. In this work, we develop a compile-time approach to dependence characterization and program transformation to enable fusion across recursively specified traversals over k-d trees. We present the FuseT source-to-source code transformation framework to automatically generate fused composite recursive operators from an input program containing a sequence of primitive recursive operators. We use our framework to implement fused operators for MADNESS, Multiresolution Adaptive Numerical Environment for Scientific Simulation. We show that locality optimization through fusion can offer significant performance improvement.

This work is the fruit of the collaboration 8.4 with OSU. The specific work on FuseT has been presented to the international conference CC 2016 [32] and the more general work on the improvement of MADNESS at the ACM/IEEE international conference SC 2016 [20].

6.4. Effective Padding of Multidimensional Arrays to Avoid Cache Conflict Misses

Participants: Changwan Hong [OSU, USA], Wenlei Bao [OSU, USA], Albert Cohen [Inria PARKAS], Sriram Krishnamoorthy [PNNL, USA], Louis-Noel Pouchet [CSU, USA], Fabrice Rastello, J. Ramanujam [LSU, USA], P. Sadayappan [OSU, USA].

Caches are used to significantly improve performance. Even with high degrees of set associativity, the number of accessed data elements mapping to the same set in a cache can easily exceed the degree of associativity. This can cause conflict misses and lower performance, even if the working set is much smaller than cache capacity. Array padding (increasing the size of array dimensions) is a well-known optimization technique that can reduce conflict misses. In this work, we develop the first algorithms for optimal padding of arrays aimed at a set-associative cache for arbitrary tile sizes. In addition, we develop the first solution to padding for nested tiles and multi-level caches. Experimental results with multiple benchmarks demonstrate a significant performance improvement from padding.

This work is the fruit of the collaboration 8.4 with OSU. It has been presented at the ACM international conference PLDI 2016 [29].

6.5. PolyCheck: Dynamic Verification of Iteration Space Transformations on Affine Programs

Participants: Sriram Krishnamoorthy [PNNL], Bao Wenlei [OSU], Louis-Noël Pouchet [UCLA], P. Sadayappan [OSU], Fabrice Rastello.

High-level compiler transformations, especially loop transformations, are widely recognized as critical optimizations to restructure programs to improve data locality and expose parallelism. Guaranteeing the correctness of program transformations is essential, and to date three main approaches have been developed: proof of equivalence of affine programs, matching the execution traces of programs, and checking bit-by-bit equivalence of program outputs. Each technique suffers from limitations in the kind of transformations supported, space complexity, or the sensitivity to the testing dataset. In this work, we take a novel approach that addresses all three limitations to provide an automatic bug checker to verify any iteration reordering transformations on affine programs, including non-affine transformations, with space consumption proportional to the original program data and robust to arbitrary datasets of a given size. We achieve this by exploiting the structure of affine program control- and data-flow to generate at compile-time lightweight checker code to be executed within the transformed program. Experimental results assess the correctness and effectiveness of our method and its increased coverage over previous approaches.

This work is the fruit of the collaboration 8.4 with OSU and was presented at ACM POPL'16 [14].

6.6. Modularizing Crosscutting Concerns in Component-Based Systems

Participants: Antoine El-Hokayem, Yliès Falcone, Mohamad Jaber [American University of Beirut, Lebanon].

We define a method to modularize crosscutting concerns in the Behavior Interaction Priority (BIP) component-based framework. Our method is inspired from the Aspect Oriented Programming (AOP) paradigm which was initially conceived to support the separation of concerns during the development of monolithic systems. BIP has a formal operational semantics and makes a clear separation between architecture and behavior to allow for compositional and incremental design and analysis of systems. We thus distinguish local from global aspects. Local aspects model concerns at the component level and are used to refine the behavior of components. Global aspects model concerns at the architecture level, and hence refine communications (synchronization and data transfer) between components. We formalize global aspects as well as their integration into a BIP system through rigorous transformation primitives and overview local aspects. We present AOP-BIP, a tool for Aspect-Oriented Programming of BIP systems, and demonstrate its use to modularize logging, security, and fault-tolerance in a network protocol.

This work results of the collaboration with American University of Beirut (Lebanon) and was presented at SEFM 2016 [15].

6.7. Predictive runtime enforcement

Participants: Srinivas Pinisetty [Aalto University, Finland], Viorel Preoteasa [Aalto University, Finland], Stavros Tripakis [Aalto University, Finland], Thierry Jéron [Inria Rennes, France], Yliès Falcone, Hervé Marchand [Inria Rennes, France].

Runtime enforcement (RE) is a technique to ensure that the (untrustworthy) output of a black-box system satisfies some desired properties. In RE, the output of the running system, modeled as a stream of events, is fed into an enforcement monitor. The monitor ensures that the stream complies with a certain property, by delaying or modifying events if necessary. This work deals with predictive runtime enforcement, where the system is not entirely black-box, but we know something about its behavior. This a-priori knowledge about the system allows to output some events immediately, instead of delaying them until more events are observed, or even blocking them permanently. This in turn results in better enforcement policies. We also show that if we have no knowledge about the system, then the proposed enforcement mechanism reduces to a classical non-predictive RE framework. All our results are formalized and proved in the Isabelle theorem prover.

This work was presented at SAC-SVT 2016 [19].

6.8. Third International Competition on Runtime Verification

Participants: Giles Reger [University of Manchester, UK], Sylvain Hallé [The University of Québec at Chicoutimi, Canada], Yliès Falcone.

We report on the Third International Competition on Runtime Verification (CRV-2016). The competition was held as a satellite event of the 16th International Conference on Runtime Verification (RV'16). The competition consisted of two tracks: offline monitoring of traces and online monitoring of Java programs. The intention was to also include a track on online monitoring of C programs but there were too few participants to proceed with this track. This report describes the format of the competition, the participating teams, the submitted benchmarks and the results. We also describe our experiences with transforming trace formats from other tools into the standard format required by the competition and report on feedback gathered from current and past participants and use this to make suggestions for the future of the competition.

This work was presented at RV 2016 [13].

6.9. Monitoring Multi-threaded Component-Based Systems

Participants: Hosein Nazarpour [Verimag, France], Yliès Falcone, Saddek Bensalem [Verimag, France], Marius Bozga [Verimag, France], Jacques Combaz [Verimag, France].

This work addresses the monitoring of logic-independent linear-time user-provided properties on multi-threaded component-based systems. We consider intrinsically independent components that can be executed concurrently with a centralized coordination for multiparty interactions. In this context, the problem that arises is that a global state of the system is not available to the monitor. A naive solution to this problem would be to plug a monitor which would force the system to synchronize in order to obtain the sequence of global states at runtime. Such solution would defeat the whole purpose of having concurrent components. Instead, we reconstruct on-the-fly the global states by accumulating the partial states traversed by the system at runtime. We define formal transformations of components that preserve the semantics and the concurrency and, at the same time, allow to monitor global-state properties. Moreover, we present RVMT-BIP, a prototype tool implementing the transformations for monitoring multi-threaded systems described in the BIP (Behavior, Interaction, Priority) framework, an expressive framework for the formal construction of heterogeneous systems. Our experiments on several multi-threaded BIP systems show that RVMT-BIP induces a cheap runtime overhead.

This work was presented at iFM 2016 [18].

6.10. Decentralized Enforcement of Artifact Lifecycles

Participants: Sylvain Hallé [The University of Québec at Chicoutimi, Canada], Raphaël Khoury [The University of Québec at Chicoutimi, Canada], Antoine El-Hokayem, Yliès Falcone.

Artifact-centric workflows describe possible executions of a business process through constraints expressed from the point of view of the documents exchanged between principals. A sequence of manipulations is deemed valid as long as every document in the workflow follows its prescribed lifecycle at all steps of the process. So far, establishing that a given workflow complies with artifact lifecycles has mostly been done through static verification, or by assuming a centralized access to all artifacts where these constraints can be monitored and enforced. We propose an alternate method of enforcing document lifecycles that requires neither static verification nor single-point access. Rather, the document itself is designed to carry fragments of its history, protected from tampering using hashing and public-key encryption. Any principal involved in the process can verify at any time that a document's history complies with a given lifecycle. Moreover, the proposed system also enforces access permissions: not all actions are visible to all principals, and one can only modify and verify what one is allowed to observe.

This work was presented at EDOC 2016 [17].

6.11. Runtime enforcement of regular timed properties by suppressing and delaying events

Participants: Yliès Falcone, Thierry Jéron [Inria Rennes, France], Hervé Marchand [Inria Rennes, France], Srinivas Pinisetty [Aalto University, Finland].

Runtime enforcement is a verification/validation technique aiming at correcting possibly incorrect executions of a system of interest. In this work, we consider enforcement monitoring for systems where the physical time elapsing between actions matters. Executions are thus modelled as timed words (i.e., sequences of actions with dates). We consider runtime enforcement for timed specifications modelled as timed automata. Our enforcement mechanisms have the power of both delaying events to match timing constraints, and suppressing events when no delaying is appropriate, thus possibly allowing for longer executions. To ease their design and their correctness-proof, enforcement mechanisms are described at several levels: enforcement functions that specify the input–output behaviour in terms of transformations of timed words, constraints that should be satisfied by such functions, enforcement monitors that describe the operational behaviour of enforcement functions, and enforcement algorithms that describe the implementation of enforcement monitors. The feasibility of enforcement monitoring for timed properties is validated by prototyping the synthesis of enforcement monitors from timed automata.

This work was published in the journal Science of Computer Programming [8].

6.12. Organising LTL monitors over distributed systems with a global clock

Participants: Christian Colombo [University of Malta, Malta], Yliès Falcone.

Users wanting to monitor distributed systems often prefer to abstract away the architecture of the system by directly specifying correctness properties on the global system behaviour. To support this abstraction, a compilation of the properties would not only involve the typical choice of monitoring algorithm, but also the organisation of submonitors across the component network. Existing approaches, considered in the context of LTL properties over distributed systems with a global clock, include the so-called orchestration and migration approaches. In the orchestration approach, a central monitor receives the events from all subsystems. In the migration approach, LTL formulae transfer themselves across subsystems to gather local information. We propose a third way of organising submonitors: choreography, where monitors are organised as a tree across the distributed system, and each child feeds intermediate results to its parent. We formalise choreography-based decentralised monitoring by showing how to synthesise a network from an LTL formula, and give a decentralised monitoring algorithm working on top of an LTL network. We prove the algorithm correct and implement it in a benchmark tool. We also report on an empirical investigation comparing these three approaches on several concerns of decentralised monitoring: the delay in reaching a verdict due to communication latency, the number and size of the messages exchanged, and the number of execution steps required to reach the verdict.

This work was published in the journal Formal Methods in System Design [6].

6.13. Decentralised LTL monitoring

Participants: Andreas Bauer [TU Munich, Software and Systems Engineering Munich, Germany], Yliès Falcone.

Users wanting to monitor distributed or component-based systems often perceive them as monolithic systems which, seen from the outside, exhibit a uniform behaviour as opposed to many components displaying many local behaviours that together constitute the system's global behaviour. This level of abstraction is often reasonable, hiding implementation details from users who may want to specify the system's global behaviour in terms of a linear-time temporal logic (LTL) formula. However, the problem that arises then is how such a specification can actually be monitored in a distributed system that has no central data collection point, where all the components' local behaviours are observable. In this case, the LTL specification needs to be decomposed into sub-formulae which, in turn, need to be distributed amongst the components' locally attached monitors, each of which sees only a distinct part of the global behaviour. The main contribution of this work is an algorithm for distributing and monitoring LTL formulae, such that satisfaction or violation of specifications can be detected by local monitors alone. We present an implementation and show that our algorithm introduces only a negligible delay in detecting satisfaction/violation of a specification. Moreover, our practical results show that the communication overhead introduced by the local monitors is generally lower than the number of messages that would need to be sent to a central data collection point. Furthermore, our experiments strengthen the argument that the algorithm performs well in a wide range of different application contexts, given by different system/communication topologies and/or system event distributions over time.

This work was published in the journal Formal Methods in System Design [4].

6.14. Using data dependencies to improve task-based scheduling strategies on NUMA architectures

Participants: Philippe Virouleau, François Broquedis, Thierry Gautier [Inria, AVALON], Fabrice Rastello.

The recent addition of data dependencies to the OpenMP 4.0 standard provides the application programmer with a more flexible way of synchronizing tasks. Using such an approach allows both the compiler and the runtime system to know exactly which data are read or written by a given task, and how these data will be used through the program lifetime. Data placement and task scheduling strategies have a significant impact on performances when considering NUMA architectures. While numerous studies focus on these topics, none of them has made extensive use of the information available through dependencies. One can use this information to modify the behavior of the application at several levels : during initialization to control data placement and during the application execution to dynamically control both the task placement and the tasks stealing strategy, depending on the topology. This work introduces several heuristics for these strategies, their implementations in the xkaapi OpenMP runtime system and the performances on linear algebra applications executed on a 192-core NUMA machine. Such approaches report noticeable performance improvement when considering both the architecture topology and the tasks data dependencies.

This work has been presented at the international conference EuroPar'2016 [22].

6.15. Description, Implementation and Evaluation of an Affinity Clause for Task Directives

Participants: Philippe Virouleau, Adrien Roussel [IFPEN], François Broquedis, Thierry Gautier [Inria, AVALON], Fabrice Rastello, Jean-Marc Gratien [IFPEN].

This work extends the affinity-based scheduling we proposed at the Europar 2016 conference to fit the philosophy of OpenMP programming. On this topic, OpenMP does not provide a lot of flexibility to the programmer yet, which lets the runtime system decide where a task should be executed. In this work, we propose our own interpretation of the new affinity clause for the task directive, which is being discussed by the OpenMP Architecture Review Board. This clause enables the programmer to give hints to the runtime about tasks placement during the program execution, which can be used to control the data mapping on the architecture. In our proposal, the programmer can express affinity between a task and the following resources: a thread, a NUMA node, and a data. We provide an implementation of this proposal in the Clang-3.8 compiler, and an implementation of the corresponding extensions in the xkaapi OpenMP runtime system.

This work has been presented at the international workshop on OpenMP IWOMP'2016 [23].

6.16. Design methodology for workload-aware loop scheduling strategies based on genetic algorithm and simulation

Participants: Pedro H. Penna [PUC Minas], Márcio Castro [UFSC], Henrique C. Freitas [PUC Minas], François Broquedis, Jean-François Méhaut.

In high-performance computing, the application's workload must be evenly balanced among threads to deliver cutting-edge performance and scalability. In OpenMP, the load balancing problem arises when scheduling loop iterations to threads. In this context, several scheduling strategies have been proposed, but they do not take into account the input workload of the application and thus turn out to be suboptimal. In this work, we introduce a design methodology to propose, study, and assess the performance of workload-aware loop scheduling strategies. In this methodology, a genetic algorithm is employed to explore the state space solution of the problem itself and to guide the design of new loop scheduling strategies, and a simulator is used to evaluate their performance. As a proof of concept, we show how the proposed methodology was used to propose and study a new workload-aware loop scheduling strategy named smart round-robin (SRR). We implemented this strategy into GNU Compiler Collection's OpenMP runtime. We carry out several experiments to validate the simulator and to evaluate the performance of SRR. Our experimental results show that SRR may deliver up to 37.89% and 14.10% better performance than OpenMP's dynamic loop scheduling strategy in the simulated environment and in a real-world application kernel, respectively.

This work is presented in the CCPE journal [9].

6.17. The Mont-Blanc prototype: An Alternative Approach for HPC Systems

Participants: Brice Videau, Kevin Pouget, Jean-François Méhaut.

The evolution of High-Performance Computing (HPC) systems is driven by the need of reducing time-to-solution and increasing the resolution of models and problems being solved by a particular program. Important milestones from the HPC system performance perspective were achieved using commodity technology. Examples are the ASCI Red and the Roadrunner supercomputers, which broke the 1 TFLOPS and 1 PFLOPS barriers, respectively. These systems showed how commodity technology could be used to take the next step in HPC system architecture.

Driven by a much larger market, commodity components evolve faster than their special-purpose counterparts, eventually achieving the same performance and eventually surpassing or replacing them. For this reason, RISC processors displaced vector processors, and x86 displaced RISC.

Nowadays commodity is in the embedded / mobile processor segment. Mobile processors develop fast, and are still not at a point of diminishing performance improvements from new designs. Furthermore, they progressively incorporate the capabilities required for HPC.

The embedded market size and endless customer requirements allow for constant investments into innovative designs, and rapid testing and adoption of new technologies. For example, LPDDR memory technology was first introduced in the mobile domain and has recently been proposed as a memory solution for energy proportional servers.

The Mont-Blanc project aims at providing an alternative HPC system solution based on the current commodity technology: mobile chips. As a demonstrator of such an approach, the project designed, built, and set-up a 1080-node HPC cluster made of Samsung Exynos 5250 SoCs. The Mont-Blanc project established the following goals: to design and deploy a sufficiently large HPC prototype system based on the current mobile commodity technology; to port and optimize the software stack, and enable its use for HPC; to port and optimize a set of HPC applications to be run at this HPC system.

Comparing the Mont-Blanc prototype to a contemporary supercomputer, MareNostrum III, reveals that a single-socket Mont-Blanc node is 9x slower than a dual-socket MareNostrum III node, while saving up to 40% of energy. MPI parallel applications show a 3.5x slowdown when running with the same number of MPI ranks on both machines, while consuming 9% less energy on the Mont-Blanc prototype on average. When targeting the same execution time, the Mont-Blanc prototype offers 12.5% space savings.

This work was funded by the European Commission with the Mont-Blanc projects 8.3.1.1. This scientific result was presented at the SuperComputing Conference SC'2016 in Salt Lake City [31]. The paper was selected as a *best paper finalist*.

6.18. Control of Autonomid Parallelism on Software Transactional Memory

Participants: Naweiluo Zhou, Gwenaël Delaval [Univ. Grenoble Alpes, Associate Professor, Ctrl-A Inria team], Bogdan Robu [Univ. Grenoble Alpes, Associate Professor, Gipsa Laboratory], Eric Rutten [Inria, Rsearcher, Ctrl-A Inria team], Jean-François Méhaut.

Parallel programs need to manage the trade-off between the time spent in synchronization and computation. A high parallelism may decrease computing time while increase synchronization cost among threads. A way to improve program performance is to adjust parallelism to balance conflicts among threads. However, there is no universal rule to decide the best parallelism for a program from an offline view. Furthermore, an offline tuning is error-prone. Hence, it becomes necessary to adopt a dynamic tuning-configuration strategy to better manage a STM system. Software Transactional Memory (STM) has emerged as a promising technique, which bypasses locks, to address syn- chronization issues through transactions. Autonomic computing offers designers a framework of methods and techniques to build automated systems with well-mastered behaviours. Its key idea is to implement feedback control loops to design safe, efficient and predictable controllers, which enable monitoring and adjusting controlled systems dynamically while keeping overhead low. We propose to design feedback control loops to automate the choice of parallelism level at runtime to diminish program execution time.

This work is funded by the Persyval laboratory (LabEx) and the HPES team 8.1.2. This scientific result is part of the Naweiluo Zhou's thesis. The thesis was defended in October 2016 [2]. This work was presented in the HPCS conference [25]. The paper was selected as *best paper finalist*. The Naweiluo Zhou's work is also presented at the ICAC conference.

6.19. Evaluating the SEE sensitivity of a 45nm SOI Multi-core Processor due to 14 MeV Neutrons

Participants: Pablo Ramos [Univ. Grenoble Alpes and ESPE Ecuador, PhD student TIMA Laboratory], Vanessa Vargas [Univ. Grenoble Alpes and ESPE Ecuador, PhD student TIMA Laboratory], Maud Baylac [CNRS, IN2P3, LSPSC Laboratory], Francesca Villa [CNRS, IN2P3, LSPSC Laboratory], Nacer-Eddine Zergainoh [Univ. Grenoble Alpes, Associate Professor, TIMA Laboratory], Jean-François Méhaut, Raoul Velazco [CNRS, Senior Scientist, TIMA Laboratory].

The aim of this work is to evaluate the SEE sensitivity of a multi-core processor having implemented ECC and parity in their cache memories. Two different application scenarios are studied. The first one configures the multi-core in Asymmetric Multi-Processing mode running a memory-bound application, whereas the second one uses the Symmetric Multi-Processsing mode running a CPU-bound application. The experiments were validated through radiation ground testing performed with 14 MeV neutrons on the Freescale P2041 multi-core manufactured in 45nm SOI technology. A deep analysis of the observed errors in cache memories was carried-out in order to reveal vulnerabilities in the cache protection mechanisms. Critical zones like tag addresses were affected during the experiments. In addition, the results show that the sensitivity strongly depends on the application and the multi-processsing mode used.

This work is part of the STIC Amsud EnergySFE project 8.4.3. These results are published in the IEEE Transactions on Nuclear Science [10].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Grants with Industry

- PSAIC Nano2017 is a bilateral Grant with STMicroelectronics. CORSE is involved in the development of trace analysis and hybrid compilation.
- DEMA Nano2017 is a bilateral Grant with STMicroelectronics. CORSE is involved in the development of debugging of multithreaded applications.

7.2. CIFRE contracts

- CORSE is involved in a contract with Kalray associated with the CIFRE PhD of Duco van Amstel who defended in Spring 2016. The subject of the collaboration is related to fine grain scheduling.
- CORSE is involved in a contract with Aselta for the CIFRE thesis of Nassim Halli. Nassim Halli was advised by Henri-Pierre Charles (CEA LIST, Grenoble and Jean-François Méhaut. The subject of this thesis is the code optimization of Java Applications. The thesis was defended in October 2016.
- CORSE is also involved in a contract with STMicroelectronics for the CIFRE thesis of Oleg Iegorov. The subject of this thesis is a Data Mining Approach to Temporal Debugging of Embedded Streaming Applications. Oleg Iegorov was advised by the SLIDE LIG team and the CORSE Inria team. The thesis was defended in April 2016.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. HEAVEN Persyval Project

- Title: HEterogenous Architectures: Versatile Exploitation and programiNg
- HEAVEN leaders: François Broquedis, Olivier Muller[TIMA lab]
- CORSE participants: François Broquedis, Frédéric Desprez, Georgios Christodoulis
- Computer architectures are getting more and more complex, exposing massive parallelism, hierarchically-organized memories and heterogeneous processing units. Such architectures are extremely difficult to program as they most of the time make application programmers choose between portability and performance.

  While standard programming environments like OpenMP are currently evolving to support the execution of applications on different kinds of processing units, such approaches suffer from two main issues. First, to exploit heterogeneous processing units from the application level, programmers need to explicitly deal with hardware-specific low-level mechanisms, such as the memory transfers between the host memory and private memories of a co-processor for example. Second, as the evolution of programming environments towards heterogeneous programming mainly focuses on CPU/GPU platforms, some hardware accelerators are still difficult to exploit from a general-purpose parallel application.

  FPGA is one of them. Unlike CPUs and GPUs, this hardware accelerator can be configured to fit the application needs. It contains arrays of programmable logic blocks that can be wired together to build a circuit specialized for the targeted application. For example, FPGAs can be configured to accelerate portions of code that are known to perform badly on CPUs or GPUs. The energy efficiency of FPGAs is also one of the main assets of this kind of accelerators compared to GPUs, which encourages the scientific community to consider FPGAs as one of the building blocks of large scale low-power heterogeneous multicore platforms.

  However, only a fraction of the community considers programming FPGAs for now, as configurations must be designed using low-level description languages such as VHDL that application programmers are not experienced with.

  The main objective of this project is to improve the accessibility of heterogeneous architectures containing FPGA accelerators to parallel application programmers. The proposed project focuses on three main aspects:

  - Portability: we don't want application programmers to redesign their applications completely to benefit from FPGA devices. This means extending standard parallel programming environments like OpenMP to support FPGA. Improving application portability also means leveraging most of the hardware-specific low-level mechanisms at the runtime system level ;
  - Performance: we want our solution to be flexible enough to get the most out of any heterogeneous platforms containing FPGA devices depending on specific performance needs, like computation throughput or energy consumption for example ;
  - Experiments: Experimenting with FPGA accelerators on real-life scientific applications is also a key element of our project proposal. In particular, the solutions developed in this project will allow comparisons between architectures on real-life applications from different domains like signal processing and computational finance.

  Efficient programming and exploitation of heterogeneous architectures implies the development of methods and tools for system design, embedded or not. The HEAVEN project proposal fits in the PCS research action of the PERSYVAL-lab. The PhD of Georgios Christodoulis is funded by this project.

8.1.2. HPES Persyval Project

- Title: High Performance Embedded Systems
- HPES leader: Henri-Pierre Charles [CEA List, CRI PILSI]
- HPES participants: Suzane Lesecq [CEA Leti], Laurent Fesquet [TIMA Lab], Stéphane Mancini [TIMA Lab], Eric Ruten [Inria/CtrlA], Nicolas Marchand [Gipsa Lab], Bogdan Robu [Gipsa Lab]
- CORSE participants: Naweiluo Zhou [PhD Persyval], Fabrice Rastello, Jean-François Méhaut
- The computing area has been recently deeply modified by the emergence of the so-called multicore processor. Within the same chip, several computing units are implemented. This architectural concept allows meeting the performance requirements under stringent energy consumption constraints. Multicores are used for laptops, Graphical Processor Units (GPU), High Performance Computing (HPC) platforms, but also for embedded systems su ch as mobile phones. Moreover, low-power high performance multicores developed for embedded systems will be soon used in data centers for HPC. This raises new scientific challenges to architecture, systems and application designers that have face massively parallel computing platforms.

  The number of cores on a chip is increasing quickly. At the same time, the memory bandwidth is increasing too slowly to ensure the performance such multicore platforms should attain. This phenomenon is known as “Memory Wall” and at the moment no efficient solution to exceed this limitation exists. With the increase in the number of cores, cache coherency is becoming as well a tremendous challenge.

  Power consumption is also a huge challenge as it imposes strong constraints on the computing platform, whatever the application domain. The first machine ranked in the Green500 has an energy performance ratio of 2 Gflops per watt. This ratio has to be improved by 30 when exascale computing is considered. The multi-core processor might help to improve this ratio; however, the software stack should as well evolve to boost this improvement.

8.1.3. AGIR DEREVES

- Title: DEcentralised Runtime Verification and Enforcement of distributed and cyber-physical Systems
- DEREVES leader: Ylies Falcone
- CORSE participants: Ylies Falcone, Antoine El-Hokayem, Raphaël Jakse
- DEREVES aims at advancing the theory of decentralised runtime verification and enforce- ment for distributed systems, with the objective of proposing realistic monitoring and monitor-synthesis algorithms for expressive specifications that can be used for the efficient monitoring of multi-threaded, dis- tributed and cyber-physical systems. The project shall help transferring runtime verification and enforcement to a wider audience of programmers of distributed systems by providing them techniques and tools to help them guaranteeing the correctness of their systems.

8.2. National Initiatives

8.2.1. IPL C2S@Exa

- Title: Computer and Computational Sciences at Exascale
- C2S@Exa leader: Stéphane Lanteri
- CORSE participants: François Broquedis, Frédéric Desprez, Jean-François Méhaut, Brice Videau, Philippe Virouleau, Nora Hagmeyer

- The C2S@Exa Inria large-scale initiative is concerned with the development of numerical modeling methodologies that fully exploit the processing capabilities of modern massively parallel architectures in the context of a number of selected applications related to important scientific and technological challenges for the quality and the security of life in our society. At the current state of the art in technologies and methodologies, a multidisciplinary approach is required to overcome the challenges raised by the development of highly scalable numerical simulation software that can exploit computing platforms offering several hundreds of thousands of cores. Hence, the main objective of the C2S@Exa Inria large-scale initiative is the establishment of a continuum of expertise in the computer science and numerical mathematics domains, by gathering researchers from Inria project-teams whose research and development activities are tightly linked to high performance computing issues in these domains. More precisely, this collaborative effort involves computer scientists that are experts of programming models, environments and tools for harnessing massively parallel systems, algorithmists that propose algorithms and contribute to generic libraries and core solvers in order to take benefit from all the parallelism levels with the main goal of optimal scaling on very large numbers of computing entities and, numerical mathematicians that are studying numerical schemes and scalable solvers for systems of partial differential equations in view of the simulation of very large-scale problems.

8.2.2. PIA ELCI

- Title: Environnement logiciel pour le calcul intensif
- ELCI leader: Corinne Marchand (BULL SAS)
- CORSE participants: François Broquedis, Philippe Virouleau
- Duration: from Sept. 2014 to Sept. 2017
- The ELCI project main goal is to develop a highly-scalable new software stack to tackle high-end supercomputers, from numerical solvers to programming environments and runtime systems. In particular, the CORSE team is studying the scalability of OpenMP runtime systems on large scale shared memory machines through the PhD of Philippe Virouleau, co-advised by researchers from the CORSE and AVALON Inria teams. This work intends to propose new approaches based on a compiler/runtime cooperation to improve the execution of scientific task-based programs on NUMA platforms. The PhD of Philippe Virouleau is funded by this project.

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

8.3.1.1. Mont-Blanc2

Title: Mont-Blanc (European scalable and power efficient HPC platform based on low-power embedded technology)

Program FP7

Duration: 01/10/2013 - 31/01/2017

Coordinator: Barcelona Supercomputing Center (BSC)

Mont-Blanc consortium: BSC, Bull, Arm, Juelich, LRZ, USTUTT, Cineca, CNRS, Inria, CEA Leti, Univ. Bristol, Allinea

CORSE contact: Jean-François Méhaut

CORSE participants: Brice Videau, Kevin Pouget

The Mont-Blanc project aims to develop a European Exascale approach leveraging on commodity power-efficient embedded technologies. The project has developed a HPC system software stack on ARM, and is deployed the first integrated ARM-based HPC prototype by 2014, and is also working on a set of 11 scientific applications to be ported and tuned to the prototype system.

The rapid progress of Mont-Blanc towards defining a scalable power efficient Exascale platform has revealed a number of challenges and opportunities to broaden the scope of investigations and developments. Particularly, the growing interest of the HPC community in accessing the Mont-Blanc platform calls for increased efforts to setup a production-ready environment. The Mont-Blanc 2 proposal has 4 objectives:

1. To complement the effort on the Mont-Blanc system software stack, with emphasis on programmer tools (debugger, performance analysis), system resiliency (from applications to architecture support), and ARM 64-bit support
2. To produce a first definition of the Mont-Blanc Exascale architecture, exploring different alternatives for the compute node (from low-power mobile sockets to special-purpose high-end ARM chips), and its implications on the rest of the system
3. To track the evolution of ARM-based systems, deploying small cluster systems to test new processors that were not available for the original Mont-Blanc prototype (both mobile processors and ARM server chips)
4. To provide continued support for the Mont-Blanc consortium, namely operations of the original Mont-Blanc prototype, the new developer kit clusters and hands-on support for our application developers

Mont-Blanc 2 contributes to the development of extreme scale energy-efficient platforms, with potential for Exascale computing, addressing the challenges of massive parallelism, heterogeneous computing, and resiliency. Mont-Blanc 2 has great potential to create new market opportunities for successful EU technology, by placing embedded architectures in servers and HPC.

8.3.1.2. EoCoE

Title: Energy oriented Centre of Excellence for computer applications

Programm: H2020

Duration: October 2015 - October 2018

Coordinator: CEA

Partners:

Barcelona Supercomputing Center - Centro Nacional de Supercomputacion (Spain)

Commissariat A L Energie Atomique et Aux Energies Alternatives (France)

Centre Europeen de Recherche et de Formation Avancee en Calcul Scientifique (France)

Consiglio Nazionale Delle Ricerche (Italy)

The Cyprus Institute (Cyprus)

Agenzia Nazionale Per le Nuove Tecnologie, l'energia E Lo Sviluppo Economico Sostenibile (Italy)

Fraunhofer Gesellschaft Zur Forderung Der Angewandten Forschung Ev (Germany)

Instytut Chemii Bioorganicznej Polskiej Akademii Nauk (Poland)

Forschungszentrum Julich (Germany)

Max Planck Gesellschaft Zur Foerderung Der Wissenschaften E.V. (Germany)

University of Bath (United Kingdom)

Universite Libre de Bruxelles (Belgium)

Universita Degli Studi di Trento (Italy)

Inria contact: Michel Kern

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

8.3.1.3. HPC4E

Title: HPC for Energy (HPC4E)

Programm: H2020

Duration: December 2015 - November 2017

Program FP7

Coordinator: Barcelona Supercomputing Center

Partners:

- Centro de Investigaciones Energeticas, Medioambientales Y Tecnologicas-Ciemat (Spain)
- Iberdrola Renovables Energia (Spain)
- Repsol (Spain)
- Total S.A. (France)
- Lancaster University (United Kingdom)

Inria contact: Stephane Lanteri

CORSE particpants: Jean-François Méhaut, Frédéric Desprez, Emmanuelle Saillard (Post-Doct since Dec 2016)

This project aims to apply the new exascale HPC techniques to energy industry simulations, customizing them, and going beyond the state-of-the-art in the required HPC exascale simulations for different energy sources: wind energy production and design, efficient combustion systems for biomass-derived fuels (biogas), and exploration geophysics for hydrocarbon reservoirs. For wind energy industry HPC is a must. The competitiveness of wind farms can be guaranteed only with accurate wind resource assessment, farm design and short-term micro-scale wind simulations to forecast the daily power production. The use of CFD LES models to analyse atmospheric flow in a wind farm capturing turbine wakes and array effects requires exascale HPC systems. Biogas, i.e. biomass-derived fuels by anaerobic digestion of organic wastes, is attractive because of its wide availability, renewability and reduction of $CO2$ emissions, contribution to diversification of energy supply, rural development, and it does not compete with feed and food feedstock. However, its use in practical systems is still limited since the complex fuel composition might lead to unpredictable combustion performance and instabilities in industrial combustors. The next generation of exascale HPC systems will be able to run combustion simulations in parameter regimes relevant to industrial applications using alternative fuels, which is required to design efficient furnaces, engines, clean burning vehicles and power plants. One of the main HPC consumers is the oil & gas (O&G) industry. The computational requirements arising from full wave-form modelling and inversion of seismic and electromagnetic data is ensuring that the O&G industry will be an early adopter of exascale computing technologies. By taking into account the complete physics of waves in the subsurface, imaging tools are able to reveal information about the Earth's interior with unprecedented quality.

8.3.2. Collaborations in European Programs, Except FP7 & H2020

Program: COST

Project acronym: ArVI

Project title: Runtime Verification beyond Monitoring

Duration: December 2014 - May 2017

Coordinator: Martin Leucker, University of Lubeck

Abstract: Runtime verification (RV) is a computing analysis paradigm based on observing a system at runtime to check its expected behavior. RV has emerged in recent years as a practical application of formal verification, and a less ad-hoc approach to conventional testing by building monitors from formal specifications.

There is a great potential applicability of RV beyond software reliability, if one allows monitors to interact back with the observed system, and generalizes to new domains beyond computers programs (like hardware, devices, cloud computing and even human centric systems). Given the European leadership in computer based industries, novel applications of RV to these areas can have an enormous impact in terms of the new class of designs enabled and their reliability and cost effectiveness.

This Action aims to build expertise by putting together active researchers in different aspects of runtime verification, and meeting with experts from potential application disciplines. The main goal is to overcome the fragmentation of RV research by (1) the design of common input formats for tool cooperation and comparison; (2) the evaluation of different tools, building a growing sets benchmarks and running tool competitions; and (3) by designing a road-map and grand challenges extracted from application domains.

8.4. International Initiatives

8.4.1. Inria International Labs

- JLESC (Joint Laboratory on Exascale Computing)
  The CORSE team is involved in the JLESC with collaborations with UIUC (Sanjay Kalé) and BSC (Mont-Blanc projects). Kevin Pouget, Brice Videau and Jean-François Méhaut attended to the two JLESC workshops (Barcelona and Bonn) in 2015.
  - **Energy Efficiency and Load Balancing**
  - The power consumption of High Performance Computing (HPC) systems is an increasing concern as large-scale systems grow in size and, consequently, consume more energy. In response to this challenge, we propose new energy-aware load balancers that aim at reducing the energy consumption of parallel platforms running imbalanced scientific applications without degrading their performance. Our research explores dynamic load balancing, low power manycore platforms and DVFS techniques in order to reduce power consumption.

  - We propose the improvement of the performance and scalability of parallel seismic wave models through dynamic load balancing. These models suffer from load imbalance for two reasons. First, they add a specific numerical condition at the borders of the domain, in order to absorb the outgoing energy. The decomposition of the domain into a grid of subdomains, which are distributed among tasks, creates load differences between the tasks that simulate the borders and those responsible for the central subdomains. Second, the propagation of waves in the simulated area changes the workload on the subdomains on different time-steps. Therefore causing dynamic load imbalance. In order to evaluate the use of dynamic load balancing, we ported a seismic wave simulator to Adaptive MPI, to benefit from its load balancing framework. Our experimental results show that dynamic load balancers can adapt to load variations during the application's execution and improve performance by 36%.
  - we also focus on reducing the energy consumption of imbalanced applications through a combination of load balancing and Dynamic Voltage and Frequency Scaling (DVFS). Our strategy employs an Energy Daemon Tool to gather power information and a load balancing module that benefits from the load balancing framework available in the CHARM++ runtime system. We propose two variants of our energy-aware load balancer (ENERGYLB) to save energy on imbalanced workloads without considerably impacting the overall system performance. The first one, called Fine- Grained EnergyLB (FG-ENERGYLB), is suitable for plat- forms composed of few tens of cores that allow per-core DVFS. The second one, called Coarse-Grained EnergyLB (CG-ENERGLB) is suitable for current HPC platforms composed of several multi-core processors that feature per-chip DVFS.

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

8.4.2.1. IOComplexity

Title: Automatic characterization of data movement complexity

International Partner (Institution - Laboratory - Researcher):

Ohio State University (United States) - P. Sadayappan

Start year: 2015

See also: https://team.inria.fr/corse/iocomplexity/

The goal of this project is to develop new techniques and tools for the automatic characterization of the data movement complexity of an application. The expected contributions are both theoretical and practical, with the ambition of providing a fully automated approach to I/O complexity characterization, in starking contrast with all known previous work that are stricly limited to pen-and-paper analysis.

I/O complexity becomes a critical factor due in large part to the increasing dominance of data movement over computation in energy consumption for current and emerging architectures. This project aims at enabling: 1. the selection of algorithms according to this new criteria (as opposed to the criteria on arithmetic complexity that has been used up to now); 2. the design of specific architectures in terms of cache size, memory bandwidth, GFlops etc. based on application-specific bounds on memory traffic; 3. higher quality feedback to the user, the compiler, or the run-time system about data traffic, a major performance and energy factor.

8.4.2.2. PROSPIEL

- Title: Profiling and specialization for locality
- International Partner (Institution - Laboratory - Researcher):

  Universidade Federal de Minas Gerais (Brazil) - Computer Science Department - Fernando Magno Quintão Pereira
- Start year: 2015

- See also: https://team.inria.fr/alf/prospiel/
- The PROSPIEL project aims at optimizing parallel applications for high performance on new throughput-oriented architectures: GPUs and many-core processors. Traditionally, code optimization is driven by a program analysis performed either statically at compile-time, or dynamically at run-time. Static program analysis is fully reliable but often over-conservative. Dynamic analysis provides more accurate data, but faces strong execution time constraints and does not provide any guarantee. By combining profiling-guided specialization of parallel programs with runtime checks for correctness, PROSPIEL seeks to capture the advantages of both static analysis and dynamic analysis. The project relies on the polytope model, a mathematical representation for parallel loops, as a theoretical foundation. It focuses on analyzing and optimizing performance aspects that become increasingly critical on modern parallel computer architectures: locality and regularity.

8.4.2.3. Exase

Title: Exascale Computing Scheduling Energy

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

Inria leader: Jean-Marc Vincent (Mescal)

Inria teams: Mescal, Moais, CORSE

CORSE participants: Jean-François Méhaut, François Broquedis, Frédéric Desprez

International Partner (Institution - Laboratory - Researcher):

> Federal University of Rio Grande do Soul (UFRGS, Porto Alegre, Brazil) - Informatics Faculty - L. Schnoor, N. Maillard, P. Navaux
>
> Pontifical University Minas (PUC Minas, Belo Horizonte, Brazil) - Computer Science faculty, Henrique Freitas
>
> University of Sao Paulo (USP, Sao Paulo, Brazil), IME faculty, Alfredo Goldman

Start year: 2014

The main scientific goal of Exase for the three years is the development of state-of- the-art energy-aware scheduling algorithms for exascale systems. As previously stated, issues on energy are fundamental for next generation parallel platforms and all scheduling decisions must be aware of that. Another goal is the development of trace analysis techniques for the behavior analysis of schedulers and the applications running on exascale machines. We list below specific objectives for each development axis presented in the previous section. analysis.

- Fundamentals for the scaling of schedulers
- Design of schedulers for large-scale infrastructures
- Tools for the analysys of large scale schedulers

8.4.3. Participation in Other International Programs

- LICIA (LIG, UFRGS Brazil)
- EnergySFE (STIC Amsud)
  - Leader: University Federal of Santa Catarina (UFSC): Màrcio Castro
  - Partners: UFSC (Florianapolis, Brazil), UFRGS (Porto Alegre, Brazil), ESPE (Ecuador), CNRS (LIG/CORSE, TIMA, LSPSC)
  - Duration: January 2016 - December 2017
  - CORSE participants: Jean-François Méhaut, François Broquedis, Frédéric Desprez
  - The main goal of the EnergySFE research project is to propose fast and scalable energy-aware scheduling and fault tolerance techniques and algorithms for large-scale highly parallel architectures. To achieve this goal, it will be crucial to answer the following research questions:

* How to schedule tasks and threads that compete for resources with different constraints while considering the complex hierarchical organization of future Exascale supercomputers?
* How to tolerate faults without incurring in too much overhead in future Exascale supercomputers?
* How scheduling and fault tolerance approaches can be adapted to be energy-aware?

The first EnergySFE workshop was organized by the CORSE team a the Inria Minatec building in September 2016.

8.5. International Research Visitors

8.5.1. Visits of International Scientists

- Louis-Noël Pouchet (OSU), visited CORSE two times one month
- Julien Langou (UCDenver) is visiting professor since September 2016
- Mohamad Jaber (AUB) visited CORSE two weeks in January 2016
- Sylvain Hallé (U of Québec) visited CORSE one week in August 2016
- Christian Colombo (U of Malta) visited CORSE two weeks in March 2016
- Henrique Freitas (PUC Minas) visited CORSE one year since July 2015 until July 2016

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

- Ylies Falcone: 1st international summer school on Runtime Verification; 3rd international Competition on Runtime Verification
- Frédéric Desprez: EuroPAR 2016 (co-chair and workshop chair)

9.1.1.2. Member of the Organizing Committees

- Fabrice Rastello: Program Committee ACM/IEEE CGO 2015; Steering Committee Journées française de la compilation; Steering Committee ACM/IEEE CGO

9.1.2. Scientific Events Selection

9.1.2.1. Chair of Conference Program Committees

- Fabrice Rastello: Program Chair ACM/IEEE CGO 2016; Program Chair “Journées française de la compilation”, Aussois, 2016
- Ylies Falcone: Program Chair RV 2016

9.1.2.2. Member of the Conference Program Committees

- Fabrice Rastello: ACM CC 2016, ACM SRC SC 2016, ACM/IEEE SRC SC 2016
- Alain Ketterlin: ACM/IEEE CGO 2016
- Ylies Falcone: CARI 2016, SSS 2016, RV 2016, Pre-Post'16, SAC-SVT'16
- Frédéric Desprez: Closer 2016, CCGrid 2016, HPC 2016, EuroPAR 2016, CloudCom 2016

9.1.3. Journal

9.1.3.1. Reviewer - Reviewing activities

- Fabrice Rastello: ACM TACO
- Ylies Falcone: Formal Aspects of Computing, ACM Transactions on Automatic and Control, Acta Informatica, Formal Methods in System Design, International Journal of Information and Computer Security, Science of Computer Programming, Software Tools for Technology Transfer, Journal of Systems and Software, NFM 2016

9.1.4. Invited talks

- Fabrice Rastello: UCDenver: "Toward Automatic Characterisation of the Data Access Complexity of Programs"
- Ylies Falcone: American University of Beirut: "On the Runtime Enforcement of Timed Properties"
- Ylies Falcone: LAAS Toulouse: "On the Runtime Enforcement of Timed Properties"
- Frédéric Desprez: Inria Alumni: "Internet des objets, Où sont les ruptures? Activités à l'Inria"
- Frédéric Desprez: SUCCES Workshop: "CIMENT, GRICAD, Grid'5000: La synergie grenobloise"
- Frédéric Desprez: CCDSC Workshop: "BOAST: Performance Portability Using Meta-Programming and Auto-Tuning"
- Frédéric Desprez: Eurecom Seminar 2016: "Challenges and Issues of Next Cloud Computing Platforms"
- Frédéric Desprez: European Commission, Brussels: "Research Issues for Future Cloud Infrastructures"
- Frédéric Desprez: CIRM, CEMRACS 2016 summer school: "OpenCL Introduction"
- François Broquedis: CIRM, CEMRACS 2016 summer school: "A Gentle Introduction to OpenMP Programming"
- Jean-François Méhaut: CEMRACS 2016 summer school: "Overview of architectures and programming language for parallel computing"

9.1.5. Scientific expertise

- Frédéric Desprez: European project in the FP7 framework
- Frédéric Desprez: Comité d'orientation stratégique de CIRRUS (COMUE Paris)
- Frédéric Desprez: Groupe Technique GENCI
- Frédéric Desprez: Conseil Scientifique GIS France Grille
- Frédéric Desprez: GENCI, expert for grants of computing resources (CT6)
- Ylies Falcone: Representative of France in the COST Action ARVI
- Ylies Falcone: COST Action ARVI, co-leader of Working Group on Core Runtime Verification
- Jean-François Mehaut: Eurolab-4-HPC, expert for cross site mobility research grants
- Jean-François Mehaut: GENCI, expert for grants of computing resources (CT6)

9.1.6. Research administration

- Frédéric Desprez: Deputy Scientific Director at Inria
- Frédéric Desprez: Director of the GIS GRID5000
- Frédéric Desprez: Conseil Scientifique ESIEE Paris

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master II: Fabrice Rastello, Advanced Compilers, 12 hours, ENS Lyon

Master I: Jean-François Méhaut, Operating System Design, 50 hours, Polytech Grenoble

L3: Jean-François Méhaut, Numerical Methods, 50 hours, Polytech Grenoble,

L3: Jean-François Méhaut, Advanced Algorithms, 50 hours, Polytech Grenoble

L3: François Broquedis, Imperative programming using python, 40 hours, Grenoble Institute of Technology (Ensimag)

L3: François Broquedis, C programming, 80 hours, Grenoble Institute of Technology (Ensimag)

M1: François Broquedis, Operating systems and concurrent programming, 40 hours, Grenoble Institute of Technology (Ensimag)

M1: François Broquedis, Operating Systems Development Project - Fundamentals, 20 hours, Grenoble Institute of Technology (Ensimag)

M1: François Broquedis, Operating Systems Project, 20 hours, Grenoble Institute of Technology (Ensimag)

Master: Florent Bouchez Tichadou, Compilation project, 15 hours, M1 Info & M1 MoSig

Licence: Florent Bouchez Tichadou, C programming, 24 hours, L3, Grenoble Institute of Technology (Ensimag)

Master: Florent Bouchez Tichadou, Algorithmic Problem Solving, 41 hours, M1 MoSIG

Licence: Florent Bouchez Tichadou, Algorithms languages and programming, 121 hours, L2 UGA

Licence: Florent Bouchez Tichadou is responsible of the second year of INF (informatique) and MIN (mathématiques et informatique) students at UGA

Master I: Ylies Falcone Proof Techniques and Logic Reminders, MoSIG, 3 hours

Master I: Ylies Falcone Recaps on Object-Oriented Programming, MoSIG, 3 hours

Master II: Ylies Falcone Introduction to Runtime Verification, MoSIG HECS, 8 hours.

Master I: Ylies Falcone Programming Language Semantics and Compiler Design, MoSIG, 66 hours

License: Ylies Falcone Languages and Automata, UJF, 105 hours

Master: Ylies Falcone is co-responsible of the first year of the International Master of Computer Science (Univ. Grenoble Alpes and INP ENSIMAG)

9.2.2. Supervision

9.2.2.1. Fabrice Rastello

PhD defended [3]: Duco van Amstel, Scheduling and optimization for memory locality of dataflow programs on many-core processors, advised by Fabrice Rastello and Benoit Dupont-de-Dinechin

PhD defended [1]: Diogo Sampaio, Profiling Guided Hybrid Compilation, October 8 2013, advised by Fabrice Rastello

PhD defended: Venmugil Elango, Dynamic Analysis for Characterization of Data Locality Potential, advised by Fabrice Rastello and P. Sadayappan.

PhD in progress: François Gindraud, Semantics and compilation for a data-flow model with a global address space and software cache coherency, January 1st 2013, advised by Fabrice Rastello and Albert Cohen.

PhD in progress: Fabian Grüber, Interactive & iterative performance debugging, September 2016, advised by Fabrice Rastello and Ylies Falcone.

PhD in progress: Philippe Virouleau, *Improving the performance of task-based runtime systems on large scale NUMA machines*, co-advised by Thierry Gautier (Inria/AVALON), Fabrice Rastello, François Broquedis

9.2.2.2. Jean-François Méhaut

PhD defended (April 2016): Oleg Iegorov, advised by Alexandre Termier (Dream/Irisa), Vincent Leroy (SLIDE/LIG) and Jean-François Méhaut

PhD defended (October 2016): Nassim Halli, CIFRE with Asselta, advised by Henri-Pierre Charles (CEA/DRT List), Jean-François Méhaut

PhD defended [36]: Naweiluo Zhou, advised by Eric Rutten (Inria, CtrlA), Gwenael Delaval (UGA, CtrlA), Jean-François Méhaut

PhD in progress: Thomas Messi Nguelé, advised by Maurice Tchuenté (Yaoundé I, LIRIMA) and Jean-François Méhaut

PhD in progress: Thomas Goncalves, advised by Marc Perache (CEA/DAM), Frédéric Desprez, Jean-François Méhaut

PhD in progress: Luis Felipe Milani, advised by Lucas Schnoor (UFRGS), François Broquedis and Jean-François Méhaut

PhD in progress: Vanessa Vargas, advised by Raoul Velazco (CNRS, TIMA) and Jean-François Méhaut

PhD in progress: Raphaël Jakse, Monitoring and Debugging Component-Based Systems, advised by Jean-François Mehaut and Ylies Falcone.

9.2.2.3. Frédéric Desprez

PhD defended (October 2016): Jonathan Pastor, advised by Frédéric Desprez, Adrien Lèbre (EMN Nantes, Ascola team)

PhD in progress: Pedro Silva, advised by Frédéric Desprez, C. Perez (Inria, Avalon team)

PhD in progress: Georgios Christodoulis, advised by Frederic Desprez, Olivier Muller (TIMA/SLS) and François Broquedis

PhD in progress: Thomas Goncalves, advised by Marc Perache (CEA/DAM), Frédéric Desprez, Jean-François Méhaut

PhD in progress: Ye Xia, advised by Thierry Coupaye (Orange), Frédéric Desprez, Xavier Etchevers (Orange)

9.2.2.4. François Broquedis

PhD in progress: Georgios Christodoulis, *Adaptation of a heterogeneous runtime system to efficiently exploit FPGA* advised by Frederic Desprez, Olivier Muller (TIMA/SLS) and François Broquedis

PhD in progress: Philippe Virouleau, *Improving the performance of task-based runtime systems on large scale NUMA machines*, co-advised by Thierry Gautier (Inria/AVALON), Fabrice Rastello, François Broquedis

9.2.2.5. Ylies Falcone

PhD in progress: Hosein Nazarpour, Monitoring Multithreaded and Distributed Component-based Systems, advised by Saddek Bensalem (Vérimag) and Ylies Falcone.

PhD in progress: Antoine El-Hokayem, Decentralised and Distributed Monitoring of Cyber-Physical Systems, advised by Ylies Falcone.

PhD in progress: Fabian Grüber, Interactive & iterative performance debugging, September 2016, advised by Fabrice Rastello and Ylies Falcone.

PhD in progress: Raphaël Jakse, Monitoring and Debugging Component-Based Systems, advised by Jean-François Mehaut and Ylies Falcone.

9.2.3. Juries

9.2.3.1. Fabrice Rastello

Venmugil Elango, Advisor, *Dynamic Analysis for Characterization of Data Locality Potential*, PhD of OSU, 06/01/2016

Arjun Suresh, Reviewer, *Intercepting Functions for Memoization*, PhD of Université de Rennes, 10/04/2016

Duco Van-Amstel, Advisor, *Scheduling and optimization for memory locality of dataflow programs on many-core processors*, Université Grenoble Alpes, 11/07/2016.

Juan Manuel Martinez Caamano, Reviewer, *Fast and Flexible Compilation Techniques for Effective Speculative Polyhedral Parallelization*, Université de Strasrbourg, 29/09/2016

Pierre Guillou, Reviewer, *Compilation efficace d'applications de traitement d'images pour processeurs manycore*, Université de recherche PAris Sciences et Lettres, 30/11/2016

9.2.3.2. Jean-François Méhaut

Oleg Iegorov, Advisor,*Data Mining Approach to Temporal Debugging of Embedded Streaming Applications*, PhD of Université Grenoble Alpes, April 2016

Nassim Halli, Advisor, *Code Optimizations of High Performance Java Applications*, PhD of Université Grenoble Alpes, October 2016

Naweiluo Zhou, Advisor, *Autonomic Thread Parallelism and Mapping Control for Software Transactional Memory System*, PhD of Université Grenoble Alpes, October 2016

Marc Sergent, Reviewer, *Passage à l'échelle d'un support d'exécution à base de tâches pour l'algèbre linéaire creuse*, PhD of Université de Bordeaux, October 2016

Jean-Charles Papin, Reviewer, *A Scheduling and Partitioning Model for Stencil-based Applications on ManyCore Devices*, PhD of Ecole Normale Supérieure de Cachan, July 2016

9.2.3.3. Frédéric Desprez

Jean-Marie Couteyen, Reviewer, *Parallélisation et passage à l'échelle du code FLUSEPA*, PhD of Université de Bordeaux, September 2016

Jonathan Pastor, Advisor, *Contributions à la mise en place d'une infrastructure de Cloud Computing à large échelle* , Ecole des Mines de Nantes, October 2016

10. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] D. N. Sampaio.*Profile Guided Hybrid Compilation*, Université Grenoble-Alpes, December 2016, https://hal.inria.fr/tel-01428425.

[2] N. Zhou. *Autonomic Thread Parallelism and Mapping Control for Software Transactional Memory*, UJF Grenoble-1 ; Inria Grenoble, October 2016, https://hal.archives-ouvertes.fr/tel-01408450.

[3] D. van Amstel.*Data Locality on Manycore Architectures*, Université Grenoble-Alpes, July 2016, https://hal.inria.fr/tel-01358312.

Articles in International Peer-Reviewed Journal

[4] A. Bauer, Y. Falcone.*Decentralised LTL Monitoring*, in "Formal Methods in System Design", May 2016, vol. 48, n^o 1-2, 48 [*DOI :* 10.1007/s10703-016-0253-8], https://hal.inria.fr/hal-01313730.

[5] M. Castro, E. Francesquini, F. Dupros, H. Aochi, P. Navaux, J.-F. Mehaut.*Seismic Wave Propagation Simulations on Low-power and Performance-centric Manycores*, in "Parallel Computing", 2016 [*DOI :* 10.1016/j.parco.2016.01.011], https://hal.archives-ouvertes.fr/hal-01273153.

[6] C. COLOMBO, Y. FALCONE.*Organising LTL Monitors over Distributed Systems with a Global Clock*, in "Formal Methods in System Design", May 2016, vol. 49, n^{o} 1-2, 50 [*DOI :* 10.1007/S10703-016-0251-X], https://hal.inria.fr/hal-01315776.

[7] Y. FALCONE, M. JABER.*Fully-automated Runtime Enforcement of Component-based Systems with Formal and Sound Recovery*, in "Software Tools for Technology Transfer (STTT)", February 2016, https://hal.inria.fr/hal-01262658.

[8] Y. FALCONE, T. JÉRON, H. MARCHAND, S. PINISETTY.*Runtime Enforcement of Regular Timed Properties by Suppressing and Delaying Events*, in "Science of Computer Programming", March 2016 [*DOI :* 10.1016/J.SCICO.2016.02.008], https://hal.inria.fr/hal-01281727.

[9] P. H. PENNA, M. CASTRO, H. C. FREITAS, F. BROQUEDIS, J.-F. MÉHAUT.*Design methodology for workload-aware loop scheduling strategies based on genetic algorithm and simulation*, in "Concurrency and Computation: Practice and Experience", 2016 [*DOI :* 10.1002/CPE.3933], https://hal.archives-ouvertes.fr/hal-01354028.

[10] P. RAMOS, V. VARGAS, M. BAYLAC, F. VILLA, S. REY, J. A. CLEMENTE, N.-E. ZERGAINOH, J.-F. MÉHAUT, R. VELAZCO.*Evaluating the SEE sensitivity of a 45nm SOI Multi-core Processor due to 14 MeV Neutrons*, in "IEEE Transactions on Nuclear Science", March 2016, vol. 63, n^{o} 4, p. 2193 - 2200 [*DOI :* 10.1109/TNS.2016.2537643], https://hal.archives-ouvertes.fr/hal-01280648.

[11] M. A. SOUZA, P. H. PENNA, M. M. QUEIROZ, A. D. PEREIRA, L. F. W. GÓES, H. C. FREITAS, M. CASTRO, P. O. NAVAUX, J.-F. MÉHAUT.*CAP Bench: a benchmark suite for performance and energy evaluation of low-power many-core processors*, in "Concurrency and Computation: Practice and Experience", 2016 [*DOI :* 10.1002/CPE.3892], https://hal.archives-ouvertes.fr/hal-01330543.

Invited Conferences

[12] C. COLOMBO, Y. FALCONE.*First International Summer School on Runtime Verification: as part of the ArVi COST Action 1402*, in "Sixteenth International Conference on Runtime Verification", Madrid, Spain, September 2016, https://hal.inria.fr/hal-01428838.

[13] G. REGER, S. HALLÉ, Y. FALCONE.*Third International Competition on Runtime Verification CRV 2016*, in "Sixteenth International Conference on Runtime Verification", Madrid, Spain, September 2016, https://hal.inria.fr/hal-01428834.

International Conferences with Proceedings

[14] W. BAO, K. SRIRAM, L.-N. POUCHET, F. RASTELLO, S. PONNUSWAMY.*PolyCheck: Dynamic Verification of Iteration Space Transformations on Affine Programs*, in "Proceedings of the 43nd Annual ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, POPL 2016", St Petersburg, United States, ACM, January 2016, https://hal.inria.fr/hal-01234104.

[15] A. EL-HOKAYEM, Y. FALCONE, M. JABER.*Modularizing Crosscutting Concerns in Component-Based Systems*, in "14th International Conference on Software Engineering and Formal Methods", Vienne, Austria, July 2016, https://hal.inria.fr/hal-01305083.

[16] F. GINDRAUD, F. RASTELLO, A. COHEN, F. BROQUEDIS.*A bounded memory allocator for software-defined global address spaces*, in "ISMM 2016 - 2016 ACM SIGPLAN International Symposium on Memory Management", Santa Barbara, United States, June 2016, https://hal.inria.fr/hal-01412919.

[17] S. HALLÉ, R. KHOURY, A. EL-HOKAYEM, Y. FALCONE.*Decentralized Enforcement of Artifact Lifecycles*, in "EDOC 2016", Vienne, Austria, Proceedings of the twentieth entreprise computing conference, September 2016, https://hal.inria.fr/hal-01365315.

[18] H. NAZARPOUR, Y. FALCONE, S. BENSALEM, M. BOZGA, J. COMBAZ.*Monitoring Multi-Threaded Component-Based Systems*, in "12th International Conference on integrated Formal Methods", Reykjavik, Finland, Proceedings of the 12th International Conference on integrated Formal Methods, June 2016, https://hal.inria.fr/hal-01285579.

[19] S. PINISETTY, V. PREOTEASA, S. TRIPAKIS, T. JÉRON, Y. FALCONE, H. MARCHAND.*Predictive Runtime Enforcement* *, in "SAC 2016 31st ACM Symposium on Applied Computing", Pisa, Italy, ACM, April 2016, 6 [*DOI :* 10.1145/2851613.2851827], https://hal.inria.fr/hal-01244369.

[20] R. SAMYAM, K. JINSUNG, K. SRIRAM, F. RASTELLO, L.-N. POUCHET, R. J. HARRISON, S. PONNUSWAMY.*A domain-specific compiler for a parallel multiresolution adaptive numerical simulation environment*, in "SC 2016 - International Conference for High Performance Computing, Networking, Storage and Analysis", Salt-Lake City, United States, November 2016, https://hal.inria.fr/hal-01412903.

[21] P. SILVA, C. PÉREZ, F. DESPREZ.*Efficient Heuristics for Placing Large-Scale Distributed Applications on Multiple Clouds*, in "16th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (CCGrid'16)", Cartagena, Colombia, 2016 16th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (CCGrid), May 2016 [*DOI :* 10.1109/CCGRID.2016.77], https://hal.archives-ouvertes.fr/hal-01301382.

[22] P. VIROULEAU, F. BROQUEDIS, T. GAUTIER, F. RASTELLO.*Using data dependencies to improve task-based scheduling strategies on NUMA architectures*, in "Euro-Par 2016", Grenoble, France, Euro-Par 2016, August 2016, https://hal.inria.fr/hal-01338761.

[23] P. VIROULEAU, A. ROUSSEL, F. BROQUEDIS, T. GAUTIER, F. RASTELLO, J.-M. GRATIEN.*Description, Implementation and Evaluation of an Affinity Clause for Task Directives*, in "IWOMP 2016", Nara, Japan, IWOMP 2016 - LLCS 9903, October 2016, https://hal.inria.fr/hal-01343442.

[24] N. ZHOU, G. DELAVAL, B. ROBU, E. RUTTEN, J.-F. MÉHAUT.*Autonomic Parallelism and Thread Mapping Control on Software Transactional Memory* , in "13th IEEE International Conference on Autonomic Computing (ICAC 2016)", Wuerzburg, Germany, July 2016, p. 189 - 198 [*DOI :* 10.1109/ICAC.2016.54], https://hal.archives-ouvertes.fr/hal-01309681.

[25] N. ZHOU, G. DELAVAL, B. ROBU, E. RUTTEN, J.-F. MÉHAUT.*Control of Autonomic Parallelism Adaptation on Software Transactional Memory*, in "International Conference on High Performance Computing & Simulation (HPCS 2016)", Innsbruck, Austria, July 2016, p. 180-187 [*DOI :* 10.1109/HPCSIM.2016.7568333], https://hal.archives-ouvertes.fr/hal-01309195.

[26] N. ZHOU, G. DELAVAL, B. ROBU, É. RUTTEN, J.-F. MÉHAUT.*Autonomic Parallelism Adaptation for Software Transactional Memory*, in "Conférence d'informatique en Parallélisme, Architecture et Système (COMPAS)", Lorient, France, July 2016, https://hal.inria.fr/hal-01312786.

National Conferences with Proceeding

[27] R. JAKSE, Y. FALCONE, J.-F. MÉHAUT, K. POUGET.*Vérification interactive de propriétés à l'exécution d'un programme avec un débogueur*, in "Compas'2016", Lorient, France, Compas'2016 : Parallélisme / Architecture / Système Lorient, France, du 5 au 8 juillet 2016, July 2016, https://hal.inria.fr/hal-01331973.

Conferences without Proceedings

[28] Ł. DOMAGAŁA, D. VAN AMSTEL, F. RASTELLO.*Generalized cache tiling for dataflow programs*, in "Conference on Languages, Compilers, Tools, and Theory for Embedded Systems", Santa Barbara, United States, Proceedings of the 17th ACM SIGPLAN/SIGBED Conference on Languages, Compilers, Tools, and Theory for Embedded Systems, June 2016, 10 [*DOI :* 10.1145/2907950.2907960], https://hal.inria.fr/hal-01336172.

[29] C. HONG, W. BAO, A. COHEN, S. KRISHNAMOORTHY, L.-N. POUCHET, F. RASTELLO, J. RAMANUJAM, S. PONNUSWANY.*Effective padding of multidimensional arrays to avoid cache conflict misses*, in "PLDI 2016: Proceedings of the 37th ACM SIGPLAN Conference on Programming Language Design and Implementation", Santa Barbara, United States, June 2016, https://hal.inria.fr/hal-01335346.

[30] K. POUGET, M. SANTANA, J.-F. MÉHAUT.*Programming-Model Centric Debugging for OpenMP*, in "2nd OpenMPCon Developpers Conference", Nara, Japan, October 2016, https://hal.archives-ouvertes.fr/hal-01351561.

[31] N. RAJOVIC, A. RICO, F. MANTOVANI, D. RUIZ, J. VILARRUBI, C. GOMEZ, D. NIETO, H. SERVAT, X. MARTORELL, J. LABARTA, C. ADENIYI-JONES, S. DERRADJI, H. GLOAGUEN, P. LANUCARA, N. SANNA, J.-F. MÉHAUT, K. POUGET, B. VIDEAU, E. BOYER, M. ALLALEN, A. AUWETER, D. BRAYFORD, D. TAFANI, V. WEINBERG, D. BRÖMMEL, R. HALVER, J. MEINKE, R. BEIVIDE, M. BENITO, E. VALLEJO, M. VALERO, A. RAMIREZ.*The Mont-Blanc prototype: An Alternative Approach for HPC Systems*, in "International Conference for High Performance Computing, Networking, Storage and Analysis (SC)", Salt Lake City, United States, November 2016, https://hal.archives-ouvertes.fr/hal-01354939.

[32] R. SAMYAM, K. JINSUNG, S. KRISHNAMOORTHY, L.-N. POUCHET, F. RASTELLO, R. J. HARRISON, S. PONNUSWANY.*On fusing recursive traversals of K-d trees*, in "Proceedings of the 25th International Conference on Compiler Construction, CC 2016", Barcelona, Spain, March 2016, https://hal.inria.fr/hal-01335355.

[33] P. VIROULEAU.*Amélioration des stratégies d'ordonnancement sur architectures NUMA à l'aidedes dépendances de données*, in "Compas 2016", Lorient, France, July 2016, https://hal.inria.fr/hal-01338750.

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[34] L. GENOVESE, B. VIDEAU, D. CALISTE, J.-F. MÉHAUT, S. GOEDECKER, T. DEUTSCH.*Wavelet-Based Density Functional Theory on Massively Parallel Hybrid Architectures*, in "Electronic Structure Calculations on Graphics Processing Units: From Quantum Chemistry to Condensed Matter Physics", R. WALKER (editor), Wiley-Blackwell, February 2016, https://hal.archives-ouvertes.fr/hal-01239245.

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[35] C. ALIAS, F. RASTELLO, A. PLESCO.*High-Level Synthesis of Pipelined FSM from Loop Nests*, Inria, April 2016, n^{o} 8900, 18, https://hal.inria.fr/hal-01301334.

[36] N. ZHOU, G. DELAVAL, B. ROBU, É. RUTTEN, J.-F. MÉHAUT.*Autonomic Parallelism Adaptation on Software Transactional Memory*, Univ. Grenoble Alpes ; Inria Grenoble, March 2016, n^{o} RR-8887, 24, https://hal.inria.fr/hal-01279599.

Other Publications

[37] D. MARGERY, F. DESPREZ.*On the sustainability of large-scale computer science testbeds: the Grid'5000 case*, February 2016, working paper or preprint, https://hal.inria.fr/hal-01273170.

[38] T. MESSI NGUÉLÉ, M. TCHUENTE, J.-F. MÉHAUT.*Social network ordering based on communities to reduce cache misses*, April 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01304968.

[39] M. RENARD, Y. FALCONE, A. ROLLET.*Optimal Enforcement of (Timed) Properties with Uncontrollable Events*, February 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01262444.

Team CTRL-A

Control techniques for Autonomic, adaptive and Reconfigurable Computing systems

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Distributed Systems and middleware

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Creation of the Team: 2014 January 01

Keywords:

Computer Science and Digital Science:

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1.1.4. - High performance computing
1.1.6. - Cloud
1.1.9. - Fault tolerant systems
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1. Members

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2. Overall Objectives

2.1. Objective: control support for autonomic computing

Computing systems are more and more ubiquitous, at scales from tiny embedded systems to large-scale cloud infrastructures. They are more and more adaptive and reconfigurable, for resource management, energy efficiency, or by functionality. Furthermore, these systems are increasingly complex and autonomous: their administration cannot any longer rely on a strong interaction with a human administrator. The correct design and implementation of automated control of the reconfigurations and/or the tuning is recognized as a key issue for the effectiveness of these adaptive systems.

In the last dozen years, the notion of Autonomic Computing has been proposed and supported by industrials like IBM, as a framework for the design of self-adaptive systems. It addresses objectives of self-configuration, w.r.t. deployment issues, self-optimization, w.r.t; resources management, self-healing, w.r.t. robustness and fault-tolerance, and self-protection, w.r.t. security aspects. It relies on a feedback control loop architecture, with: monitors and reconfiguration actions, connected to the API infrastructure of the system under control ; an autonomic management component , transforming flows of monitoring information into adaptation actions, which can be addressed naturally by reactive programming ; a decision mechanism inside the latter manager, which can rely on behavioral models of the managed system.

Our objective is to build methods and tools for the design of safe controllers for autonomic, adaptive, reconfigurable computing systems. To attain this goal, we propose to combine Computer Science and Control Theory, at the levels of systems infrastructures, programming support, and modeling and control techniques. We explore this topic along three main thematic axes: **modeling and control theory** with discrete time, continuous time and hybrid models (distributed control, event-based control, discrete event systems, supervisory control) ; **programming support** with reactive (synchronous languages, controller synthesis, higher-order) and component-based approaches (Fractal framework, language-level support of reconfiguration, Event-Condition-Action (ECA) rules) ; **infrastructure-level support** (operating system, middleware) for monitors/sensors, administration actions/actuators, architectures for controllability, software and hardware reconfiguration mechanisms.

We aim to address applications with reconfiguration control problems from the small scale (facing variability for system on chips (SoCs), reconfigurable architectures, networks on chips (NoCs), etc.) up to the extra large scale (administration, coordination, optimization of data centers and cloud computing, green computing, smart grids, etc.)

We propose to form a team grouping the most active community in France on Control of Computing, with members until now separated by laboratories structure, in order to contribute more efficiently in the local context to the high potential impact on micro- and nanotechnologies in Grenoble, and more widely nationally and internationally in the emerging community on Feedback Computing.

2.2. Motivation: safe and optimal autonomic management

2.2.1. The problem of automating computing systems administration

It lies in the difficulty of manual management in a safe or optimal way, of computing systems which become more and more complex and flexible. There is a deep need for the automation of their management, handled in a closed-loop: the system is monitored by sensors, which enable updating a self-representation of the system, upon which reconfiguration actions are decided, and in turn they are executed, with an effect on the system, that will be measured by sensors. Such dynamically reconfigurable systems, also called adaptive or autonomic computing systems, are characterized by the ability to modify, on-line, their computing structure, in reaction to conditions in their execution environment or platform.

Motivations for dynamic adaptivity are in important questions like : resource management e.g., energy, computation, memory, bandwidth, circuit area, time ; quality of service e.g., levels of precision in computing, of urgence of treatment, graceful degradation ; dependability and fault tolerance, e.g., controlling migrations in response to loss of a processor. Adaptivity concerns systems ranging from hardware to operating systems to services and applications, and in size from tiny embedded systems to large-scale data-centers, from multi-core processors to the Cloud. Their complexity is growing, in scale (software of hardware), but also in interactions between different aspects of reconfiguration.

The design of the adaptation controllers is largely done in an *ad-hoc* fashion, involving lots of different approaches, intuitions, and heuristics. There is an important need for well-founded models and techniques for the safe design of these control loops, which can provide designers with a support to master the complexity of designs, and with guarantees w.r.t. the correctness of the designed controllers.

2.2.2. Our model-based control approach

We aim to build general methodologies and tools for the model-based control of reconfigurable computing system, validated in a representative range of reconfigurable systems.

The classical approach in computer science consists of: first programming, and then verifying. We want to explore, in contrast to this, an alternative approach, more effective (easier for the designer) and safer (better guarantees), inspired by control techniques: first model behaviors of the (uncontrolled) system, and its control interfaces, at each component's level ; then specify the adaptation strategy or policy, i.e., control objectives, and possibly check controllability ; finally, derive the controller solution: automatically synthesize the controller (for classes of problems where it is possible).

Our general topic is considering computing systems as object of automatic control, which is a newly emerging scientific theme, often considering continuous models. We will be using our complementary backgrounds in reactive systems and synchronous languages, in Control Theory and in experiences in applying various control techniques to computing systems, as well as a general orientation to apply formal methods to real-world systems. We are reversing the classical view of computer science for control systems, and consider, more originally, *control techniques for computing systems*.

2.2.3. Opportunities between computer science and control theory

This new and emerging combination of computing and control can bring novel contributions both ways : adaptive computing can benefit from control techniques, which provide designers with a broad range of results, and begin to be equipped with efficient tools e.g., connected to the synchronous technology, which is essential for concrete impact on real-world systems. Research in Control Theory can benefit from computing systems, embedded or large scale, as new application domain, where theoretical results can be evaluated and transferred, and from where new interesting and relevant problems can come up.

Risks could be in e.g., the fact that such a new and mixed topic of systems and control techniques does not yet correspond to an identified scientific community, making it difficult to find people involving themselves rather than staying in their respective community of origin. But this is in direct relationship to the originality of the subject, and is compensated by the identification of concrete potentials in our ongoing work. This multi-disciplinary work takes much more exploratory time and cooperative discussion than more classical research programs, but it brings all the more original results.

Control for Computing is in its founding phase: the disadvantage is there are no comfortable inherited results and community, the advantages are in the novelty and relevance of founding a new direction.

3. Research Program

3.1. Modeling and control techniques for autonomic computing

3.1.1. Continuous control

Continuous control was used to control computer systems only very recently and in few occasions, despite the promising results that were obtained. This is probably due to many reasons, but the most important seems to be the difficulty by both communities to transform a computer system problem into an automatic control problem. The aim of the team is to explore how to formalize typical autonomic commuting cases into typical control problems. Many new methodological tools will probably be useful for that, e.g., we can cite the hybrid system approach, predictive control or event-based control approach. Computer systems are not usual for the control system community and they often present non-conventional control aspects like saturation control. New methodological tools are required for an efficient use of continuous-time control in computer science.

3.1.2. Discrete control

Discrete control techniques are explored at long-term, to integrate more control in the BZR language, and adress more general control issues, wider than BZR's limitations. Directions are : expressiveness (taking into account in the LTS models value domains of the variables in the program) ; adaptive control (where the controller itself can dynamically switch between differents modes) ; distributed control (for classes of problems where communicating controllers can be designed) ; optimal control (w.r.t. weight functions, on states, transitions, and paths, with multicriteria techniques) ; timed and hybrid control bringing a new dimension for modeling and control, giving solutions where discrete models fail.

3.2. Design and programming for autonomic computing

3.2.1. Reactive programming

Autonomic systems are intrinsically reconfigurable. To describe, specify or design these systems, there is a need to take into account this reconfigurability, within the programming languages used. We propose to consider the reconfigurability of systems from the angle of two properties: the notion of time, as we want to describe the state and behavior of the system before, and after its reconfiguration; the notion of dynamicity of the system, i.e., considering that the system's possible behaviors throughout execution are not completely known, neither at design-time nor at initial execution state. To describe and design such reactive systems, we propose to use the synchronous paradigm. It has been successfully used, in industry, for the design of embedded systems. It allows the description of behaviors based on a specific model of time (discrete time scale, synchronous parallel composition), providing properties which are important w.r.t. the safety of the described system: reactivity, determinism, preservation of safety properties by parallel composition (with other parts of the system or with its environment). Models and languages for control, proposed in this framework, provide designers, experts of the application domain, with a user-friendly access to highly technical formal methods of DCS, by encapsulating them in the compilation of concrete programming languages, generating concrete executable code. They are based on discrete models, but also support programming of sampled continuous controllers.

3.2.2. Component-based approach and domain-specific languages

For integration of the previous control kernels into wider frameworks of reconfigurable systems, they have to be integrated in a design flow, and connected on the one side with higher-level specification languages (with help of DSLs), and on the other side with the generated code level target execution machines. This calls for the adoption of a component-based approach with necessary features, available typically in Fractal, for explicitly identifying the control interfaces and mechanisms.

Structuring and instrumentation for controllability will involve encapsulation of computations into components, specification of their local control (activation, reconfiguration, suspension, termination), and exporting appropriate interfaces (including behavior abstraction). Modeling the configurations space requires determining the controlled aspects (e.g., heterogenous CPUs loads, fault-tolerance and variability, memory, energy/power consumption, communication/bandwidth, QoS level) and their control points, as well as APIs for monitors and actions. Compilation and execution will integrate this in a complete design flow involving : extraction of a reactive model from components; instrumentation of execution platforms to be controllable; combination with other controllers; general "glue" and wrapper code.

Integration of reactive languages and control techniques in component-based systems brings interesting questions of co-existence w.r.t. other approaches like Event-Condition-Action (ECA) rules, or Complex Event Processing (CPE).

3.3. Infrastructure-level support for autonomic computing

The above general kernel of model-based control techniques can be used in a range of different computing infrastructures, representing complementary targets and abstraction levels, exploring the two axes :

- from hardware, to operating system/virtual machine, to middleware, to applications/service level;
- across different criteria for adaptation: resources and energy, quality of service, dependability.

3.3.1. Software and adaptive systems

Autonomic administration loops at operating systems or middleware level are already very widespread. An open problem remains in design techniques for controllers with predictability and safety, e.g. w.r.t. the reachable states. We want to contribute to the topic of discrete control techniques for these systems, and tackle e.g. problems of coordination of multiple autonomic loops in data-centers, as in the ANR project CtrlGreen. Another target application is the control of clusters in map-reduce applications. The objective is to use continuous time control in order to tune finely the number of required clusters for an application running on a map-reduce server. This will use results of the ANR project MyCloud that enables to simulate clients on a real map-reduce server. On a longer term, we are interested in control problems in administration loops of event-based virtual machines, or in the deployment of massively parallel computation of the Cloud.

3.3.2. Hardware and reconfigurable architectures

Reconfigurable architectures based on Field Programmable Gate Arrays (FPGA) are an active research area, where infrastructures are more and more supportive of reconfiguration, but its correct control remains an important issue. Work has begun in the ANR Famous project on identifying domain-specific control criteria and objectives, monitors and management APIs, and on integrating control techniques in the high-level RecoMARTE environment. On a longer term, we want to work on methods and tools for the programming of **multicore architectures**, exploiting the reconfigurability potentials and issues (because of variability, loss of cores), e.g. in our cooperation with ST Microelectronics, using a Fractal-based programming framework in the P2012 project, and in cooperation with Inria Lille (Adam), or with the CEA and TIMA on integrating control loops in the architecture for a fine control of the energy and of the required nodes for running a given application task.

3.3.3. Applications and autonomic systems

In autonomic systems, control systems remain a lively source of inspiration, partly because the notion of control loop implementation is known and practiced naturally. On a wider scale, we started a cooperation with Orange Labs on "intelligent" building automation and control for the Smart Grid, through modeling and control of appliances w.r.t. their power consumption modes, at home, building, and city levels. Other partners on these topics are CEA LETI/DACLE and Schneider Electric.

We could explore more systems and applications e.g., Human-Machine Interfaces, or the orchestration of services. They can help design more general solutions, and result in a more complete methodology.

4. Application Domains

4.1. Distributed systems and High-Performance Computing

Distributed systems have grown to levels of scale and complexity where it is difficult to master their administration and resources management, in dynamic ans open environments. One of the growing concerns is that the energy consumption has reached levels where it can not be considered negligible anymore, ecologically or economically. Data centers or high performance computing grids need to be controlled in order to combine minimized power needs with sustained performance and quality of service. As mentioned above, this motivates the automation of their management, and is the major topic of, amongst others, our ANR project Ctrl-Green.

Another challenge in distributed systems is in the fast growing amounts of data to process and store. Currently one of the most common ways of dealing with these challenges is the parallel programming paradigm MapReduce which is slowly becoming the de facto tool for Big Data analytics. While its use is already widespread in the industry, ensuring performance constraints while also minimizing costs provides considerable challenges. Current approaches to ensure performance in cloud systems can be separated into three categories: static, reactive, predictive and hybrid approaches. In the industry, static deployments are the standard and usually tuned based on the application peak demand and are generally over-provisioned. Reactive approaches are usually based on reacting to an input metric such as the current CPU utilisation, request rate, response time by adding and removing servers as necessary. Some public cloud providers offer reactive techniques such as the Amazon Auto Scaler. They provide the basic mechanisms for reactive controllers, but it is up to the user to define the static scaling thresholds which is difficult and not optimal. To deal with this issue, we propose a control theoretical approach, based on techniques that have already proved their usefulness for the control community.

In the domain of parallel systems and High Performance Computing, systems are traditionally less open and more controlled by administrators, but this trend is changing, as they are facing the same challenges in energy consumption, needs for adaptivity in reaction to changing workloads, and security issues in computation outsourcing. Topics of interest for us in this domain concern problem in dynamical management of memory and communications features, which we are exploring in the HPES project of the Labex Persybal-lab (see 9.1).

4.2. Reconfigurable architectures in embedded systems

Dynamically reconfigurable hardware has been identified as a promising solution for the design of energy efficient embedded systems. A common argument in favor of this kind of architecture is the specialization of processing elements, that can be adapted to application functions in order to minimize the delay, the control cost and to improve data locality. Another key benefit is the hardware reuse to minimise the area, and therefore the static power and cost. Further advantages such as hardware updates in long-life products and self-healing capabilities are also often mentioned. In presence of context changes (e.g. environment or application functionality), self-adaptive technique can be applied as a solution to fully benefit from the runtime reconfigurability of a system.

Dynamic Partial Reconfiguration (DPR) of FPGA is another accessible solution to implement and experiment reconfigurable hardware. It has been widely explored and detailed in literature. However, it appears that such solutions are not extensively exploited in practice for two main reasons: i) the design effort is extremely high and strongly depends on the available chip and tool versions; and ii) the simulation process, which is already complex for non-reconfigurable systems, is prohibitively large for reconfigurable architectures. As a result, new adequate methods are required to fully exploit the potential of dynamically reconfigurable and self-adaptive architectures. We are working in this topic, especially on the reconfiguration control aspect, in cooperation with teams specialized in reconfigurable architectures such as the former DaRT team at Inria Lille, and LabSticc in Lorient, as in the recently ended ANR project Famous.

A new ANR project in this application domain, starting end of 2015, is called HPeC, in cooperation with amongst others LabSticc in Lorient and Clermont-Ferrand U., will consider embedded video processing on drones (see 9.2.1).

4.3. Smart environments and Internet of Things

Another application domain for autonomic systems design and control is the Internet of Things, and especially the design of smart environments, at the level of homes, buildings, or cities. These domains are often considered at the level of sensors networks, with a strong emphasis on the acquisition of data in massive scales. The infrastructures are sometimes also equipped with actuators, with a wide range of applications, for example concerning lighting or heating, or access and security aspects. We are interested in closing the control loop in such environments, which is less often studied. In particular, rule-based languages are often used to define the automated systems, and we want to contribute to the safe design of such controllers with guarantees on their behaviors. We are working in this topic in cooperation with teams specialized in infrastructures for smart environments at CEA LETI/DACLE and Orange labs (see 8.1).

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Outstanding publications

Results from our work in the ANR project Ctrl Green (see Section 7.2.1) were published in IEEE Transactions on Software Engineering [16].

Our work on Control of Autonomic Parallelism Adaptation on Software Transactional Memory [20] was nominated in the short list for best papers at the International Conference on High Performance Computing & Simulation (HPCS 2016), Innsbruck, Austria, July 2016.

5.1.2. Community

We have been invited to participate to the organization of events, which highlight our active presence in the scientific life in the two domains which we are bridging :

- autonomic computing:

  Eric Rutten is PC co-chair of the International Workshop on Autonomic High Performance Computing (AHPC 2016) (http://hpcs2016.cisedu.info/2-conference/workshops—hpcs2016/workshop08-ahpc) as part of the International Conference on High Performance Computing & Simulation (HPCS 2016) (http://hpcs2016.cisedu.info or http://cisedu.us/rp/hpcs16), July 18 - July 22, 2016, The University of Innsbruck, Innsbruck, Austria ; and PC member of the two major conferences on the topic : the 13th IEEE International Conference on Autonomic Computing (ICAC 2016) Wuerzburg, Germany, July 19-22, 2016 (http://icac2016.uni-wuerzburg.de) and the 4th International Conference on Cloud and Autonomic Computing (ICCAC 2016), Augsburg, Germany on September 12-16, 2016 (http://iccac2016.se.rit.edu), Part of FAS* - Foundation and Applications of Self* Computing Conferences, Collocated with the IEEE Self-Adaptive and Self-Organizing System Conference.

He is PC member of the 2017 edition of these two conferences as well.

He is invited editor of Cluster Computing, The Journal of Networks, Software Tools and Applications (Springer), foe the special issue of ICCAC 2015 Best Papers (http://link.springer.com/journal/10586/19/2/page/1).

He is PC member for the SEfSAS Book 3 (Software Engineering for Self-Adaptive Systems: Assurances) Volume 3 to be published by Springer LNCS as nr. 9640 in 2017.

Gwenaël Delaval is PC member of the International Workshop on Autonomic High Performance Computing (AHPC 2016).

- control:

  Eric Rutten is organizer of an Open Invited Track on "Control for Computing Systems" at the 20th IFAC World Congress, to be held in Toulouse, July 9-14, 2017, (https://www.ifac2017.org/OIT#geht5).

  He is PC member of the 13th International Workshop on Discrete Event Systems (WODES 2016), Xi'an, China on May 30 - June 1, 2016 (http://wodes2016.diee.unica.it).

  He is on the IFAC Technical Committee 1.3 on Discrete Event and Hybrid Systems, (http://tc.ifac-control.org/1/3/) and on the IEEE Control Systems Society Discrete Event Systems Technical Committee (http://discrete-event-systems.ieeecss.org).

5.1.3. Invited talk

Eric Rutten was invited to give a talk at the 9th Cloud Control Workshop (by invitation only), Stockholm, June 27-29 2016 (http://cloudresearch.org/workshops/9th) and at the séminaire LIP / Avalon, 16 février 2016, ENS Lyon (https://intranet.inria.fr/Actualite/SEMINAIRE-16-02-16-ERIC-RUTTEN-ENS-DE-LYON).

6. New Software and Platforms

6.1. Heptagon BZR

FUNCTIONAL DESCRIPTION

Heptagon is an experimental language for the implementation of embedded real-time reactive systems. It is developed inside the Synchronics large-scale initiative, in collaboration with Inria Rhones-Alpes. It is essentially a subset of Lucid Synchrone, without type inference, type polymorphism and higher-order. It is thus a Lustre-like language extended with hierchical automata in a form very close to SCADE 6. The intention for making this new language and compiler is to develop new aggressive optimization techniques for sequential C code and compilation methods for generating parallel code for different platforms. This explains much of the simplifications we have made in order to ease the development of compilation techniques.

Heptagon BZR is an extension of Heptagon, equipped with a behavioral contract mechanisms, where assumptions can be described, as well as an "enforce" property part. Its main feature is to include discrete controller synthesis within its compilation. The semantics of contracts is that the property should be enforced by controlling the behaviour of the node equipped with the contract. This property will be enforced by an automatically built controller, which will act on free controllable variables given by the programmer.

- Participants: Adrien Guatto, Marc Pouzet, Cédric Pasteur, Léonard Gerard, Brice Gelineau, Gwenael Delaval and Eric Rutten
- Contact: Gwenaël Delaval
- http://bzr.inria.fr

7. New Results

7.1. Design and programming

7.1.1. Component-based approaches

Participants: Gwenaël Delaval, Eric Rutten.

Architecting in the context of variability has become a real need in today's software development. Modern software systems and their architecture must adapt dynamically to events coming from the environment (e.g., workload requested by users, changes in functionality) and the execution platform (e.g., resource availability). Component-based architectures have shown to be very suited for self-adaptation especially with their dynamical reconfiguration capabilities. However, existing solutions for reconfiguration often rely on low level, imperative, and non formal languages. We have defined Ctrl-F, a domain-specific language whose objective is to provide high-level support for describing adaptation behaviors and policies in component-based architectures. It relies on reactive programming for formal verification and control of reconfigurations. We integrate Ctrl-F with the FraSCAti Service Component Architecture middleware platform, and apply it to the Znn.com self-adaptive case study

We have obtained new results in the application of modular controller synthesis and BZR compilation integrated in Ctrl-F, in order to attack issues in scalability, and reusability. We are also considering integration at the DSL level of expressivity extensions, for which the compilation and controller synhesis is relying on the ReaX tool developed at Inria Rennes, in the Sumo team.

7.1.2. Rule-based systems

Participants: Adja Sylla, Eric Rutten.

We are starting a cooperation with CEA LETI/DACLE on the topic of a high-level language for safe rule-based programming in the LINC platform. The general context is that of the runtime redeployment of distributed applications, for example managing smart buildings. Motivations for redeployment can be diverse: load balancing, energy saving, upgrading, or fault tolerance. Redeployment involves changing the set of components in presence, or migrating them. The basic functionalities enabling to start, stop, migrate, or clone components, and the control managing their safe coordination, will have to be designed in the LINC middleware developed at CEA.

Rule based middlewares such as LINC enable high level programming of distributed adaptive systems behaviours. LINC also provides the systems with transactional guarantees and hence ensures their reliability at runtime. However, the set of rules may contain design errors (e.g. conflicts, violations of constraints) that can bring the system in unsafe safe or undesirables states, despite the guarantees provided by LINC. On the other hand, automata based languages such as Heptagon/BZR enable formal verification and especially synthesis of discrete controllers to deal with design errors. Our work studies these two languages and combines their execution mechanisms, from a technical perspective. A case study taken in the field of building automation is treated to illustrate the proposed approach [18].

The PhD of Adja Sylla at CEA on this topic is co-advised with F. Pacull and M. Louvel.

7.2. Infrastructure-level support

We apply the results of the previous axes of the team's activity to a range of infrastructures of different natures, but sharing a transversal problem of reconfiguration control design. From this very diversity of validations and experiences, we draw a synthesis of the whole approach, towards a general view of Feedback Control as MAPE-K loop in Autonomic Computing [23], [22].

7.2.1. Autonomic Cloud and Big-Data systems

Participants: Soguy Mak Kare Gueye, Gwenaël Delaval, Eric Rutten.

Complex computing systems are increasingly self-adaptive, with an autonomic computing approach for their administration. Real systems require the co-existence of multiple autonomic management loops, each complex to design. However their uncoordinated co-existence leads to performance degradation and possibly to inconsistency. There is a need for methodological supports facilitating the coordination of multiple autonomic managers. To tackle this problem, we take a global view and underscore that Autonomic Management Systems (AMS) are intrinsically reactive, as they react to flows of monitoring data by emitting flows of reconfiguration actions. Therefore we propose a new approach for the design of AMSs, based on synchronous programming and discrete controller synthesis techniques. They provide us with high-level languages for modeling the system to manage, as well as means for statically guaranteeing the absence of logical coordination problems. Hence, they suit our main contribution, which is to obtain guarantees at design time about the absence of logical inconsistencies in the taken decisions. We detail our approach, illustrate it by designing an AMS for a realistic multi-tier application, and evaluate its practicality with an implementation [16].

We addressed these problems in the context of follow-ups of the ANR project Ctrl-Green, in cooperation with LIG (N. de Palma) in the framework of the PhD of S. Gueye [17] and the post-doc of N. Berthier.

7.2.2. Reconfiguration control in DPR FPGA

Participants: Soguy Mak Kare Gueye, Eric Rutten.

Dynamically reconfigurable hardware has been identified as a promising solution for the design of energy efficient embedded systems. However, its adoption is limited by the costly design effort including verification and validation, which is even more complex than for non dynamically reconfigurable systems. We worked on this topic in the context of a ensign environment, developed in the framework of the ANR project Famous, in cooperation with LabSticc in Lorient and Inria Lille (DaRT team). We proposed a tool-supported formal method to automatically design a correct-by-construction control of the reconfiguration. By representing system behaviors with automata, we exploit automated algorithms to synthesize controllers that safely enforce reconfiguration strategies formulated as properties to be satisfied by control. We design generic modeling patterns for a class of reconfigurable architectures, taking into account both hardware architecture and applications, as well as relevant control objectives. We validate our approach on two case studies implemented on FPGAs [3].

We are currently valorizing results in more publications [15], and extending the use of control techniques by evaluating the new tool ReaX developed at Inria Rennes (Sumo).

We are starting a new ANR project called HPeC, within which some of these topics will be extended, especially regarding hierarchical and modular control, and logico-numeric aspects.

7.2.3. Autonomic memory management in HPC

Participants: Naweiluo Zhou, Gwenaël Delaval, Bogdan Robu, Eric Rutten.

Parallel programs need to manage the time trade-off between synchronization and computation. A high parallelism may decrease computing time but meanwhile increase synchronization cost among threads. Software Transactional Memory (STM) has emerged as a promising technique, which bypasses locks, to address synchronization issues through transactions. A way to reduce conflicts is by adjusting the parallelism, as a suitable parallelism can maximize program performance. However, there is no universal rule to decide the best parallelism for a program from an offline view. Furthermore, an offline tuning is costly and error-prone. Hence, it becomes necessary to adopt a dynamical tuning-configuration strategy to better manage a STM system. Autonomic control techniques begin to receive attention in computing systems recently. Control technologies offer designers a framework of methods and techniques to build autonomic systems with well-mastered behaviors. The key idea of autonomic control is to implement feedback control loops to design safe, efficient and predictable controllers, which enable monitoring and adjusting controlled systems dynamically while keeping overhead low. We propose to design feedback control loops to automate the choice of parallelism at runtime and diminish program execution time [20], [24], [21]. It is then combined with another objective related to Thread Mapping Control [19]

In the context of the action-team HPES of the Labex Persyval-lab [0] (see 9.1), this work is performed in cooperation with LIG (J.F. Méhaut) in the framework of the PhD of N. Zhou [14].

7.2.4. *Control of smart environments*

Participants: Adja Sylla, Armando Ochoa, Eric Rutten, Stéphane Mocanu.

7.2.4.1. A service-oriented approach to smart home applications control with reactive programming

The need for adaptability in pervasive computing is growing, driven in part by the increasing number and variety of communication devices. In autonomic applications, however, the control architecture frequently becomes itself a complex system that needs to be adapted. Autonomic applications are often composed of multiple control loops ? each addressing a specific aspect ? whose execution needs to be coordinated for efficient and correct administration. We therefore propose to investigate the use of reactive control models with events and states to coordinate autonomic loops in service-oriented architectures. In this work, we illustrate our approach by integrating a controller based on discrete controller synthesis in an autonomic pervasive environment. The role of the controller is to influence the service-binding criteria of multiple control loops, while respecting logical constraints. In particular, we consider reconfiguration operations of known and dynamic service sets. This work constituted the M2R internship of Armando Ochoa, and was performed in cooperation with the Adele team at LIG, co-advised by E. Rutten and V. Lestideau, in the framework of the Labex Persyval-lab project CASE.

Another activity in this topic was the M2R internship of Ronak Feizimirkhani, co-advised by S. Mocanu and V. Lestideau, The context is the development of an application for a smart home in which automation devices are connected through a wireless communication protocol, Z-Wave, and controlled by a central controller, USB plug in. This involves methods and tools to design fail-safe controllers for autonomic, adaptive, reconfigurable computing systems by combining Computer Science and Control Theory techniques. For this purpose, it is necessary to access required information over the network, derive out a simplified model of the physical network, and then link it to the User interface application. According to the information achieved, there will be an estimation of the network diagnostics to find some probable solutions for. The final application is in a user media to do installing, maintaining or even optimizing the network and devices.

7.2.4.2. Rule-based specification of smart environments control

In the context of IoT applications like mart home environments, the rules for programming in the LINC framework are used as a flexible tool to govern the relations between sensors and actuators. Runtime coordination and formal analysis becomes a necessity to avoid side effects mainly when applications are critical. In cooperation with CEA LETI/DACLE, we are working on a case study for safe applications development in IoT and smart home environments.

New results from Section 7.1.2 are applied in case studies regarding smart environments (offices or homes) [18].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Grants with Industry

Our cooperation with CEA LETI/LIST DACLE at Grenoble Minatec is bilateral, involving the CEA PhD grant of Adja Sylla, to work with F. Pacull and M. Louvel on high-level programming on top of a rule-based middleware.

[0] https://persyval-lab.org/en/sites/hpes

9. Partnerships and Cooperations

9.1. Regional Initiatives

The Labex Persyval-lab is a large regional initiative, supported by ANR, where we are contributing through two projects:

9.1.1. Equipe-action HPES

This project (2013-17) groups members from Inria, LIG, Gipsa-lab, TIMA and Gipsa-lab, around the topic of High-Performance Computing benefitting from technologies originally developed for Embedded Systems : https://persyval-lab.org/en/sites/hpes. Ctrl-A is directly involved in the co-advising of the PhD of Naweiluo Zhou, with J.F. Méhaut (LIG), on the topic of autonomic management of software transactional memory mechanisms : https://persyval-lab.org/en/research/phd/autonomic-thread-parallelism-and-mapping-control-software-transactional-memory.

9.1.2. Projet Exploratoire CASE

This project (2015-16) grouped members from Inria, LIG, Gipsa-lab and CEA LETI/DACLE and concerned the general topic of Control techniques for Autonomic Smart Environments, with a special emphasis on relating discrete and stochastic control models with middleware platforms applied to smart environments. It enables us to hire two Masters students for 2016.

9.2. National Initiatives

9.2.1. ANR

HPeC is an ANR project on Self-Adaptive, Energy Efficient High Performance Embedded Computing, with a UAV case study. The Coordinator is Lab-STICC / MOCS (Lorient / Brest), and the duration: 42 month from october 2015. Others Partners are: UBO, U. Clermont-Ferrand, InPixal.

In Ctrl-A, it is funding a PhD thesis or a post-doc position, to be hired in Grenoble and co-adivsed with Lorient. Another PhD based in Brest is co-advised by Stéphane Mocanu.

9.2.2. Informal National Partners

We have contacts with colleagues in France, in addition to the cooperation mentioned before, and with whom we are submitting collaboration projects, co-organizing events and workshops, etc. They feature : Avalon Inria team in Lyon (F. Desprez), LIP6 (J. Malenfant), Scales Inria team in Sophia-Antipolis (L. Henrio), LIRRM in Montpellier (A. Gamatié, K. Godary, D. Simon), IRISA/Inria Rennes (J. Buisson, J.L. Pazat, ...), Telecom Paris-Tech (A. Diaconescu, E. Najm), LAAS (Thierry Monteil), LURPA ENS Cachan (J.M. Faure, J.J. Lesage).

9.2.3. Informal National Industrial Partners

We have ongoing discussions with several industrial actors in our application domains, some of them in the framework of cooperation contracts, other more informal: Eolas/Business decision (G. Dulac), ST Microelectronics (V. Bertin), Schneider Electric (C. El-Kaed, P. Nappey, M. Pitel), Orange labs (J. Pulou, T. Coupaye, G. Privat).

9.3. International Initiatives

9.3.1. Inria International Labs

We participated to the 6th Workshop of the JLESC, with partners Inria, the University of Illinois, Argonne National Laboratory, Barcelona Supercomputing Center, Jülich Supercomputing Centre and RIKEN AICS. We presented the potential of Autonomic Computing, examplified by our results from Section 7.2.3, and had contacts with collaboration potentials.

9.3.2. Inria International Partners

9.3.2.1. Informal International Partners

We have ongoing relations with international colleagues in the emerging community on our topic of control for computing e.g., in Sweden at Lund (K.E. Arzen, M. Maggio) and Linnaeus Universities (D. Weyns, N. Khakpour), in the Netherlands at CWI/leiden University (F. Arbab), in China at Heifei University (Xin An), in Italy at University Milano (C. Ghezzi, A. Leva), in the USA at Ann Arbor University (S. Lafortune) and UMass (P. Shenoy, E. Cecchet).

9.3.3. Participation in Other International Programs

Eric Rutten is a member of the IFAC Technical Committee 1.3 on Discrete Event and Hybrid Systems, for the 2011-2014 triennium, and for the 2014-2017 triennum http://tc.ifac-control.org/1/3 ; and of the IEEE Control Systems Society Discrete Event Systems Technical Committee http://discrete-event-systems.ieeecss.org.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Organizing Committees

Stéphane Mocanu is OC member of RESSI 2017 national meeting (https://ressi2017.sciencesconf.org/).

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

Eric Rutten was program co-chair of the International Workshop on Autonomic High Performance Computing (AHPC 2016) (http://hpcs2016.cisedu.info/2-conference/workshops—hpcs2016/workshop08-ahpc) as part of the International Conference on High Performance Computing & Simulation (HPCS 2016) (http://hpcs2016.cisedu.info or http://cisedu.us/rp/hpcs16), July 18 - July 22, 2016, The University of Innsbruck, Innsbruck, Austria

Eric Rutten is organizer of an Open Invited Track on "Control for Computing Systems" at the 20th IFAC World Congress, to be held in Toulouse, July 9-14, 2017, (https://www.ifac2017.org/OIT#geht5).

10.1.2.2. Member of the Conference Program Committees

Gwenaël Delaval is PC member of the International Workshop on Autonomic High Performance Computing (AHPC 2016). (http://hpcs2016.cisedu.info/2-conference/workshops—hpcs2016/workshop08-ahpc)

Eric Rutten is PC member of the 13th International Workshop on Discrete Event Systems (WODES 2016), Xi'an, China on May 30 - June 1, 2016 (http://wodes2016.diee.unica.it) ; for the SEfSAS Book 3 (Software Engineering for Self-Adaptive Systems: Assurances) Volume 3 to be published by Springer LNCS. ; for the two major conferences on the topic : the 13th IEEE International Conference on Autonomic Computing (ICAC 2016) Wuerzburg, Germany, July 19-22, 2016 (http://icac2016.uni-wuerzburg.de) and the 4th International Conference on Cloud and Autonomic Computing (ICCAC 2016), Augsburg, Germany on September 12-16, 2016 (http://iccac2016.se.rit.edu), Part of FAS* - Foundation and Applications of Self* Computing Conferences, Collocated with the IEEE Self-Adaptive and Self-Organizing System Conference ; he is PC member of the 2017 edition of these two conferences as well.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

Eric Rutten is invited editor of Cluster Computing, The Journal of Networks, Software Tools and Applications (Springer), for the special issue of ICCAC 2015 Best Papers (http://link.springer.com/journal/10586/19/2/page/1).

10.1.3.2. Reviewer - Reviewing Activities

Stéphane Mocanu is reviewer for the journal of Discrete Events Dynamical Systems.

Eric Rutten is reviewer for the journal of Distributed Computing (Springer) ; the IEEE Transactions on Software Engineering ; the ACM Transactions on Adaptative and Aautonomic Systems.

10.1.4. Invited Talks

Eric Rutten was invited to give a talk at the 9th Cloud Control Workshop, Stockholm, June 27-29 2016 (by invitation only) (http://cloudresearch.org/workshops/9th) and at the séminaire LIP / Avalon, 16 février 2016, ENS Lyon (https://intranet.inria.fr/Actualite/SEMINAIRE-16-02-16-ERIC-RUTTEN-ENS-DE-LYON).

10.1.5. Scientific Expertise

Eric Rutten is remote referee for the ERC advanced grants program.

10.1.6. Research Administration

Eric Rutten is member of the LIG laboratory concil, and in charge of scientific relations between Inria Grenoble Rhône-Alpes and CEA Tech.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

S. Mocanu teaches at ENSE3 school of INPG : TCP/IP networks, Real-time communications, Smart-grid communications and IEC 61850, Reliability, Embedded and real-time systems. He is Head of the Control Systems Master program at ENSE3.

G. Delaval teaches at levels L2, L3, M1 at UFRIM2AG (Computer Science Dept.) of UGA : Algorithmic, Programming, Compilation. Soguy Gueye gives tutorials in Programming in the same program.

10.2.2. Supervision

- PhDs in progress :
  - Adja Ndeye SYLLA ; Generation of coordination rules from an automaton, in the context of the redeployment of distributed contra; applications ; feb. 2015 ; E. Rutten, F. Pacull and M. Louvel (CEA)
  - Chabha Hireche, Etude et implémentation d'une approche probabiliste de contrôle de mission de drone autonome ; oct 2015 ; S. Mocanu, Catherine Dezan (U. Bretagne Occidentale), and Jean-Philippe Diguet (U. Bretagne Sud)
  - Ahmed Altaher : Mise en oeuvre d'un cadre de sureté de fonctionnement pour les systèmes de contrôle industriel : application à des systèmes de distribution d'énergie électrique (smart grids) ; april 2013 ; S. Mocanu, and J-M Thiriet (Gipsa-lab)
  - Maëlle Kabir-Querrec; Cybersécurité des systèmes de contrôle pour les smart-grids ; nov. 2014 ; S. Mocanu, and J-M Thiriet (Gipsa-lab)
  - Oualid Koucham, Détection d'intrusions dans les systèmes de contrôle industriels ; oct 2015 ; S. Mocanu, and J-M Thiriet (Gipsa-lab)
- PhD defended : Naweiluo Zhou ; Application-aware policies and control for transactional memory systems ; defended 19 oct. 2016 ; E. Rutten, G. Delaval, J.F. Mehaut (Inria/LIG Corse) [14] .

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[6] G. DELAVAL, S. M.-K. GUEYE, E. RUTTEN, N. DE PALMA.*Modular Coordination of Multiple Autonomic Managers*, in "17th International ACM Sigsoft Symposium on Component-Based Software Engineering (CBSE 2014)", Lille, France, June 2014, 291 [*DOI :* 10.1145/2602458.2602465], https://hal.archives-ouvertes.fr/hal-01006106.

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Project-Team DANTE

Dynamic Networks: Temporal and Structural Capture Approach

IN COLLABORATION WITH: Laboratoire de l'Informatique du Parallélisme (LIP)

IN PARTNERSHIP WITH:
Ecole normale supérieure de Lyon

Université Claude Bernard (Lyon 1)

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Networks and Telecommunications

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Project-Team DANTE

Creation of the Team: 2012 November 01, updated into Project-Team: 2015 January 01

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Other Research Topics and Application Domains:

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2. Overall Objectives

2.1. Overall Objectives

The goal of DANTE is to develop **novel models, algorithms and methods to analyse the dynamics of large-scale networks**, (*e.g. social networks, technological networks such as the Web and hyperlinks, Articles and co-citation, email exchanges, economic relations, bacteria/virus propagation in human networks...*). Large datasets describing such networks are nowadays more "accessible" due to the emergence of online activities and new techniques of data collection. These advantages provide us an unprecedented avalanche of large data sets, recording the digital footprints of millions of entities (*e.g.* individuals, computers, documents, stocks, etc.) and their temporal interactions [0]. Such large amount of information allows for easier and

[0] YouTube claims to receive 48 hours of video every minute, Google and Facebook represent major world companies that generate millions of traces on our activities every second. Every day, hundreds of millions of posts are added to the blogosphere, from which information on citizen opinions and their evolutions can be collected.

more precise traceability of social activities, better observation of the structural and temporal evolution of social/technological/economical networks, the emergence of their localized and cascading failures, and provides information about the general roles of self-organization in an interdisciplinary sense. All these questions represent a major scientific, economic, and social challenge, which has the potential to revolutionize our understanding of the arising socio-technical world of our age.

Our main challenge is to propose **generic methodologies and concepts to develop relevant formal tools to model, analyse the dynamics and evolution of such networks, that is, to formalise the dynamic properties of both structural and temporal interactions of network entities/relations**:

- **Ask** application domains relevant questions, to learn something new about such domains instead of merely playing with powerful computers on huge data sets.
- **Access** and collect data with adapted and efficient tools. This includes a reflexive step on the biases of the data collected and their relations to real activities/application domain.
- **Model** the dynamics of networks by analyzing their structural and temporal properties jointly, inventing original approaches combining graph theory with signal processing. A key point is to capture temporal features in the data, which may reveal meaningful insights on the evolution of the networks.
- **Interpret** the results, make the knowledge robust and useful in order to be able to control, optimise and (re)-act on the network structure itself and on the protocols exchange/interactions in order to obtain a better performance of the global system.

The challenge is to solve a major scientific puzzle, common to several application domains (*e.g.*, sociology, information technology, epidemiology) and central in network science: how to understand the causality between the evolution of macro-structures and individuals, at local and global scales?

3. Research Program

3.1. Graph-based signal processing

Participants: Christophe Crespelle, Éric Fleury, Paulo Gonçalves Andrade, Márton Karsai, Sarah de Nigris, Sarra Ben Alaya, Hadrien Hours.

Evolving networks can be regarded as "*out of equilibrium*" systems. Indeed, their dynamics is typically characterized by non standard and intricate statistical properties, such as non-stationarity, long range memory effects, intricate space and time correlations.

Analyzing, modeling, and even defining adapted concepts for dynamic graphs is at the heart of DANTE. This is a largely open question that has to be answered by keeping a balance between specificity (solutions triggered by specific data sets) and generality (universal approaches disconnected from social realities). We will tackle this challenge from a graph-based signal processing perspective involving signal analysts and computer scientists, together with experts of the data domain application. One can distinguish two different issues in this challenge, one related to the graph-based organisation of the data and the other to the time dependency that naturally exits in the dynamic graph object. In both cases, a number of contributions can be found in the literature, albeit in different contexts. In our application domain, high-dimensional data "naturally reside" on the vertices of weighted graphs. The emerging field of signal processing on graphs merges algebraic and spectral graph theoretic concepts with computational harmonic analysis to process such signals on graphs [70].

As for the first point, adapting well-founded signal processing techniques to data represented as graphs is an emerging, yet quickly developing field which has already received key contributions. Some of them are very general and delineate ambitious programs aimed at defining universal, generally unsupervised methods for exploring high-dimensional data sets and processing them. This is the case for instance of the Â« diffusion wavelets Â» and Â« diffusion maps Â» pushed forward at Yale and Duke [54]. Others are more traditionally connected with standard signal processing concepts, in the spirit of elaborating new methodologies via some bridging between networks and time series, see, *e.g.*, ([65] and references therein). Other viewpoints can be found as well, including multi-resolution Markov models [73], Bayesian networks or distributed processing over sensor networks [64]. Such approaches can be particularly successful for handling static graphs and unveiling aspects of their organisation in terms of dependencies between nodes, grouping, etc. Incorporating possible time dependencies within the whole picture calls however for the addition of an extra dimension to the problem "as it would be the case when switching from one image to a video sequence", a situation for which one can imagine to take advantage of the whole body of knowledge attached to non-stationary signal processing [55].

3.2. Theory and Structure of dynamic Networks

Participants: Christophe Crespelle, Éric Fleury, Anthony Busson, Márton Karsai.

Characterization of the dynamics of complex networks. We need to focus on intrinsic properties of evolving/dynamic complex networks. New notions (as opposed to classical static graph properties) have to be introduced: rate of vertices or links appearances or disappearances, the duration of link presences or absences. Moreover, more specific properties related to the dynamics have to be defined and are somehow related to the way to model a dynamic graph.

Through the systematic analysis and characterization of static network representations of many different systems, researchers of several disciplines have unveiled complex topologies and heterogeneous structures, with connectivity patterns statistically characterized by heavy-tails and large fluctuations, scale-free properties and non trivial correlations such as high clustering and hierarchical ordering [67]. A large amount of work has been devoted to the development of new tools for statistical characterisation and modelling of networks, in order to identify their most relevant properties, and to understand which growth mechanisms could lead to these properties. Most of those contributions have focused on static graphs or on dynamic process (*e.g.* diffusion) occurring on static graphs. This has called forth a major effort in developing the methodology to characterize the topology and temporal behavior of complex networks [67], [58], [74], [63], to describe the observed structural and temporal heterogeneities [52], [58], [53], to detect and measure emerging community structures [56], [71], [72], to see how the functionality of networks determines their evolving structure [62], and to determine what kinds of correlations play a role in their dynamics [59], [61], [66].

The challenge is now to extend this kind of statistical characterization to dynamical graphs. In other words, links in dynamic networks are temporal events, called contacts, which can be either punctual or last for some period of time. Because of the complexity of this analysis, the temporal dimension of the network is often ignored or only roughly considered. Therefore, fully taking into account the dynamics of the links into a network is a crucial and highly challenging issue.

Another powerful approach to model time-varying graphs is via activity driven network models. In this case, the only assumption relates to the distribution of activity rates of interacting entities. The activity rate is realistically broadly distributed and refers to the probability that an entity becomes active and creates a connection with another entity within a unit time step [69]. Even the generic model is already capable to recover some realistic features of the emerging graph, its main advantage is to provide a general framework to study various types of correlations present in real temporal networks. By synthesizing such correlations (*e.g.* memory effects, preferential attachment, triangular closing mechanisms, ...) from the real data, we are able to extend the general mechanism and build a temporal network model, which shows certain realistic feature in a controlled way. This can be used to study the effect of selected correlations on the evolution of the emerging structure [60] and its co-evolution with ongoing processes like spreading phenomena, synchronisation, evolution of consensus, random walk etc. [60], [68]. This approach allows also to develop control and immunisation strategies by fully considering the temporal nature of the backgrounding network.

3.3. Distributed Algorithms for dynamic networks: regulation, adaptation and interaction

Participants: Thomas Begin, Anthony Busson, Paulo Gonçalves Andrade, Isabelle Guérin Lassous.

Dedicated algorithms for dynamic networks. First, the dynamic network object itself trigger original algorithmic questions. It mainly concerns distributed algorithms that should be designed and deployed to efficiently measure the object itself and get an accurate view of its dynamic behavior. Such distributed measure should be "transparent", that is, it should introduce no bias or at least a bias that is controllable and corrigible. Such problem is encountered in all distributed metrology measures / distributed probes: P2P, sensor network, wireless network, QoS routing... This question raises naturally the intrinsic notion of adaptation and control of the dynamic network itself since it appears that autonomous networks and traffic aware routing are becoming crucial.

Communication networks are dynamic networks that potentially undergo high dynamicity. The dynamicity exhibited by these networks results from several factors including, for instance, changes in the topology and varying workload conditions. Although most implemented protocols and existing solutions in the literature can cope with a dynamic behavior, the evolution of their behavior operates identically whatever the actual properties of the dynamicity. For instance, parameters of the routing protocols (*e.g.* hello packets transmission frequency) or routing methods (*e.g.* reactive / proactive) are commonly hold constant regardless of the nodes mobility. Similarly, the algorithms ruling CSMA/CA (*e.g.* size of the contention window) are tuned identically and they do not change according to the actual workload and observed topology.

Dynamicity in computer networks tends to affect a large number of performance parameters (if not all) coming from various layers (viz. physical, link, routing and transport). To find out which ones matter the most for our intended purpose, we expect to rely on the tools developed by the two former axes. These quantities should capture and characterize the actual network dynamicity. Our goal is to take advantage of this latter information in order to refine existing protocols, or even to propose new solutions. More precisely, we will attempt to associate “fundamental” changes occurring in the underlying graph of a network (reported through graph-based signal tools) to quantitative performance that are matter of interests for networking applications and the end-users. We expect to rely on available testbeds such as Senslab and FIT to experiment our solutions and ultimately validate our approach.

4. Application Domains

4.1. Life Science & Health

In parallel to the advances in modern medicine, health sciences and public health policy, epidemic models aided by computer simulations and information technologies offer an increasingly important tool for the understanding of transmission dynamics and of epidemic patterns. The increased computational power and use of Information and Communication Technologies make feasible sophisticated modelling approaches augmented by detailed in vivo data sets, and allow to study a variety of possible scenarios and control strategies, helping and supporting the decision process at the scientific, medical and public health level. The research conducted in the DANTE project finds direct applications in the domain of LSH since modelling approaches crucially depend on our ability to describe the interactions of individuals in the population. In the MOSAR/iBird project we are collaborating with the team of Pr. Didier Guillemot (Inserm/Institut. Pasteur/Université de Versailles). Within the TUBEXPO and ARIBO projects, we are collaborating with Pr. Jean-Christopge Lucet (Professeur des université Paris VII, Praticien hospitalier APHP).

4.2. Network Science / Complex networks

In the last ten years the science of complex networks has been assigned an increasingly relevant role in defining a conceptual framework for the analysis of complex systems. Network science is concerned with graphs that map entities and their interactions to nodes and links. For a long time, this mathematical abstraction has contributed to the understanding of real-world systems in physics, computer science, biology, chemistry, social sciences, and economics. Recently, however, enormous amounts of detailed data, electronically collected and meticulously catalogued, have finally become available for scientific analysis and study. This has led to the discovery that most networks describing real world systems show the presence of complex properties and heterogeneities, which cannot be neglected in their topological and dynamical description. This has called forth a major effort in developing the methodology to characterise the topology and temporal behaviour of complex networks, to describe the observed structural and temporal heterogeneities, to detect and measure emerging community structure, to see how the functionality of networks determines their evolving structure, and to determine what kinds of correlations play a role in their dynamics. All these efforts have brought us to a point where the science of complex networks has become advanced enough to help us to disclose the deeper roles of complexity and gain understanding about the behaviour of very complicated systems.

In this endeavour the DANTE project targets the study of dynamically evolving networks, concentrating on questions about the evolving structure and dynamical processes taking place on them. During the last year we developed developed several projects along these lines concerning three major datasets:

- Mobile telephony data: In projects with academic partners and Grandata we performed projects based on two large independent datasets collecting the telephone call and SMS event records for million of anonymised individuals. The datasets record the time and duration of mobile phone interactions and some coarse grained location and demographic data for some users. In addition one of the dataset is coupled with anonymised bank credit information allowing us to study directly the socioeconomic structure of a society and how it determines the communication dynamics and structure of individuals.
- Skype data: Together with Skype Labs/STACC and other academic groups we were leading projects in the subject of social spreading phenomena. These projects were based on observations taken from a temporally detailed description of the evolving social network of (anonymised) Skype users registered between 2003 and 2011. This data contains dates of registration and link creation together with gradual information about their location and service usage dynamics.
- Twitter data: In collaboration with ICAR-ENS Lyon we collected a large dataset about the microblogs and communications of millions of Twitter users in the French Twitter space. This data allows us to follow the spreading of fads/opinions/hashtags/ideas and more importantly linguistic features in online communities. The aim of this collaboration is to set the ground for a quantitative framework studying the evolution of linguistic features and dialects in an social-communication space mediated by online social interactions.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Network Science Semester

Dante organised in 2016 a full semester on Network Science (https://project.inria.fr/netspringlyon/) in conjunction with the SiSyPhe team at ENS de Lyon, the Centre de Physique Théorique of Marseille, the Excellence Laboratory MILYON and the Institute of Scientific Interchange of Turino. This program intends to cover both the basics of and recent advances in Network Science. These questions, which are in the focus of contemporary network science, set the scope of the actual proposal where we aim to bring together world-known experts from the fields of mathematics, physics, signal processing, computer science, social science, epidemiology and linguistic to discuss and enhance our understanding about the interaction between the structure, evolution, and coupled dynamical processes of complex networks. The semester gathered 2 workshops and 1 conference. during the two workshop, 14 invited speakers spend time within Dante in short or long visit. Members of Dante also organised in June Socionet (http://www.socionet2016.fr) for young researchers and focus on the interdisciplinary meeting on social network: description, data, modelling, interpretation. It was a great success with a Datathon organised by the PhD student and PostDoc of DANTE.

5.1.2. Frutfull collaboration with GranData (http://www.grandata.com/)

Grandata integrates first-party and telco partner data to understand key market trends, predict customer behaviour, and deliver novel business results. We have published several papers [12], [41], [36], [11], [10] in collaboration with them on the socioeconomic correlations and stratification in social-communication networks, on the impact of university admission on freshmen' social egocentric network, on the correlations of consumption patterns in social-economic networks but also to validate DTN like protocols by taking benefits of the density and locality of urban communication patterns.

6. New Software and Platforms

6.1. GraSP

Graph Signal Processing
KEYWORDS: Matlab - LaTeX - Graph - Graph visualization - Signal processing - GNU Octave
FUNCTIONAL DESCRIPTION

Matlab / GNU Octave toolbox to manipulate and visualize signals on graphs. LaTeX package to draw signals.

- Contact: Benjamin Girault
- URL: https://gforge.inria.fr/projects/grasp/

6.2. IoT-LAB aggregation-tools

KEYWORD: Internet of things
FUNCTIONAL DESCRIPTION

IoT-LAB aggregation-tools allow aggregating data results from many nodes at a time. It connects to several tcp connections and handle the received data.

- Participant: Gaetan Harter
- Contact: Eric Fleury
- URL: https://github.com/iot-lab/aggregation-tools

6.3. IoT-LAB cli-tools

KEYWORD: Internet of things
FUNCTIONAL DESCRIPTION

IoT-LAB cli-tools provide a basic set of operations for managing IoT-LAB experiments from the command-line.

- Participants: Gaetan Harter and Frédéric Saint-Marcel
- Contact: Eric Fleury
- URL: https://github.com/iot-lab/cli-tools

6.4. IoT-LAB gateway

KEYWORD: Internet of things
FUNCTIONAL DESCRIPTION

IoT-LAB software embedded on a IoT-LAB gateway node new generation provides the local management of the experiment on that node. It is a software bridge between the IoT-LAB server, the user open node and the control node.

- Contact: Frédéric Saint-Marcel
- URL: https://github.com/iot-lab/iot-lab-gateway

6.5. Queueing Systems

FUNCTIONAL DESCRIPTION

This tool aims at providing a simple web interface to promote the use of our proposed solutions to numerically solve classical queueing systems.

- Participants: Thomas Begin and Alexandre Brandwajn
- Contact: Thomas Begin
- URL: http://queueing-systems.ens-lyon.fr/

6.6. Data analysis tools

6.6.1. Twitter link predictions

FUNCTIONAL DESCRIPTION

Inference, study and prediction of the dynamics of the Twitter mention network

- Participants: Hadrien Hours, Eric Fleury and Márton Karsai
- Contact: Márton Karsai
- URL: https://github.com/HadrienHours/TwitterMentionNetworkLinkPrediction

6.7. Platforms

6.7.1. FIT IoT-LAB

FUNCTIONAL DESCRIPTION

IoT-LAB provides full control of network IoT nodes and direct access to the gateways to which nodes are connected, allowing researchers to monitor nodes energy consumption and network-related metrics, e.g. end-to-end delay, throughput or overhead. The facility offers quick experiments deployment, along with easy evaluation, results collection and analysis. Defining complementary testbeds with different node types, topologies and environments allows for coverage of a wide range of real-life use-cases.

- Partner: FIT is one of 52 winning projects from the first wave of the French Ministry of Higher Education and Researchâs âÃquipements dâExcellenceâ (Equipex) research grant programme. Th eFIT consortium is composed of: Université Pierre et Marie Curie (UPMC), Inria, Université de Strasbourg, Institut Mines Télécom and CNRS
- Contact: Éric Fleury
- URL: https://www.iot-lab.info/

7. New Results

7.1. Graph & Signal Processing

Participants: Sarra Ben Alaya, Éric Fleury, Paulo Gonçalves Andrade.

7.1.1. Isometric graph shift operator]

Following up the PhD work of Benjamin Girault [57], we demonstrated in [26] that the isometric graph shift operator we originally proposed, does have a vertex-domain interpretation as a diffusion operator using a polynomial approximation. We showed that its impulse response exhibits an exponential decay of the energy way from the impulse, demonstrating localisation preservation. Additionally, we formalised several techniques that can be used to study other graph signal operators.

7.2. Performance analysis and networks protocols

Participants: Mohammed Amer, Thomas Begin, Anthony Busson, Éric Fleury, Paulo Gonçalves Andrade, Yannick Léo, Isabelle Guérin Lassous, Philippe Nain, Huu Nghi Nguyen, Laurent Reynaud.

7.2.1. Use of large scale CDR for protocol performance evaluation and modelling

In [11] we use large scale CDR (Call Data Records) coming from a nationwide cellular telecommunication operator during a two month period to validate several DTN approaches for conveying SMS traffic in dense urban areas taking benefits of the density of users and the mobility of the users. We study a mobile dataset including 8 Million users living in large urban area. This gives us a precise estimation of the average transmission time and the global performance of our approach. Our analysis shows that after 30 min, half of the SMS are delivered successfully to destination. In [10], we study the temporal activity of a user and the user movements. At the user scale, the usage is not only defined by the amount of calls but also by the userâs mobility. At a higher level, the base stations have a key role on the quality of service. From a very large Call Detail Records (CDR) we first study call duration and inter-arrival time parameters. Then, we assess user movements between consecutive calls (switching from a station to another one). Our study suggests that user mobility is pretty dependent on user activity. Furthermore, we show properties of the inter-call mobility by making an analysis of the call distribution.

7.2.2. End-to-end delay

Because of the growing complexity of computer networks, a new paradigm has been introduced to ease their design and management, namely, the SDN (Software-defined Networking). In particular, SDN defines a new entity, the controller that is in charge of controlling the devices belonging to the data plane In order to let the controller take its decisions, it must have a global view on the network. This includes the topology of the network and its links capacity, along with other possible performance metrics such delays, loss rates, and available bandwidths. This knowledge can enable a multi-class routing, or help guarantee levels of Quality of Service. In [33], [20], [42], we proposed new algorithms that allow a centralised entity, such as the controller in an SDN network, to accurately estimate the end-to-end delay for a given flow in its network. The proposed methods are passive in the sense that they do not require any additional traffic to be run. Through extensive simulations, we show that these methods are able to accurately estimate the expectation and the standard deviation of end-to-end delays.

In [14] we investigated the traversal time of a file across N communication links subject to stochastic changes in the sending rate of each link. Each link's sending rate is modelled by a finite-state Markov process. Two cases, one where links evolve independently of one another (N mutually independent Markov processes), and the second where their behaviours are dependent (these N Markov processes are not mutually independent) were considered. A particular instance where the above is

7.2.3. Circumventing the complexity of multi-server queues

Many real-life systems can be viewed as instances of multi-server queues. However, when the number of servers is high (say more than 16) and the arrival or/and service process exhibit high variability, current state-of-the-art solutions often become intractable due to the combinatorial growth of the underlying state space of the Markov chain. We proposed two efficient, fast and easy-to-implement approximate solutions to deal with *G/G/c*-like queues in [4], [2]. Our solutions rely the use of an original, though incomplete, state description that heavily breaks the complexity of multi-server queues. We have extensively validated our approximations against discrete-event simulation for several QoS performance metrics such as mean sojourn time and blocking probability with excellent results.

7.2.4. Wi-Fi networks optimization

Densification of Wi-Fi networks has led to the possibility for a station to choose between several access points (APs). On the other hand, the densification of APs generates interference, contention and decreases the global throughput as APs have to share a limited number of channels. Optimizing the association step between APs and stations can alleviate this problem and increase the overall throughput and fairness between stations.

We proposed original solutions [23], [22] to this optimization problem based on two contributions. First, we modeled the association optimization problem assuming a realistic share of the medium between APs and stations and among APs when using the 802.11 DCF (Distributed Coordination Function) mode. Then, we introduced a local search algorithm to solve this problem through a suitable neighborhood structure. We show that the classical approaches in the literature, based on a time based fairness scheme, is less efficient than our solution when the number of orthogonal channels is limited. Also, we show through a large set of simulations and scenarios that our models are able to capture the real throughputs of Wi-Fi networks.

7.2.5. Controlled mobility in wireless networks

In this work, we have investigated the application of an adapted controlled mobility strategy on self-propelling nodes, which could efficiently provide network resource to users scattered on a designated area. In [7], we describe an adapted controlled mobility strategy and detail the design of our Virtual Force Protocol (VFP) which allows a swarm of vehicles to track and follow hornets to their nests, while maintaining connectivity through a wireless multi-hop communication route with a remote ground station used to store applicative data such as hornet trajectory and vehicle telemetry. In [43], we design a physics-based controlled mobility strategy, which we name the extended Virtual Force Protocol (VFPe), allowing self-propelled nodes, and in particular here unmanned aerial vehicles, to fly autonomously and cooperatively. In this way, ground devices scattered on the operation site may establish communications through the wireless multi-hop communication routes formed by the network of aerial nodes. In [28], we design a virtual force-based controlled mobility scheme, named VFPc, and evaluate its ability to be jointly used with a dual packet-forwarding and epidemic routing protocol. In particular, we study the possibility for end-users to achieve synchronous communications at given times of the considered scenarios.

7.3. Modeling of Dynamics of Complex Networks

Participants: Christophe Crespelle, Éric Fleury, Márton Karsai, Yannick Léo, Philippe Nain, Matteo Morini.

7.3.1. Data Driven studies on socioeconomic data and communication networks

The study of correlations between the social network and economic status of individuals is difficult due to the lack of large-scale multimodal data disclosing both the social ties and economic indicators of the same population. Thanks to our collaboration with GranData, we close this gap through the analysis of coupled datasets recording the mobile phone communications and bank transaction history of one million anonymised individuals living in a Latin American country. From this large scale data set based on a representative, society-large population we empirically demonstrate some long-lasting hypotheses on socioeconomic correlations, which potentially lay behind social segregation, and induce differences in human mobility. More precisely, in [12] we show that wealth and debt are unevenly distributed among people in agreement with the Pareto principle; the observed social structure is strongly stratified, with people being better connected to others of their own socioeconomic class rather than to others of different classes; the social network appears to have assortative socioeconomic correlations and tightly connected ârich clubsâ; and that individuals from the same class live closer to each other but commute further if they are wealthier. In [41], we show that typical consumption patterns are strongly correlated with identified socioeconomic classes leading to patterns of stratification in the social structure. In addition we measure correlations between merchant categories and introduce a correlation network, which emerges with a meaningful community structure. We detect multivariate relations between merchant categories and show correlations in purchasing habits of individuals. Our work provides novel and detailed insight into the relations between social and consuming behaviour with potential applications in recommendation system design. In [36] we provide insight about the effects of marking events on the structure and the dynamics of egocentric networks. More precisely, we study the impact of university admission on the composition and evolution of the egocentric networks of freshmen. In other words, we study whether university helps to build connections between egos from different socioeconomic classes, or new social ties emerge via homophilic effects between students of similar economic status. Finally, in [44],

7.3.2. Generalisation of multilayer and temporal graphs

In [16] we introduce the concept of MultiAspect Graph (MAG) as a graph generalisation that we prove to be isomorphic to a directed graph, and also capable of representing all previous generalisations of multilayer and temporal networks. In our proposal, the set of vertices, layers, time instants, or any other independent features are considered as an aspect of the MAG. For instance, a MAG is able to represent multilayer or time-varying networks, while both concepts can also be combined to represent a multilayer time-varying network and even other higher-order networks. Since the MAG structure admits an arbitrary (finite) number of aspects, it hence introduces a powerful modelling abstraction for networked complex systems. In [17] we develop the algebraic representation and basic algorithms for MultiAspect Graphs (MAGs). In particular, we show that, as a consequence of the properties associated with the MAG structure, a MAG can be represented in matrix form. Moreover, we also show that any possible MAG function (algorithm) can be obtained from this matrix-based representation. This is an important theoretical result since it paves the way for adapting well-known graph algorithms for application in MAGs. We present a set of basic MAG algorithms, constructed from well-known graph algorithms, such as degree computing, Breadth First Search (BFS), and Depth First Search (DFS).

Multilayer networks arise in scenarios when a common set of nodes form multiple networks via different co-existing, and sometimes interdependent means of connectivity. In [6] we studied the threshold on the occupation density in the individual network layers for long-range connectivity to emerge in a large multilayer network. For a multilayer network formed via merging M random instances of a graph G with site-occupation probability q in each layer, we showed that when q exceeds a threshold $q_c(M)$, a giant connected component appears in the M-layer network. We showed that $q_c(M) \lesssim \sqrt{-\ln(1-p_c)}/\sqrt{M}$, where p_c is the bond percolation threshold of G, and $q_c(1) \equiv q_c$ is by definition the site percolation threshold of G. We found $q_c(M)$ exactly for when G is a large random graph with any given node-degree distribution. We calculated $q_c(M)$ numerically for various regular lattices, and obtained an exact lower bound for the kagome lattice. Finally, we established an intriguing close connection between the aforesaid multilayer percolation model and the well-studied problem of site-bond (or, mixed) percolation, in the sense that both models provide a bridge between the traditional independent site and independent bond percolation models. Using this connection, and leveraging some analytical approximations to the site-bond critical region developed in the 1990s, we derived an excellent general approximation to the multilayer threshold $q_c(M)$ for regular lattices, which are not only functions solely of the p_c and q_c of the respective lattices, but also closely match the true values of $q_c(M)$ for a large class of lattices, even for small (single-digit) vales of M.

7.3.3. User-based representation of dynamical multimodal public transportation networks

In this project published as an invited paper [9], we provide a novel user-based representation of public transportation systems, which combines representations, accounting for the presence of multiple lines and reducing the effect of spatial embeddedness, while considering the total travel time, its variability across the schedule, and taking into account the number of transfers necessary. After the adjustment of earlier techniques to the novel representation framework, we analyse the public transportation systems of several French municipal areas and identify hidden patterns of privileged connections. Furthermore, we study their efficiency as compared to the commuting flow. The proposed representation could help to enhance resilience of local transportation systems to provide better design policies for future developments.

7.3.4. Local cascades induced global contagion

In this paper [8] we analyse and model product adoption dynamics in the world's largest voice over internet service, the social network of Skype. We provide empirical evidence about the heterogeneous distribution of fractional behavioural thresholds, which appears to be independent of the degree of adopting egos. We show that the structure of real-world adoption clusters is radically different from previous theoretical expectations, since vulnerable adoptions induced by a single adopting neighbour appear to be important only locally, while spontaneous adopters arriving at a constant rate and the involvement of unconcerned individuals govern the global emergence of social spreading.

7.3.5. Asymptotic theory of time-varying social networks with heterogeneous activity and tie allocation

In this work [15] we empirically characterise social activity and memory in seven real networks describing temporal human interactions in three different settings: scientific collaborations, Twitter mentions, and mobile phone calls. We find that the individuals' social activity and their strategy in choosing ties where to allocate their social interactions can be quantitatively described and encoded in a simple stochastic network modelling framework. The Master Equation of the model can be solved in the asymptotic limit. The analytical solutions provide an explicit description of both the system dynamic and the dynamical scaling laws characterising crucial aspects about the evolution of the networks. The analytical predictions match with accuracy the empirical observations, thus validating the theoretical approach. Our results provide a rigorous dynamical system framework that can be extended to include other processes shaping social dynamics and to generate data driven predictions for the asymptotic behaviour of social networks.

7.3.6. Link prediction in the Twitter mention network

In this project [35] we analyse a large Twitter data corpus and quantify similarities between people by considering the set of their common friends and the set of their commonly shared hashtags in order to predict mention links among them. We show that these similarity measures are correlated among connected people and that the combination of contextual and local structural features provides better predictions as compared to cases where they are considered separately.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. GranDATA

Participants: Márton Karsai [correspondant], Éric Fleury.

Founded in 2012, Grandata is a Palo Alto-based company that leverages advanced research in Human Dynamics (the application of âbig dataâ to social relationships and human behaviour) to identify market trends and predict customer actions. Leading telecom and financial services firms are using Grandataâs Social Universe product to transform âbig dataâ into impressive business results.

The DANTE team and Grandata started to collaborate in 2014 on the analysis of large datasets provided by the company. The aim of the collaboration is to gain better understanding about the dynamical patterns of human interactions, mobility, and the socio-economic structure of the society.

8.1.2. STACC, Skype/Microsoft Labs

Participant: Márton Karsai [correspondant].

The Software Technology and Applications Competence Centre (STACC) is a research and development centre conducting high-priority applied research in the field of data mining and software and services engineering. Together with Skype/Microsoft Labs, STACC maintains a long lasting research collaboration with Márton Karsai (DANTE) on the modelling the adoption dynamics of online services.

8.2. Inria Alcatel-Lucent Bell Labs joint laboratory

Participants: Isabelle Guérin Lassous, Paulo Gonçalves Andrade, Thomas Begin, Éric Fleury [correspondant].

The main scientific objectives of the collaboration within the framework Inria Alcatel-Lucent Bell Labs joint laboratory is focused on network science:

- to design efficient tools for measuring specific properties of large scale complex networks and their dynamics;

- to propose accurate graph and dynamics models (*e.g.*, generators of random graph fulfilling measured properties);
- to use this knowledge with an algorithmic perspectives, for instance, for improving the QoS of routing schemes, the speed of information spreading, the selection of a target audience for advertisements, etc.

8.3. Bilateral Grants with Industry

8.3.1. Orange R&D

Participant: Isabelle Guérin Lassous.

A contract has been signed between Inria and France Télécom for the PhD supervision of Laurent Reynaud. The PhD thesis subject concerns mobility strategies for fault resilience and energy conservation in wireless networks.

9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

9.1.1.1. Equipex FIT (Futur Internet of Things)

Participant: Éric Fleury [correspondant].

FIT is one of 52 winning projects in the Equipex research grant program. It will set up a competitive and innovative experimental facility that brings France to the forefront of Future Internet research. FIT benefits from 5.8Ã¢Â€Â¬Ã… million grant from the French government Running from 22.02.11 – 31.12.2019. The main ambition is to create a first-class facility to promote experimentally driven research and to facilitate the emergence of the Internet of the future.

9.1.1.2. ANR GRAPHSIP (Graph Signal Processing)

Participants: Paulo Gonçalves Andrade [correspondant], Éric Fleury, Thomas Begin, Sarra Ben Alaya, Hadrien Hours.

An increasing number of application areas require the processing of massive datasets. These data can often be represented by graphs in order to encode complex interactions. When data vectors are associated with graph vertices, a so-called graph signal is obtained. The processing of such graph signals includes several open challenges because of the nature of the involved information. Indeed graph theory and signal and image processing methodologies do not combine readily. In particular, such a combination requires new developments, allowing classical signal processing methods to work on irregular grids and non Euclidean spaces. Considering the significant success of classical signal processing tools, it appears essential to generalise their use to graph signals. The GRAPHSIP project aims at developing a set of advanced methods and algorithms for the processing of graph signals: multi-scale transforms and solutions of variational problems on graphs. The major outcomes of this project are expected to lead to significant breakthroughs for graph data processing. The project will also focus on two novel applications on instances of graph signals: brain networks and 3D colour point clouds. They will exemplify and illustrate the proposed methodological advances on emerging applications.

9.1.1.3. ANR INFRA DISCO (DIstributed SDN COntrollers for rich and elastic network services)

Participants: Thomas Begin [correspondant], Anthony Busson, Isabelle Guérin Lassous, Huu Nghi Nguyen.

The DANTE team will explore the way SDN (Software Designed Network) can change network monitoring, control, urbanisation and abstract description of network resources for the optimisation of services. More specifically, the team will address the issues regarding the positioning of SDN controllers within the network, and the implementation of an admission control that can manage IP traffic prioritisation.

9.1.1.4. ANR REFLEXION (REsilient and FLEXible Infrastructure for Open Networking)

Participants: Thomas Begin [correspondant], Anthony Busson, Isabelle Guérin Lassous, Guillaume Artero Gallardo, Zidong Su.

The DANTE team will work on the monitoring of NFV proposing passive and light-weight metrology tools. They will then investigate the modelling of low-level resources consumptions and finally propose methods to dynamically allocate these resources taking into account performance constraints.

9.1.1.5. ANR CONTINT CODDDE

Participants: Éric Fleury [correspondant], Christophe Crespelle, Márton Karsai, Hadrien Hours.

It is a collaborative project between the ComplexNetwork team at LIP6/UPMC; Linkfluence and Inria Dante. The CODDDE project aims at studying critical research issues in the field of real-world complex networks study:

- How do these networks evolve over time?
- How does information spread on these networks?
- How can we detect and predict anomalies in these networks?

In order to answer these questions, an essential feature of complex networks will be exploited: the existence of a community structure among nodes of these networks. Complex networks are indeed composed of densely connected groups of that are loosely connected between themselves.

The CODDE project will therefore propose new community detection algorithms to reflect complex networks evolution, in particular with regards to diffusion phenomena and anomaly detection.

These algorithms and methodology will be applied and validated on a real-world online social network consisting of more than 10 000 blogs and French media collected since 2009 on a daily basis (the dataset comprises all published articles and the links between these articles).

9.1.1.6. ANR SoSweet

Participants: Jean Pierre Chevrot, Éric Fleury, Márton Karsai [correspondant], Jean-Philippe Magué.

The SoSweet project focuses on the synchronic variation and the diachronic evolution of the variety of French used on Twitter. The recent rise of novel digital services opens up new areas of expression which support new linguistics behaviours. In particular, social medias such as Twitter provide channels of communication through which speakers/writers use their language in ways that differ from standard written and oral forms. The result is the emergence of new varieties of languages. The main goal of SoSweet is to provide a detailed account of the links between linguistic variation and social structure in Twitter, both synchronically and diachronically. Through this specific example, and aware of its bias, we aim at providing a more detailed understanding of the dynamic links between individuals, social structure and language variation and change.

9.1.1.7. ANR DylNet

Participants: Jean Pierre Chevrot, Éric Fleury [correspondant], Márton Karsai.

The DylNet project aims to observe and to characterise the relationships between childhood sociability and oral-language learning at kindergarten. With a view to this, it takes an multidisciplinary approach combining work on language acquisition, sociolinguistics, and network science. It will be implemented by following all the children (≈ 150) and teaching staff in one kindergarten over a 3-year period. The use of wireless proximity sensors will enable collection of social contacts throughout the study. The data on sociability will be linked to the results of language tests and recordings of verbal interactions used to follow the childrenâs progress on both a psycholinguistic level (lexicon, syntax, pragmatics) and a sociolinguistic level (features showing belonging to a social group). The aim is to better understand the mechanisms of adaptation and integration at work when young children first come into contact with the school context.

9.2. European Initiatives

9.2.1. FP7 & H2020 Projects

9.2.1.1. EMBERS

Title: Enabling a Mobility Back-End as a Robust Service

Programm: H2020

Duration: December 2015 - November 2018

Coordinator: UPMC

Partners:

Fraunhofer Gesellschaft Zur Forderung Der Angewandten Forschung Ev (Germany)

Technische Universitat Berlin (Germany)

Universite Pierre et Marie Curie - Paris 6 (France)

Ubiwhere Lda (Portugal)

Inria contact: Eric Fleury

EMBERS will bring to market a back-end for smart city mobility that is developed by a European small enterprise based upon its smart parking and smart traffic management products that two municipalities in Portugal currently deploy. The Mobility Back-end as a Service (MBaaS) replaces such all-in-one systems, in which a municipality purchases the full set of components from a single vendor. Instead, the city manager can purchase best-of-breed devices and apps developed by third parties, with the only constraint being that they interoperate with the back-end via a free, open, smart city mobility API. This domain-specific API lowers barriers to entry for app and device developers, making it easier for innovative SMEs to enter the market. Furthermore, the API is offered via a variety of generic interfaces, including oneM2M, ETSI M2M, OMA LWM2M, and FIWARE NGSI. EMBERS thus clears the way for developers and to municipalities that have adopted any one of these potential emerging machine-to-machine (M2M) communication standards. Beyond its primary goal of bringing the MBaaS to market, EMBERS will stimulate development of an entire ecosystem around the MBaaS smart city mobility API. Separating out the back-end from the other components will, however, require rigorous testing. EMBERS will experiment with the system on two testbeds that are part of the FIRE OneLab facility: the FUSECO Playground, for M2M communications, and FIT IoT-LAB, for wireless sensor devices. EMBERS will host a hackathon and an app challenge to bring in third party developers. The project will also include three demonstrators by third parties via an open call. These activities will contribute back to FIRE by demonstrating successful experimentation by SMEs developing close-to-market products. The project will also conduct real world pilots in two or more cities as a final step in bringing the MBaaS to market.

9.2.1.2. ARMOUR

Title: Large-Scale Experiments of IoT Security & Trust (Project nÂ°688237)

Programm: H2020

Duration: 2015 Dec to 2018

Coordinator: UPMC

Partners:

Synelixis Lyseis Pliroforikis Automatismou & Tilepikoinonion Monoprosopi EPE (Greece)

Smartesting Solutions & Services (France)

Unparallel Innovation, Lda (Portugal)

Easy Global Market (France)

ODIN Solutions (Spain)

Universite Pierre et Marie Curie - Paris 6 (France)

Inria contact: Eric Fleury

ARMOUR will provide duly tested, benchmarked and certified Security & Trust solutions for large-scale IoT using upgraded FIRE large-scale IoT/Cloud testbeds properly-equipped for Security & Trust experimentations. ARMOUR takes the top large-scale FIT IoT-LAB testbed â a FIRE OpenLAB / FIT IoT LAB facility â and enhances it as to enable experimentally-driven research on a key research dimension: large-scale IoT Security & Trust. Presently, no proper installations exist to experiment IoT Security & Trust on large-scale conditions; ARMOUR will develop and install such capability.

9.3. International Initiatives

9.3.1. Inria International Partners

9.3.1.1. Declared Inria International Partners

Taiwan, ACADEMIA SINICA & IIIS. Signature of a MoU in the framework of IoT-LAB.

Algorithms research group of the University of Bergen, Norway. PICS project of CNRS on graph editing problems for analysis and modeling of complex networks.

9.3.1.2. Informal International Partners

University of Namur: Department of Mathematics/Naxys (Belgium). Collaboration with Renaud Lambiotte on dynamical processes on dynamical networks and communities detections.

Aalto University: Department of Biomedical Engineering and Computational Science (Finland). Collaboration with Jari Saramaki on modeling temporal networks and community like modular structure

Central European University (Hungary). Collaboration with János Kertész on modeling complex contagion phenomena.

ISI Foundation (Italy). Collaboration with Laetitia Gauvin on multiplex networks and transportation systems

University of South California (USA). Collaboration with Antonio Ortega on Graph Signal Processing

University of Pennsylvania (USA). Collaboration with Alejandro Ribeiro on Graph Signal Processing

LNCC, Petropolis (Brazil). Collaboration with Arthur Ziviani on Temporal Graph modeling ans algorithms.

College of Information and Computer Sciences at the University of Massachusetts Amherst.

University of California, Santa Cruz (USA). Collaboration with Alexandre Brandwajn on the solutions to multi-server queues.

9.3.2. Participation in Other International Programs

9.3.2.1. PHC Peridot

Participants: Mohammed Amer, Thomas Begin, Anthony Busson, Isabelle Guérin Lassous.

Framework for Control and Monitoring of Wireless Mesh Networks (WMN) using Software-Defined Networking (SDN). The main objective of this project is propose mechanisms and modifications in the SDN architecture, specifically in the OpenFlow, which allow SDN mechanisms to operate over WMN considering the dynamic network topology that WMN may experience and some other relevant characteristics. The project will involve devising mechanisms for controlling mesh switches through controllers in a wireless environment, which will require developing novel and WMN-specific rules, actions and commands. The project will involve proposing mechanism that consider dynamic environment of WMN along with providing redundancy in the network. Besides, there is a requirement to have an adaptive measurement API for WMN. This is the second objective of our research project. The proposed measurement API will enable the network operators to monitor network traffic over WMN which may be content-specific or host-specific. This is a joint project between DANTE and M. A. Jinnah University, Islamabad. It started in June 2015 and will end in June 2018.

9.3.2.2. STIC AMSUD UCOOL: Understanding and predicting human demanded COntent and mObiLity

Participants: Éric Fleury, Márton Karsai, Christophe Crespelle.

Finding new ways to manage the increased data usage and to improve the level of service required by the new wave of applications for smartphones is an essential issue nowadays. The improved understanding of user mobility (i.e. the context they experience) and the content they demand is of fundamental importance when looking for solutions for this problem in the modern communication landscape. The resulting knowledge can help at the design of more adaptable networking protocols or services as well as can help determining, for instance, where to deploy networking infrastructure, how to reduce traffic congestion, or how to fill the gap between the capacity granted by the infrastructure technology and the traffic load generated by mobile users.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

Jacob Eisenstein

Date: May 2016

Institution: Georgia Tech (USA)

Alfred Hero

Date: May 2016

Institution: University of Michigan (USA)

Kimmo Kaski

Date: May 2016

Institution: Aalto University (Finland)

Nicola Perra

Date: June 2016

Institution:Greenwich University (England)

Alejandro Ribeiro

Date: June 2016

University of Pennsylvania (US)

János Kertész

Date: June-July 2016

Central European University (Hungary)

9.4.2. Visits to International Teams

9.4.2.1. Sabbatical programme

Begin Thomas

Date: Sep 2015 - Aug 2016

Institution: DIVA lab – University of Ottawa (Canada) on a CNRS grant and Inria sabbatical grant.

Christophe Crespelle

Date: Sep 2015 - Aug 2016

Institution: Institute of Mathematics, Vietnam Academy of Science and Technology, Hanoi (Vietnam) on a CNRS grant.

9.4.2.2. Research Stays Abroad

- Márton Karsai stayed 1 month at Aalto University Espoo, Finland
- Christophe Crespelle stayed 2 weeks at University of Bergen, Norway

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

- Jean Pierre Chevrot, Éric Fleury, Márton Karsai, Jean-Philippe Magué were scientific chairs of the Workshop on Data Driven Approach to Networks and Language.
- Éric Fleury, Márton Karsai and Paulo Gonąlves were scientific chairs of the Workshop on Processes On and Of Networks.

10.1.1.2. Member of the Organizing Committees

- Éric Fleury, Mátrton Karsai and Laetitia Lecot were on the Organizing committee for the Network Science Thematic Semester
- Márton Karsai was in the organising committee of Computational Social Science: from social contagion to collective behaviour ECCS 2016 Satellite.

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

- Isabelle Guérin Lassous was the general chair of ACM PE-WASUN 2016.
- Márton Karsai was the one of the program chairs of the conferences Do2Net, ComplexNetworks2016, D2NetLang, CSS2016.

10.1.2.2. Member of the Conference Program Committees

- Éric Fleury was on the PC of the conference ComplexNet, of the Conference on Complex Networks: From Theory to Interdisciplinary Applications, SensorNet 2017 and CoRes 2016.
- Márton Karsai was on the PC of the conferences NetSci-X 2016, IC2S2 2016, CompleNet 2016, WebSci16, Do2Net, AlgoTel 2016, ComplexNetworks2016, D2NetLang 2016, DyNo 2016 IEEE/ACM ASONAM 2016, CCS 2016, SocInfo 2016, CSS 2016, Contagion'16, COMPLEX NETWORKS 2016
- Isabelle Guérin Lassous was on the PC of: ACM MSWiM 2016, ICC 2016, Globecom 2016, ISCC 2016 and MedHocNet 2016.
- Thomas Begin was on the PC of: IEEE LCN 2016.
- Christophe Crespelle was on the PC of WG 2016.

10.1.2.3. Reviewer

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- Isabelle Guérin Lassous is member of the editorial boards of Computer Communications (Elsevier), Ad Hoc Networks (Elsevier) and Discrete Mathematics & Computer Science.
- Anthony Busson is member of the editorial boards of Computer Communications (Elsevier).
- Márton Karsai is member of the editorial boards of Advances in Complex Systems (World Scientific).
- Jean Pierre Chevrot, K. Drager (U. of Hawaii), P. Foulkes (U. of York) are the chief editors of a special issue in the journal TopiCS in Cognitive Science on the theme "Sociolinguistic variation and cognitive science, coordination".
- Philippe Nain is Editor-in-Chief of Performance Evaluation (Elsevier)

10.1.3.2. Reviewer - Reviewing Activities

- Márton Karsai was acting as reviewer for the journals of Nature Communications, PNAS, PRL, PRX, PRE, Scientific Reports, EPJ Data Science, SNAM, EPL, EPJ B, PLoS One, Journal of Statistical Mechanics, Physics Letter A, Advanced in Complex Systems, Journal of Physics: Condensed Matter, Complex Networks, New Journal of Physics, Physica Scripta, Network Science,
- Jean-Pierre Chevrot was acting as reviewer for he journal Animal Behavior.

10.1.4. Invited Talks

- Márton Karsai gave invited talks at NetSciX'16 (January 2016, Wroclaw, Poland), Workshop on mechanisms underlying local to global signals in networks (19 May 2016, Lyon, France), HOMS NetSci'16 Satellite (30 May 2016, Seoul, Korea), Social Connectome NetSci'16 Satellite (30 May 2016, Seoul, Korea), SocioNet'16 workshop ENS Lyon (8 June 2016, Lyon, France), Coarse-graining of Complex Systems CCS'16 Satellite (21 September 2016, Amsterdam, The Netherlands), BURSTINESS in human behaviour and other natural phenomena, CCSÃ16 Satellite (21 September 2016, Amsterdam, The Netherlands), PhD course on Network Science (guest lecturer) Uppsala University, Department of Information Technology (18 November 2016, Uppsala, Sweden).
- Éric Fleury gave a invited talk at ISI foundation, Torino Italy and SocioNet'16 workshop ENS Lyon (8 June 2016, Lyon, France).
- Thomas Begin gave an invited talk at Diva Lab, University of Ottawa, Canada.
- Jean Pierre Chevrot gave two invited talks Ã the University of Oslo (Norway) at the Workshop Bridging gaps: Conceptual and epistemological approaches, Center for Multilingualism in Society across the Lifespan (MultiLing)
- Christophe Crespelle gave an invited talk at the Vietnam Institute for Advanced Studies in Mathematics, Hanoi, and the University of Bergen, Norway.

10.1.5. Leadership within the Scientific Community

10.1.6. Scientific Expertise

- Isabelle Guérin Lassous is a member of the research committee of the Milyon labex.
- Isabelle Guérin Lassous was a member of the HCERES evaluation committee of the IRISA laboratory.
- Isabelle Guérin Lassous is vice-chair of the HCERES evaluation committee of the LORIA laboratory.
- Isabelle Guérin Lassous was a member of the National Committee of the CNRS, section 06.
- Éric Fleury is member of the Inria senior research position (DR2) jury and junior research position (CR2/CR1)
- Éric Fleury has been an expert for the Fund for Scientific Research - FNRS.
- Éric Fleury has been a member of evaluation panels as part of the French National Research Agencyâs (ANR) for ANR.
- Éric Fleury is member of the Inria Evaluation Committee.
- Éric Fleury is Co-chair of the Networking group ResCom of the CNRS GDR ASR. He is also a member of the scientific committee of the GDR ASR.
- Márton Karsai was reviewer for ANR, H2020 FET Open RIA.
- Philippe Nain is the coordinator of the "Strategic Technology Monitoring & Prospective Studies Inria Unit".
- Jean-Pierre Chevrot reviewed a ten-year track application for the University of New Mexico (UNM, US)

10.1.7. Research Administration

- Paulo Gonçalves is scientific liaison officer for international relations in Inria Research Centre of Rhône-Alpes.
- Paulo Gonçalves was scientific correspondent of the International Relations for the Computer Science Department at ENS Lyon. Responsibility ended in September 2016.
- Paulo Gonçalves is a member of the executive committee of the Milyon labex and referent for its valorisation committee.
- Christophe Crespelle is member of the steering committee of the IXXI - Rhône-Alpes Complex Systems Institute.
- Isabelle Guérin Lassous is vice-chair of the LIP laboratory.
- Isabelle Guérin Lassous is member of the department council of the Computer Science department of Université Lyon 1.
- Anthony Busson is Vice-president of the Thesis Commission at LIP.
- Anthony Busson is member of the committee of “Ecole Doctorale” 512 in computer science and mathematics.
- Éric Fleury is Deputy Scientific Delegate for Inria Grenoble Rhône Alpes
- Éric Fleury is in the in the Executive Committee of the IXXI â Rhône-Alpes Complex Systems Institute.
- Éric Fleury is member of the Council of the LIP laboratory.
- Éric Fleury is a member of the executive committee of the Milyon labex.
- Anthony Busson is the vice president of the thesis committee of the LIP laboratory.
- Thomas Begin is an elected member of the Council of the LIP laboratory.
- Jean Pierre Chevrot is member of the steering committee of the IXXI - Rhône-Alpes Complex Systems Institute.
- Márton Karsai is the co-responsible for the M2 master program in Modelling of Complex Systems at ENS Lyon
- Márton Karsai is the elected council member of the Complex System Society (2015-)
- Márton Karsai is the elected member of the steering committee of the IXXI Complex System Institute (2016-)

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

10.2.1.1. Teaching by Éric Fleury

Éric Fleury is Professor at the Computer Science department of ENS de Lyon and holds a Inria chair.

Master: CR15 - Complex Networks, 18H, M2, ENS de Lyon, France

10.2.1.2. Teaching by Márton Karsai

Márton Karsai is Associate Professor at the Computer Science department of ENS de Lyon and holds a Inria chair.

Master: CR15 - Complex Networks, 21H, M2, ENS de Lyon, France

Master: Dynamical Processes on Networks, 6H, M2, ENS de Lyon, France

Master: Modeling Social Systems, 9H, M2, ENS de Lyon, France

Master: Complex Networks 16H, Collegio Carlo Alberto, Torino Italy (guest lecturer)

10.2.1.3. Teaching by Paulo Gonçalves

Engineering school CPE-Lyon (years 3-5): Signal Processing (80 hours/yr)

10.2.1.4. Teaching by Isabelle Guérin Lassous

Professor at Université Claude Bernard Lyon 1 in the Computer Science department since 2006. She lectures at the University.

Master: "Networking", 20h, Master (M1), University Lyon 1, France

Master: "QoS and Multimedia Networks", 30h, Master (M2), University Lyon 1, France

Master: "Wireless Networks", 15h, Master (M2), University Lyon 1, France

Master: "Introduction to Networking", 30h, Master (M2), University Lyon 1, France

10.2.1.5. Teaching by Anthony Busson

Professor at the IUT (Institut Universitaire de Technologie) of Université Claude Bernard Lyon 1 in the computer science department since 2012.

Master: "MPLS", 6h, Master (M2), University Lyon 1, France

DUT: full service (192h) in networking, opertaing-systems, and programmation.

10.2.1.6. Teaching by Thomas Begin

Assistant Professor at Université Claude Bernard Lyon 1 in the Computer Science department since 2009.

Master: "Networking", 20h, Master (M1), University Lyon 1, France

Master: "Advanced networks", 20h, Master (M2 SRIV), University Lyon 1, France

Master: "Computer networks", 20h, Bachelor (L3), University Lyon 1, France

Master: "Introduction to Networking", 30h, Master (M2 CCI), University Lyon 1, France

Master: "Distributed systems", 10h, Master (M1), University Lyon 1, France

10.2.1.7. Teaching by Christophe Crespelle

Assistant Professor at Université Claude Bernard Lyon 1 in the Computer Science department since 2009.

Master: "Complex networks", 15h, Master (M2), ENS de Lyon, France

Master: "Introduction to Computer Science", 30h, Master (M2), ENS de Lyon, France

Bachelor: "Combinatorial Optimisation", 18h, Bachelor (4th year), Vietnam National University in Hanoi, Vietnam

10.2.1.8. Teaching by Philippe Nain

University of Massachusetts at Amherst: graduate course on "Performance Modelling of Communication Networks and Distributed Systems" (32 hours).

10.2.2. Supervision

PhD defense: Yannick Léo, Deep dive into social network and economic data: a data driven approach for uncovering temporal ties, human mobility and socioeconomic correlations, ENS de Lyon, Dec 2016, Éric Fleury, Christophe Crespelle and Márton Karsai.

PhD in progress: Sarra Ben Alaya, Multi-scale classification and analysis of data on networks. Nov. 2015, P. Gonçalves (P. Borgnat, co-advisor)

PhD in progress: Esteban Bautista Ruiz, Statistical Graph Signal Processing. P. Gonçalves (P. Abry, co-advisor). Started Sept. 1st, 2016.

PhD in progress: Laurent Reynaud, Optimised mobility strategies for wireless networks. March 2013, I. Guérin Lassous

PhD in progress: Huu-Nghi Nguyen, Admission control in SDN networks. April 2014, T. Begin and A. Busson and I. Guérin Lassous

PhD in progress: Mohammed Amer, WiFi network management: a SDN approach. January 2015, A. Busson and I. Guérin Lassous

PhD in progress: Matteo Morini, New tools for understanding the dynamics of social networks, Oct 2013, E. Fleury, P. Jensen and M. Karsai

PhD in progress: Samuel Unicomb, Spreading processes on temporal networks, Oct 2016, E. Fleury and M. Karsai

PhD in progress: Jacobo Levy Abitbol, Information diffusion and language evolution on dynamical social networks, Oct 2016, E. Fleury and M. Karsai

PhD in progress: Marija Stojanova, Performance Modelling of IEEE 802.11 networks , Oct 2016, T. Begin

PhD in progress: Imen Achour, Data Dissemination Protocols for Vehicular Ad hoc Networks, informal supervising by A. Busson with T. Bejaoui and S. Tabbane (Supcom - Tunis)

10.2.3. Juries

- Isabelle Guérin Lassous was a member of the HDR examination boards of Christoph Neumann at Technicolor/Université de Rennes 1 and Frédéric Le Mouël at INSA de Lyon.
- Isabelle Guérin Lassous was a member of the Ph.D thesis examination board of Guillaume Gaillard at INSA de Lyon.
- Éric Fleury was member and reviewer of the HdR examination board of Tommasso Venturini at ENS de Lyon.
- Éric Fleury was president of the PhD examination boards of Michal Krol at UGA.
- Anthony Busson was member of the PhD examination boards of Lyad Cherif at Université Paris XI. December 2016.
- Anthony Busson was member of the PhD examination boards of Saiefeddine Bouallegue at Sup'Com / University of Carthage. June 2016.
- Anthony Busson was member of the mid-term examination boards for the PhD of Tu Lam Thanh at Supélèc. November 2016.

11. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] Y. LÉO.*Deep dive into social network and economic data: a data driven approach for uncovering temporal ties, human mobility, and socioeconomic correlations*, ENS de Lyon, December 2016, https://hal.inria.fr/tel-01429593.

Articles in International Peer-Reviewed Journal

[2] T. ATMACA, T. BEGIN, A. BRANDWAJN, H. CASTEL-TALEB.*Performance Evaluation of Cloud Computing Centers with General Arrivals and Service*, in "IEEE Transactions on Parallel and Distributed Systems", August 2016, vol. 27, n^{o} 8, p. 2341 - 2348 [*DOI :* 10.1109/TPDS.2015.2499749], https://hal.archives-ouvertes.fr/hal-01241713.

[3] T. BEGIN, B. BAYNAT, I. GUÉRIN LASSOUS, T. ABREU.*Performance analysis of multi-hop flows in IEEE 802.11 networks: A flexible and accurate modeling framework*, in "Performance Evaluation", February 2016, vol. 96, p. 12–32 [*DOI :* 10.1016/J.PEVA.2015.12.003], https://hal.archives-ouvertes.fr/hal-01246822.

[4] A. BRANDWAJN, T. BEGIN.*Breaking the dimensionality curse in multi-server queues*, in "Computers and Operations Research", 2016 [*DOI :* 10.1016/J.COR.2016.04.011], https://hal.inria.fr/hal-01322249.

[5] C. CRESPELLE, T.-N. LE, K. PERROT, T. H. D. PHAN.*Linearity is Strictly More Powerful than Contiguity for Encoding Graphs*, in "Discrete Mathematics", 2016, vol. 339, n^{o} 8, p. 2168-2177, https://hal.archives-ouvertes.fr/hal-01424428.

[6] S. GUHA, D. TOWSLEY, P. NAIN, C. CAPAR, A. SWAMI, P. BASU.*Spanning connectivity in a multilayer network and its relationship to site-bond percolation*, in "Physical Review E ", June 2016, https://hal.inria.fr/hal-01257188.

[7] I. GUÉRIN LASSOUS, L. REYNAUD.*Design of a force-based controlled mobility on aerial vehicles for pest management*, in "Elsevier Ad Hoc Networks", 2016, vol. 53, https://hal.inria.fr/hal-01427874.

[8] M. KARSAI, G. IÑIGUEZ, R. KIKAS, K. KASKI, J. KERTÉSZ.*Local cascades induced global contagion: How heterogeneous thresholds, exogenous effects, and unconcerned behaviour govern online adoption spreading*, in "Scientific Reports", June 2016, vol. 6, 27178 [*DOI :* 10.1038/SREP27178], https://hal.inria.fr/hal-01403282.

[9] A. L. LAURA, M. KARSAI, L. GAUVIN.*User-based representation of time-resolved multimodal public transportation networks*, in "Royal Society Open Science", July 2016, vol. 3, 160156 [*DOI :* 10.1098/RSOS.160156], https://hal.inria.fr/hal-01249860.

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[13] M. MORINI, P. SIMONE.*Personal Income Tax Reforms: A Genetic Algorithm Approach*, in "European Journal of Operational Research", August 2016 [*DOI :* 10.1016/J.EJOR.2016.07.059], https://hal.inria.fr/hal-01388958.

[14] P. NAIN, D. TOWSLEY.*File dissemination in dynamic graphs: The case of independent and correlated links in series*, in "ACM Transactions on Modeling and Performance Evaluation of Computing Systems", November 2016, vol. 2, n^{o} 1 [*DOI :* 10.1145/2981344], https://hal.inria.fr/hal-01266505.

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Invited Conferences

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[20] H.-N. NGUYEN, T. BEGIN, A. BUSSON, I. GUÉRIN LASSOUS.*Approximating the end-to-end delay using local measurements: a preliminary study based on conditional expectation*, in "IEEE 3rd International Symposium on Networks, Computers and Communications, ISNCC", Hammamet, Tunisia, May 2016, https://hal.archives-ouvertes.fr/hal-01387732.

International Conferences with Proceedings

[21] I. ACHOUR, T. BEJAOUI, A. BUSSON, S. TABBANE.*Delay-based strategy for safety message dissemination in Vehicular Ad hoc NETworks: Slotted or continuous?*, in "IWCMC 2016 - International Conference on Wireless Communications and Mobile Computing", Cyprus, Cyprus, September 2016, p. 268 - 274 [*DOI :* 10.1109/IWCMC.2016.7577069], https://hal.inria.fr/hal-01378827.

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Team DATAMOVE

Data Aware Large Scale Computing

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Distributed and High Performance Computing

Table of contents

Team DATAMOVE

Creation of the Team: 2016 January 01

Keywords:

Computer Science and Digital Science:

1.1.4. - High performance computing
1.1.5. - Exascale
2.1.10. - Domain-specific languages
2.6.2. - Middleware
7.1. - Parallel and distributed algorithms

Other Research Topics and Application Domains:

1.1.2. - Molecular biology
5.5. - Materials

The DataMove team is localized in the Imag building on the Campus of Univ. Grenoble Alpes.

1. Members

Research Scientist

Bruno Raffin [Team leader, Inria, Senior Researcher, Research Scientist, HDR]

Faculty Members

Yves Denneulin [Grenoble-INP, Faculty Member, Professor]
Pierre Francois Dutot [Univ. Grenoble-Alpes, Faculty Member, Associate Professor]
Gregory Mounie [Grenoble-INP, Faculty Member, Associate Professor]
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Tristan Ezequel [Inria]
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Pierre Neyron [CNRS]
Baptiste Pichot [Inria]
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PhD Students

Marcos Amaris Gonzalez [USP, until Oct 2016]
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Estelle Dirand [CEA]
Mohammed Khatiri [partly Inria]
Alessandro Kraemer [Federal Technological University of Paraná]
Fernando Machado Mendonca [USP]
Michael Mercier [ATOS/BULL, granted by CIFRE]
Millian Poquet [Univ. Grenoble-Alpes]
Valentin Reis [Grenoble-Alpes]
Marwa Sridi [CEA, until Apr 2016]
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Julio Toss [UFRGS]
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Giorgio Lucarelli [Inria, until Oct 2017]

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Sirine Marakchi [ISBS SFAX, Jan 2016]
Wafa Nafti [ESSTT, until May 2016]
Ioannis Milis [Athens UEB, June 2016]
Katrin Scharnowski [University of Stuttgart, from May 2016 until Aug 2016]

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Bruno Bzeznik [Univ. Grenoble-Alpes]
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Luis Omar Alvarez Mures [Inria, Student, from March 2016 until Mai 2016]
Clement Mommessin [Inria, Student, from Feb 2016 until Dec 2016]
Waqas Imtiaz [Inria,Student, from Feb 2016 until Jun 2016]
Matthias Kohl [Inria, Student, from Feb 2016 until Jun 2016]
Thomas Lavocat [Inria, Student, from Feb 2016 until Aug 2016]
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Mohamed Dyab [Inria, Student, from Feb 2016 until Sep 2016]
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Jad Darrous [Inria, Student, from Feb 2016 until June 2016]

2. Overall Objectives

2.1. Overall Objectives

Moving data on large supercomputers is becoming a major performance bottleneck, and the situation is expected to worsen even more at exascale and beyond. Data transfer capabilities are growing at a slower rate than processing power ones. The profusion of flops available will be difficult to use efficiently due to constrained communication capabilities. Moving data is also an important source of power consumption. The DataMove team focuses on **data aware large scale computing**, investigating approaches to reduce data movements on large scale HPC machines. We will investigate data aware scheduling algorithms for job management systems. The growing cost of data movements requires adapted scheduling policies able to take into account the influence of intra-application communications, IOs as well as contention caused by data traffic generated by other concurrent applications. At the same time experimenting new scheduling policies on real platforms is unfeasible. Simulation tools are required to probe novel scheduling policies. Our goal is to investigate how to extract information from actual compute centers traces in order to replay job allocations and executions with new scheduling policies. Schedulers need information about the jobs behavior on the target machine to actually make efficient allocation decisions. We will research approaches relying on learning techniques applied to execution traces to extract data and forecast job behaviors. In addition to traditional computation intensive numerical simulations, HPC platforms also need to execute more and more often data intensive processing tasks like data analysis. In particular, the ever growing amount of data generated by numerical simulation calls for a tighter integration between the simulation and the data analysis. The goal is to reduce the data traffic and to speed-up result analysis by processing results in situ, i.e. as closely as possible to the locus and time of data generation. Our goal is here to investigate how to program and schedule such analysis workflows in the HPC context, requiring the development of adapted resource sharing strategies, data structures and parallel analytics schemes. To tackle these issues, we will intertwine theoretical research and practical developments to elaborate solutions generic and effective enough to be of practical interest. Algorithms with performance guarantees will be designed and experimented on large scale platforms with realistic usage scenarios developed with partner scientists or based on logs of the biggest available computing platforms. Conversely, our strong experimental expertise will enable to feed theoretical models with sound hypotheses, to twist proven algorithms with practical heuristics that could be further retro-feeded into adequate theoretical models.

3. Research Program

3.1. Motivation

Today's largest supercomputers [0] are composed of few millions of cores, with performances almost reaching 100 PetaFlops [0] for the largest machine. Moving data in such large supercomputers is becoming a major performance bottleneck, and the situation is expected to worsen even more at exascale and beyond. The data transfer capabilities are growing at a slower rate than processing power ones. The profusion of available flops will very likely be underused due to constrained communication capabilities. It is commonly admitted that data movements account for 50% to 70% of the global power consumption [0]. Thus, data movements are potentially one of the most important source of savings for enabling supercomputers to stay in the commonly adopted energy barrier of 20 MegaWatts. In the mid to long term, non volatile memory (NVRAM) is expected to deeply change the machine I/Os. Data distribution will shift from disk arrays with an access time often considered as uniform, towards permanent storage capabilities at each node of the machine, making data locality an even more prevalent paradigm.

The DataMove team works on **optimizing data movements for large scale computing** mainly at two related levels:

- Resource allocation
- Integration of numerical simulation and data analysis

The resource and job management system (also called batch scheduler or RJMS) is in charge of allocating resources upon user requests for executing their parallel applications. The growing cost of data movements requires adapted scheduling policies able to take into account the influence of intra-application communications, I/Os as well as contention caused by data traffic generated by other concurrent applications. Modelling the application behavior to anticipate its actual resource usage on such architecture is known to be challenging, but it becomes critical for improving performances (execution time, energy, or any other relevant objective). The job management system also needs to handle new types of workloads: high performance platforms now need to execute more and more often data intensive processing tasks like data analysis in addition to traditional computation intensive numerical simulations. In particular, the ever growing amount of data generated by numerical simulation calls for a tighter integration between the simulation and the data analysis. The challenge here is to reduce data traffic and to speed-up result analysis by performing result processing (compression, indexation, analysis, visualization, etc.) as closely as possible to the locus and time of data generation. This emerging trend called *in situ analytics* requires to revisit the traditional workflow (loop of batch processing followed by postmortem analysis). The application becomes a whole including the simulation, in situ processing and I/Os. This motivates the development of new well-adapted resource sharing strategies, data structures and parallel analytics schemes to efficiently interleave the different components of the application and globally improve the performance.

[0] Top500 Ranking, http://www.top500.org
[0] 10^{15} floating point operations per second
[0] SciDAC Review, 2010, http://www.scidacreview.org/1001/pdf/hardware.pdf

3.2. Strategy

DataMove targets HPC (High Performance Computing) at Exascale. But such machines and the associated applications are expected to be available only in 5 to 10 years. Meanwhile, we expect to see a growing number of petaflop machines to answer the needs for advanced numerical simulations. A sustainable exploitation of these petaflop machines is a real and hard challenge that we address. We may also see in the coming years a convergence between HPC and Big Data, HPC platforms becoming more elastic and supporting Big Data jobs, or HPC applications being more commonly executed on cloud like architectures. This is the second top objective of the 2015 US Strategic Computing Initiative [0]: *Increasing coherence between the technology base used for modelling and simulation and that used for data analytic computing*. We contribute to that convergence at our level, considering more dynamic and versatile target platforms and types of workloads.

Our approaches should entail minimal modifications on the code of numerical simulations. Often large scale numerical simulations are complex domain specific codes with a long life span. We assume these codes as being sufficiently optimized. We influence the behavior of numerical simulations through resource allocation at the job management system level or when interleaving them with analytics code.

To tackle these issues, we propose to intertwine theoretical research and practical developments in an agile mode. Algorithms with performance guarantees are designed and experimented on large scale platforms with realistic usage scenarios developed with partner scientists or based on logs of the biggest available computing platforms (national supercomputers like Curie, or the BlueWaters machine accessible through our collaboration with Argonne National Lab). Conversely, a strong experimental expertise enables to feed theoretical models with sound hypotheses, to twist proven algorithms with practical heuristics that could be further retro-feeded into adequate theoretical models.

A central scientific question is to make the relevant choices for optimizing performance (in a broad sense) in a reasonable time. HPC architectures and applications are increasingly complex systems (heterogeneity, dynamicity, uncertainties), which leads to consider the **optimization of resource allocation based on multiple objectives**, often contradictory (like energy and run-time for instance). Focusing on the optimization of one particular objective usually leads to worsen the others. The historical positioning of some members of the team who are specialists in multi-objective optimization is to generate a (limited) set of trade-off configurations, called *Pareto points*, and choose when required the most suitable trade-off between all the objectives. This methodology differs from the classical approaches, which simplify the problem into a single objective one (focus on a particular objective, combining the various objectives or agglomerate them). The real challenge is thus to combine algorithmic techniques to account for this diversity while guaranteeing a target efficiency for all the various objectives.

The DataMove team aims to elaborate generic and effective solutions of practical interest. We make our new algorithms accessible through the team flagship software tools, **the OAR batch scheduler and the in situ processing framework FlowVR**. We maintain and enforce strong links with teams closely connected with large architecture design and operation, as well as scientists of other disciplines, in particular computational biologists, with whom we elaborate and validate new usage scenarios.

3.3. Research Directions

DataMove targets HPC (High Performance Computing) at Exascale. But such machines and the associated applications are expected to be available only in 5 to 10 years. Meanwhile, we expect to see a growing number of petaflop machines to answer the needs for advanced numerical simulations. A sustainable exploitation of these petaflop machines is a real and hard challenge that we address. We may also see in the coming years a convergence between HPC and Big Data, HPC platforms becoming more elastic and supporting Big Data jobs, or HPC applications being more commonly executed on cloud like architectures. This is the second top objective of the 2015 US Strategic Computing Initiative [0]: *Increasing coherence between the technology*

[0] https://www.whitehouse.gov/the-press-office/2015/07/29/executive-order-creating-national-strategic-computing-initiative
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4. Application Domains

4.1. Data Aware Batch Scheduling

Large scale high performance computing platforms are becoming increasingly complex. Determining efficient allocation and scheduling strategies that can adapt to technological evolutions is a strategic and difficult challenge. We are interested in scheduling jobs in hierarchical and heterogeneous large scale platforms. On such platforms, application developers typically submit their jobs in centralized waiting queues. The job management system aims at determining a suitable allocation for the jobs, which all compete against each other for the available computing resources. Performances are measured using different classical metrics like maximum completion time or slowdown. Current systems make use of very simple (but fast) algorithms that however rely on simplistic platform and execution models, and thus, have limited performances.

For all target scheduling problems we aim to provide both theoretical analysis and complementary analysis through simulations. Achieving meaningful results will require strong improvements on existing models (on power for example) and the design of new approximation algorithms with various objectives such as stretch, reliability, throughput or energy consumption, while keeping in focus the need for a low-degree polynomial complexity.

4.1.1. Status of Current Algorithms

The most common batch scheduling policy is to consider the jobs according to the First Come First Served order (FCFS) with backfilling (BF). BF is the most widely used policy due to its easy and robust implementation and known benefits such as high system utilization. It is well-known that this strategy does not optimize any sophisticated function, but it is simple to implement and it guarantees that there is no starvation (i.e. every job will be scheduled at some moment).

More advanced algorithms are seldom used on production platforms due to both the gap between theoretical models and practical systems and speed constraints. When looking at theoretical scheduling problems, the generally accepted goal is to provide polynomial algorithms (in the number of submitted jobs and the number of involved computing units). However, with millions of processing cores where every process and data transfer have to be individually scheduled, polynomial algorithms are prohibitive as soon as the polynomial degree is too large. The model of *parallel tasks* simplifies this problem by bundling many threads and communications into single boxes, either rigid, rectangular or malleable. Especially malleable tasks capture the dynamicity of the execution. Yet these models are ill-adapted to heterogeneous platforms, as the running time depends on more than simply the number of allotted resources, and some of the common underlying assumptions on the speed-up functions (such as monotony or concavity) are most often only partially verified.

In practice, the job execution times depend on their allocation (due to communication interferences and heterogeneity in both computation and communication), while theoretical models of parallel jobs usually consider jobs as black boxes with a fixed (maximum) execution time. Though interesting and powerful, the classical models (namely, synchronous PRAM model, delay, LogP) and their variants (such as hierarchical delay), are not well-suited to large scale parallelism on platforms where the cost of moving data is significant, non uniform and may change over time. Recent studies are still refining such models in order to take into account communication contentions more accurately while remaining tractable enough to provide a useful tool for algorithm design.

Today, all algorithms in use in production systems are oblivious to communications. One of our main goals is to **design a new generation of scheduling algorithms fitting more closely job schedules according to platform topologies**.

4.1.2. Locality Aware Allocations

Recently, we developed modifications of the standard back-filling algorithm taking into account platform topologies. The proposed algorithms take into account locality and contiguity in order to hide communication patterns within parallel tasks. The main result here is to establish good lower bounds and small approximation ratios for policies respecting the locality constraints. The algorithms work in an online fashion, improving the global behavior of the system while still keeping a low running time. These improvements rely mainly on our past experience in designing approximation algorithms. Instead of relying on complex networking models and communication patterns for estimating execution times, the communications are disconnected from the execution time. Then, the scheduling problem leads to a trade-off: optimizing locality of communications on one side and a performance objective (like the makespan or stretch) on the other side.

In the perspective of taking care of locality, other ongoing works include the study of schedulers for platforms whose interconnection network is a static structured topology (like the 3D-torus of the BlueWaters platform we work on in collaboration with the Argonne National Laboratory). One main characteristic of this 3D-torus platform is to provide I/O nodes at specific locations in the topology. Applications generate and access specific data and are thus bounded to specific I/O nodes. Resource allocations are constrained in a strong and unusual way. This problem is close for actual hierarchical platforms. The scheduler needs to compute a schedule such that I/O nodes requirements are filled for each application while at the same time avoiding communication interferences. Moreover, extra constraints can arise for applications requiring accelerators that are gathered on the nodes at the edge of the network topology.

While current results are encouraging, they are however limited in performance by the low amount of information available to the scheduler. We look forward to extend ongoing work by progressively increasing application and network knowledge (by technical mechanisms like profiling or monitoring or by more sophisticated methods like learning). It is also important to anticipate on application resource usage in terms of compute units, memory as well as network and I/Os to efficiently schedule a mix of applications with different profiles. For instance, a simple solution is to partition the jobs as "communication intensive" or "low communications". Such a tag could be achieved by the users them selves or obtained by learning techniques. We could then schedule low communications jobs using leftover spaces while taking care of high communication jobs. More sophisticated options are possible, for instance those that use more detailed communication patterns and networking models. Such options would leverage the work proposed in Section 4.2 for gathering application traces.

4.1.3. Data-Centric Processing

Exascale computing is shifting away from the traditional compute-centric models to a more data-centric one. This is driven by the evolving nature of large scale distributed computing, no longer dominated by pure computations but also by the need to handle and analyze large volumes of data. These data can be large databases of results, data streamed from a running application or another scientific instrument (collider for instance). These new workloads call for specific resource allocation strategies.

Data movements and storage are expected to be a major energy and performance bottleneck on next generation platforms. Storage architectures are also evolving, the standard centralized parallel file system being complemented with local persistent storage (Burst Buffers, NVRAM). Thus, one data producer can stage data on some nodes' local storage, requiring to schedule close by the associated analytics tasks to limit data movements. This kind of configuration, often referred as *in situ analytics*, is expected to become common as it enables to switch from the traditional I/O intensive workflow (batch-processing followed by *post mortem* analysis and visualization) to a more storage conscious approach where data are processed as closely as possible to where and when they are produced (in situ processing is addressed in details in section 4.3). By reducing data movements and scheduling the extra processing on resources not fully exploited yet, in situ processing is expected to have also a significant positive energetic impact. Analytics codes can be executed in the same nodes than the application, often on dedicated cores commonly called helper cores, or on dedicated nodes called stagging nodes. The results are either forwarded to the users for visualization or saved to disk through I/O nodes. In situ analytics can also take benefit of node local disks or burst buffers to reduce data movements. Future job scheduling strategies should take into account in situ processes in addition to the job allocation to optimize both energy consumption and execution time. On the one hand, this problem can be reduced to an allocation problem of extra asynchronous tasks to idle computing units. But on the other hand, embedding analytics in applications brings extra difficulties by making the application more heterogeneous and imposing more constraints (data affinity) on the required resources. Thus, the main point here is to develop efficient algorithms for dealing with heterogeneity without increasing the global computational cost.

4.1.4. Learning

Another important issue is to adapt the job management system to deal with the bad effects of uncertainties, which may be catastrophic in large scale heterogeneous HPC platforms (jobs delayed arbitrarly far or jobs killed). A natural question is then: *is it possible to have a good estimation of the job and platform parameters in order to be able to obtain a better scheduling ?* Many important parameters (like the number or type of required resources or the estimated running time of the jobs) are asked to the users when they submit their jobs. However, some of these values are not accurate and in many cases, they are not even provided by the end-users. In DataMove, we propose to study new methods for a better prediction of the characteristics of the jobs and their execution in order to improve the optimization process. In particular, the methods well-studied in the field of big data (in supervised Machine Learning, like classical regression methods, Support Vector Methods, random forests, learning to rank techniques or deep learning) could and must be used to improve job scheduling in large scale HPC platforms. This topic received a great attention recently in the field of parallel and distributed processing. A preliminary study has been done recently by our team with the target of predicting the job running times (called wall times). We succeeded to improve significantly in average the reference EASY Back Filling algorithm by estimating the wall time of the jobs, however, this method leads to big delay for the stretch of few jobs. Even if we succeed in determining more precisely hidden parameters, like the wall time of the jobs, this is not enough to determine an optimized solution. The shift is not only to learn on dedicated parameters but also on the scheduling policy. The data collected from the accounting and profiling of jobs can be used to better understand the needs of the jobs and through learning to propose adaptations for future submissions. The goal is to propose extensions to further improve the job scheduling and improve the performance and energy efficiency of the application. For instance preference learning may enable to compute on-line new priorities to back-fill the ready jobs.

4.1.5. Multi-objective Optimization

Several optimization questions that arise in allocation and scheduling problems lead to the study of several objectives at the same time. The goal is then not a single optimal solution, but a more complicated mathematical object that captures the notion of trade-off. In broader terms, the goal of multi-objective optimization is not to externally arbitrate on disputes between entities with different goals, but rather to explore the possible solutions to highlight the whole range of interesting compromises. A classical tool for studying such multi-objective optimization problems is to use *Pareto curves*. However, the full description of the Pareto curve can be very hard because of both the number of solutions and the hardness of computing each point. Addressing this problem will opens new methodologies for the analysis of algorithms.

To further illustrate this point here are three possible case studies with emphasis on conflicting interests measured with different objectives. While these cases are good representatives of our HPC context, there are other pertinent trade-offs we may investigate depending on the technology evolution in the coming years. This enumeration is certainly not limitative.

Energy versus Performance. The classical scheduling algorithms designed for the purpose of performance can no longer be used because performance and energy are contradictory objectives to some extent. The scheduling problem with energy becomes a multi-objective problem in nature since the energy consumption should be considered as equally important as performance at exascale. A global constraint on energy could be a first idea for determining trade-offs but the knowledge of the Pareto set (or an approximation of it) is also very useful.

Administrators versus application developers. Both are naturally interested in different objectives: In current algorithms, the performance is mainly computed from the point of view of administrators, but the users should be in the loop since they can give useful information and help to the construction of better schedules. Hence, we face again a multi-objective problem where, as in the above case, the approximation of the Pareto set provides the trade-off between the administrator view and user demands. Moreover, the objectives are usually of the same nature. For example, *max stretch* and *average stretch* are two objectives based on the slowdown factor that can interest administrators and users, respectively. In this case the study of the norm of stretch can be also used to describe the trade-off (recall that the L_1-norm corresponds to the average objective while the L_∞-norm to the max objective). Ideally, we would like to design an algorithm that gives good approximate solutions at the same time for all norms. The L_2 or L_3-norm are useful since they describe the performance of the whole schedule from the administrator point of view as well as they provide a fairness indication to the users. The hard point here is to derive theoretical analysis for such complicated tools.

Resource Augmentation. The classical resource augmentation models, i.e. speed and machine augmentation, are not sufficient to get good results when the execution of jobs cannot be frequently interrupted. However, based on a resource augmentation model recently introduced, where the algorithm may reject a small number of jobs, some members of our team have given the first interesting results in the non-preemptive direction. In general, resource augmentation can explain the intuitive good behavior of some greedy algorithms while, more interestingly, it can give ideas for new algorithms. For example, in the rejection context we could dedicate a small number of nodes for the usually problematic rejected jobs. Some initial experiments show that this can lead to a schedule for the remaining jobs that is very close to the optimal one.

4.2. Empirical Studies of Large Scale Platforms

Experiments or realistic simulations are required to take into account the impact of allocations and assess the real behavior of scheduling algorithms. While theoretical models still have their interest to lay the groundwork for algorithmic designs, the models are necessarily reflecting a purified view of the reality. As transferring our algorithm in a more practical setting is an important part of our creed, we need to ensure that the theoretical results found using simplified models can really be transposed to real situations. On the way to exascale computing, large scale systems become harder to study, to develop or to calibrate because of the costs in both time and energy of such processes. It is often impossible to convince managers to use a production cluster for several hours simply to test modifications in the RJMS. Moreover, as the existing RJMS production systems need to be highly reliable, each evolution requires several real scale test iterations. The consequence is that scheduling algorithms used in production systems are mostly outdated and not customized correctly. To circumvent this pitfall, we need to develop tools and methodologies for alternative empirical studies, from analysis of workload traces, to job models, simulation and emulation with reproducibility concerns.

4.2.1. Workload Traces with Resource Consumption

Workload traces are the base element to capture the behavior of complete systems composed of submitted jobs, running applications, and operating tools. These traces must be obtained on production platforms to provide relevant and representative data. To get a better understanding of the use of such systems, we need to look at both, how the jobs interact with the job management system, and how they use the allocated resources. We propose a general workload trace format that adds jobs resource consumption to the commonly used SWF [0] workload trace format. This requires to instrument the platforms, in particular to trace resource consumptions like CPU, data movements at memory, network and I/O levels, with an acceptable performance impact. In a previous work we studied and proposed a dedicated job monitoring tool whose impact on the system has been measured as lightweight (0.35% speed-down) with a 1 minute sampling rate. Other tools also explore job monitoring, like TACC Stats. A unique feature from our tool is its ability to monitor distinctly jobs sharing common nodes.

Collected workload traces with jobs resource consumption will be publicly released and serve to provide data for works presented in Section 4.1. The trace analysis is expected to give valuable insights to define models encompassing complex behaviours like network topology sensitivity, network congestion and resource interferences.

We expect to join efforts with partners for collecting quality traces (ATOS/Bull, Ciment meso center, Joint Laboratory on Extreme Scale Computing) and will collaborate with the Inria team POLARIS for their analysis.

4.2.2. Simulation

Simulations of large scale systems are faster by multiple orders of magnitude than real experiments. Unfortunately, replacing experiments with simulations is not as easy as it may sound, as it brings a host of new problems to address in order to ensure that the simulations are closely approximating the execution of typical workloads on real production clusters. Most of these problems are actually not directly related to scheduling algorithms assessment, in the sense that the workload and platform models should be defined independently from the algorithm evaluations, in order to ensure a fair assessment of the algorithms' strengths and weaknesses. These research topics (namely platform modeling, job models and simulator calibration) are addressed in the other subsections.

We developed an open source platform simulator within DataMove (in conjunction with the OAR development team) to provide a widely distributable test bed for reproducible scheduling algorithm evaluation. Our simulator, named Batsim, allows to simulate the behavior of a computational platform executing a workload scheduled by any given scheduling algorithm. To obtain sound simulation results and to broaden the scope of the experiments that can be done thanks to Batsim, we did not chose to create a (necessarily limited) simulator from scratch, but instead to build on top of the SimGrid simulation framework.

[0] Standard Workload Format: http://www.cs.huji.ac.il/labs/parallel/workload/swf.html

To be open to as many batch schedulers as possible, Batsim decouples the platform simulation and the scheduling decisions in two clearly-separated software components communicating through a complete and documented protocol. The Batsim component is in charge of simulating the computational resources behaviour whereas the scheduler component is in charge of taking scheduling decisions. The scheduler component may be both a resource and a job management system. For jobs, scheduling decisions can be to execute a job, to delay its execution or simply to reject it. For resources, other decisions can be taken, for example to change the power state of a machine i.e. to change its speed (in order to lower its energy consumption) or to switch it on or off. This separation of concerns also enables interfacing with potentially any commercial RJMS, as long as the communication protocol with Batsim is implemented. A proof of concept is already available with the OAR RJMS.

Using this test bed opens new research perspectives. It allows to test a large range of platforms and workloads to better understand the real behavior of our algorithms in a production setting. In turn, this opens the possibility to tailor algorithms for a particular platform or application, and to precisely identify the possible shortcomings of the theoretical models used.

4.2.3. Job and Platform Models

The central purpose of the Batsim simulator is to simulate job behaviors on a given target platform under a given resource allocation policy. Depending on the workload, a significant number of jobs are parallel applications with communications and file system accesses. It is not conceivable to simulate individually all these operations for each job on large plaforms with their associated workload due to implied simulation complexity. The challenge is to define a coarse grain job model accurate enough to reproduce parallel application behavior according to the target platform characteristics. We will explore models similar to the BSP (Bulk Synchronous Program) approach that decomposes an application in local computation supersteps ended by global communications and a global synchronization. The model parameters will be established by means of trace analysis as discussed previously, but also by instrumenting some parallel applications to capture communication patterns. This instrumentation will have a significant impact on the concerned application performance, restricting its use to a few applications only. There are a lot of recurrent applications executed on HPC platform, this fact will help to reduce the required number of instrumentations and captures. To assign each job a model, we are considering to adapt the concept of application signatures as proposed in. Platform models and their calibration are also required. Large parts of these models, like those related to network, are provided by Simgrid. Other parts as the filesystem and energy models are comparatively recent and will need to be enhanced or reworked to reflect the HPC platform evolutions. These models are then generally calibrated by running suitable benchmarks.

4.2.4. Emulation and Reproducibility

The use of coarse models in simulation implies to set aside some details. This simplification may hide system behaviors that could impact significantly and negatively the metrics we try to enhance. This issue is particularly relevant when large scale platforms are considered due to the impossibility to run tests at nominal scale on these real platforms. A common approach to circumvent this issue is the use of emulation techniques to reproduce, under certain conditions, the behavior of large platforms on smaller ones. Emulation represents a natural complement to simulation by allowing to execute directly large parts of the actual evaluated software and system, but at the price of larger compute times and a need for more resources. The emulation approach was chosen in to compare two job management systems from workload traces of the CURIE supercomputer (80000 cores). The challenge is to design methods and tools to emulate with sufficient accuracy the platform and the workload (data movement, I/O transfers, communication, applications interference). We will also intend to leverage emulation tools like Distem from the MADYNES team. It is also important to note that the Batsim simulator also uses emulation techniques to support the core scheduling module from actual RJMS. But the integration level is not the same when considering emulation for larger parts of the system (RJMS, compute node, network and filesystem).

Replaying traces implies to prepare and manage complex software stacks including the OS, the resource management system, the distributed filesystem and the applications as well as the tools required to conduct experiments. Preparing these stacks generate specific issues, one of the major one being the support for reproducibility. We propose to further develop the concept of reconstructability to improve experiment reproducibility by capturing the build process of the complete software stack. This approach ensures reproducibility over time better than other ways by keeping all data (original packages, build recipe and Kameleon engine) needed to build the software stack.

In this context, the Grid'5000 (see Sec. 5.3) experimentation infrastructure that gives users the control on the complete software stack is a crucial tool for our research goals. We will pursue our strong implication in this infrastructure.

4.3. Integration of High Performance Computing and Data Analytics

Data produced by large simulations are traditionally handled by an I/O layer that moves them from the compute cores to the file system. Analysis of these data are performed after reading them back from files, using some domain specific codes or some scientific visualisation libraries like VTK. But writing and then reading back these data generates a lot of data movements and puts under pressure the file system. To reduce these data movements, **the in situ analytics paradigm proposes to process the data as closely as possible to where and when the data are produced**. Some early solutions emerged either as extensions of visualisation tools or of I/O libraries like ADIOS. But significant progresses are still required to provide efficient and flexible high performance scientific data analysis tools. Integrating data analytics in the HPC context will have an impact on resource allocation strategies, analysis algorithms, data storage and access, as well as computer architectures and software infrastructures. But this paradigm shift imposed by the machine performance also sets the basis for a deep change on the way users work with numerical simulations. The traditional workflow needs to be reinvented to make HPC more user-centric, more interactive and turn HPC into a commodity tool for scientific discovery and engineering developments. In this context DataMove aims at investigating programming environments for in situ analytics with a specific focus on task scheduling in particular, to ensure an efficient sharing of resources with the simulation.

4.3.1. Programming Model and Software Architecture

In situ creates a tighter loop between the scientist and her/his simulation. As such, an in situ framework needs to be flexible to let the user define and deploy its own set of analysis. A manageable flexibility requires to favor simplicity and understandability, while still enabling an efficient use of parallel resources. Visualization libraries like VTK or Visit, as well as domain specific environments like VMD have initially been developed for traditional post-mortem data analysis. They have been extended to support in situ processing with some simple resource allocation strategies but the level of performance, flexibility and ease of use that is expected requires to rethink new environments. There is a need to develop a middleware and programming environment taking into account in its fundations this specific context of high performance scientific analytics.

Similar needs for new data processing architectures occurred for the emerging area of Big Data Analytics, mainly targeted to web data on cloud-based infrastructures. Google Map/Reduce and its successors like Spark or Stratosphere/Flink have been designed to match the specific context of efficient analytics for large volumes of data produced on the web, on social networks, or generated by business applications. These systems have mainly been developed for cloud infrastructures based on commodity architectures. They do not leverage the specifics of HPC infrastructures. Some preliminary adaptations have been proposed for handling scientific data in a HPC context. However, these approaches do not support in situ processing.

Following the initial development of FlowVR, our middleware for in situ processing, we will pursue our effort to develop a programming environment and software architecture for high performance scientific data analytics. Like FlowVR, the map/reduce tools, as well as the machine learning frameworks like TensorFlow, adopted a dataflow graph for expressing analytics pipe-lines. We are convinced that this dataflow approach is both easy to understand and yet expresses enough concurrency to enable efficient executions. The graph description can be compiled towards lower level representations, a mechanism that is intensively used by Stratosphere/Flink for instance. Existing in situ frameworks, including FlowVR, inherit from the HPC way of programming with a thiner software stack and a programming model close to the machine. Though this approach enables to program high performance applications, this is usually too low level to enable the scientist to write its analysis pipe-line in a short amount of time. The data model, i.e. the data semantics level accessible at the framework level for error check and optimizations, is also a fundamental aspect of such environments. The key/value store has been adopted by all map/reduce tools. Except in some situations, it cannot be adopted as such for scientific data. Results from numerical simulations are often more structured than web data, associated with acceleration data structures to be processed efficiently. We will investigate data models for scientific data building on existing approaches like Adios or DataSpaces.

4.3.2. Resource Sharing

To alleviate the I/O bottleneck, the in situ paradigm proposes to start processing data as soon as made available by the simulation, while still residing in the memory of the compute node. In situ processings include data compression, indexing, computation of various types of descriptors (1D, 2D, images, etc.). Per se, reducing data output to limit I/O related performance drops or keep the output data size manageable is not new. Scientists have relied on solutions as simple as decreasing the frequency of result savings. In situ processing proposes to move one step further, by providing a full fledged processing framework enabling scientists to more easily and thoroughly manage the available I/O budget.

The most direct way to perform in situ analytics is to inline computations directly in the simulation code. In this case, in situ processing is executed in sequence with the simulation that is suspended meanwhile. Though this approach is direct to implement and does not require complex framework environments, it does not enable to overlap analytics related computations and data movements with the simulation execution, preventing to efficiently use the available resources. Instead of relying on this simple time sharing approach, several works propose to rely on space sharing where one or several cores per node, called *helper cores*, are dedicated to analytics. The simulation responsibility is simply to handle a copy of the relevant data to the node-local in situ processes, both codes being executed concurrently. This approach often lead to significantly beter performance than in-simulation analytics.

For a better isolation of the simulation and in situ processes, one solution consists in offloading in situ tasks from the simulation nodes towards extra dedicated nodes, usually called *staging nodes*. These computations are said to be performed *in-transit*. But this approach may not always be beneficial compared to processing on simulation nodes due to the costs of moving the data from the simulation nodes to the staging nodes.

FlowVR enables to mix these different resources allocation strategies for the different stages of an analytics pile-line. Based on a component model, the scientist designs analytics workflows by first developing processing components that are next assembled in a dataflow graph through a Python script. At runtime the graph is instantiated according to the execution context, FlowVR taking care of deploying the application on the target architecture, and of coordinating the analytics workflows with the simulation execution.

But today the choice of the resource allocation strategy is mostly ad-hoc and defined by the programmer. We will investigate solutions that enable a cooperative use of the resource between the analytics and the simulation with minimal hints from the programmer. In situ processings inherit from the parallelization scale and data distribution adopted by the simulation, and must execute with minimal perturbations on the simulation execution (whose actual resource usage is difficult to know a priori). We need to develop adapted scheduling strategies that operate at compile and run time. Because analysis are often data intensive, such solutions must take into consideration data movements, a point that classical scheduling strategies designed first for compute intensive applications often overlook. We expect to develop new scheduling strategies relying on the methodologies developed in Section 4.1.5. Simulations as well as analysis are iterative processes exposing a strong spatial and temporal coherency that we can take benefit of to anticipate their behavior and then take more relevant resources allocation strategies, possibly based on advanced learning algorithms or as developed in Section 4.1.

In situ analytics represent a specific workload that needs to be scheduled very closely to the simulation, but not necessarily active during the full extent of the simulation execution and that may also require to access data from previous runs (stored in the file system or on specific burst-buffers). Several users may also need to run concurrent analytics pipe-lines on shared data. This departs significantly from the traditional batch scheduling model, motivating the need for a more elastic approach to resource provisioning. These issues will be conjointly addressed with research on batch scheduling policies (Section 4.1).

4.3.3. Co-Design with Data Scientists

Given the importance of users in this context, it is of primary importance that in situ tools be co-designed with advanced users, even if such multidisciplinary collaborations are challenging and require constant long term investments to learn and understand the specific practices and expectations of the other domain.

We will tightly collaborate with scientists of some application domains, like molecular dynamics or fluid simulation, to design, develop, deploy and assess in situ analytics scenarios, as already done with Marc Baaden, a computational biologist from LBT.

We recently extended our collaboration network. We started in 2015 a PhD co-advised with CEA DAM to investigate in situ analytics scenarios in the context of atomistic material simulations. CEA DAM is a French energy lab hosting one of the largest european supercomputer. They gather physicists, numerical scientists as well as high performance computer engineers, making it a very interesting partner for developing new scientific data analysis solutions. We also got a national grant (2015-2018) to compute in situ statistics for multi-parametric parallel studies with the research department of French power company EDF. In this context we collaborate with statisticians and fluid simulation experts to define in situ scenarios, revisit the statistic operators to be amenable to in situ processing, and define an adapted in situ framework.

5. New Software and Platforms

5.1. OAR

KEYWORDS: HPC - Cloud - Clusters - Resource manager - Light grid
SCIENTIFIC DESCRIPTION This batch system is based on a database (PostgreSQL (preferred) or MySQL), a script language (Perl) and an optional scalable administrative tool (e.g. Taktuk). It is composed of modules which interact mainly via the database and are executed as independent programs. Therefore, formally, there is no API, the system interaction is completely defined by the database schema. This approach eases the development of specific modules. Indeed, each module (such as schedulers) may be developed in any language having a database access library.
FUNCTIONAL DESCRIPTION OAR is a versatile resource and task manager (also called a batch scheduler) for HPC clusters, and other computing infrastructures (like distributed computing experimental testbeds where versatility is a key).
The OAR ecosystem also include several associated software tools that proved to be useful independently from OAR. Among theses, two softwares play a major role in the support our research studies. The first one is Kameleon (http://kameleon.imag.fr), a tool to help enhancing reproducibility of experiments by guarantee the ability to reproduce the complete used software stacks. The second one is Batsim (https://gforge.inria.fr/projects/batsim) a RJMS simulator based on SimGrid. Batsim simulates job execution taking into account the target platform hardware capabilities through SimGrid, while scheduling is performed by an actual job management system. A comprehensive API enables to easily plug into BatSim various job management systems like OAR.

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- Partners: CIMENT - CNRS - Grid'5000 - LIG
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- URL: http://oar.imag.fr

5.2. FlowVR

KEYWORDS: HPC - In Situ Processing - Computational Steering

SCIENTIFIC DESCRIPTION FlowVR is an open source middelware to augment parallel simulations running on thousands of cores with in situ processing capabilities and live steering. FlowVR offers a very flexible environment while enabling high performance asynchronous in situ and in transit processing.
FUNCTIONAL DESCRIPTION FlowVR adopts the "data-flow" paradigm, where your application is divided as a set of components exchanging messages (think of it as a directed graph). FlowVR enables to encapsulate existing codes in components, interconnect them through data channels, and deploy them on distributed computing resources. FlowVR takes care of all the heavy lifting such as application deployment and message exchange.

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5.3. Platforms

5.3.1. Grid'5000 (https://www.grid5000.fr/) and meso center Ciment (https://ciment.ujf-grenoble.fr)

We have been very active in promoting the factorization of compute resources at a regional and national level. We have a three level implication, locally to maintain a pool of very flexible experimental machines (hundreds of cores), regionally through the CIMENT meso center (Equipex Grant), and nationally by contributing to the Grid'5000 platform, our local resources being included in this platform. Olivier Richard is member of Grid'5000 scientific committee and Pierre Neyron is member of the technical committee. The OAR scheduler in particular is deployed on both infrastructures. We are currently preparing proposals for the next generation machines within the context of the new university association (Univ. Grenoble-Alpes).

6. New Results

6.1. In Situ Statistical Analysis for Parametric Studies

In situ processing proposes to reduce storage needs and I/O traffic by processing results of parallel simulations as soon as they are available in the memory of the compute processes. We focus in this paper [11] on computing in situ statistics on the results of N simulations from a parametric study. The classical approach consists in running various instances of the same simulation with different values of input parameters. Results are then saved to disks and statistics are computed post mortem, leading to very I/O intensive applications. Our solution is to develop Melissa, an in situ library running on staging nodes as a parallel server. When starting, simulations connect to Melissa and send the results of each time step to Melissa as soon as they are available. Melissa implements iterative versions of classical statistical operations, enabling to update results as soon as a new time step from a simulation is available. Once all statistics ar updated, the time step can be discarded. We also discuss two different approaches for scheduling simulation runs: the jobs-in-job and the multi-jobs approaches. Experiments run instances of the Computational Fluid Dynamics Open Source solver Code_Saturne. They confirm that our approach enables one to avoid storing simulation results to disk or in memory.

6.2. Online Non-preemptive Scheduling in a Resource Augmentation Model based on Duality

Resource augmentation is a well-established model for analyzing algorithms, particularly in the online setting. It has been successfully used for providing theoretical evidence for several heuristics in scheduling with good performance in practice. According to this model, the algorithm is applied to a more powerful environment than that of the adversary. Several types of resource augmentation for scheduling problems have been proposed up to now, including speed augmentation, machine augmentation and more recently rejection. In this paper [7], we present a framework that unifies the various types of resource augmentation. Moreover, it allows generalize the notion of resource augmentation for other types of resources. Our framework is based on mathematical programming and it consists of extending the domain of feasible solutions for the algorithm with respect to the domain of the adversary. This, in turn allows the natural concept of duality for mathematical programming to be used as a tool for the analysis of the algorithm's performance. As an illustration of the above ideas, we apply this framework and we propose a primal-dual algorithm for the online scheduling problem of minimizing the total weighted flow time of jobs on unrelated machines when the preemption of jobs is not allowed. This is a well representative problem for which no online algorithm with performance guarantee is known. Specifically, a strong lower bound of $\Omega(\sqrt{n})$ exists even for the offline unweighted version of the problem on a single machine. In this paper, we first show a strong negative result even when speed augmentation is used in the online setting. Then, using the generalized framework for resource augmentation and by combining speed augmentation and rejection, we present an $(1+\epsilon_s)$-speed $O(\frac{1}{\epsilon_s \epsilon_r})$-competitive algorithm if we are allowed to reject jobs whose total weight is an ϵ_r-fraction of the weights of all jobs, for any $\epsilon_s > 0$ and $\epsilon_r \in (0,1)$. Furthermore, we extend the idea for analysis of the above problem and we propose an $(1+\epsilon_s)$-speed ϵ_r-rejection $O(\frac{k^{\frac{(k+3}{k}}}{\epsilon_r^{1/k}\epsilon_s^{\frac{(k+2)}{k}}})$-competitive algorithm for the more general objective of minimizing the weighted l_k-norm of the flow times of jobs.

6.3. Batsim: a Realistic Language-Independent Resources and Jobs Management Systems Simulator

As large scale computation systems are growing to exascale, Resources and Jobs Management Systems (RJMS) need to evolve to manage this scale modification. However, their study is problematic since they are critical production systems, where experimenting is extremely costly due to downtime and energy costs. Meanwhile, many scheduling algorithms emerging from theoretical studies have not been transferred to production tools for lack of realistic experimental validation. To tackle these problems we propose Batsim [6], an extendable, language-independent and scalable RJMS simulator. It allows researchers and engineers to test and compare any scheduling algorithm, using a simple event-based communication interface, which allows different levels of realism. In this paper we show that Batsim's behavior matches the one of the real RJMS OAR. Our evaluation process was made with reproducibility in mind and all the experiment material is freely available.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

BULL-ATOS SE (2015-2018). Two PhD grants (David Glesser and Michael Mercier). Job and resource management algorithms.

7.2. Bilateral Grants with Industry

CEA DAM (2016-2018). PhD grant support contract (PhD of Estelle Dirand, funded by CEA). In situ analysis for Molecular Simulations.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

- **ANR grant MOEBIUS (2013-2017).** Multi-objective scheduling for large computing platforms. Coordinator: Grenoble-INP (DataMove). Partners: Grenoble-INP, Inria, BULL-ATOS .

8.1.2. Competitivity Clusters

- **PIA Avido (2015-2018)**. In situ analysis and visualization for large scale numerical simulation. Coordinator: EDF SA. Partners: EDF SA, Total SA, Kitware SAS , Université Pierre et Marie CURIE, Inria (DataMove).
- **FUI OverMind (2015-2017)**. Task planification and asset management for the cartoon productions. Coordinator: Teamto Studio. Partners: Teamto Studio, Folimage Studio, Ecole de Gobelins, Inria (DataMove).

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. VELaSSCo

Title: Visualization For Extremely Large-Scale Scientific Computing

Program: STREP (Specific Targeted Research Project)

Duration: January 2014 - December 2016

Coordinator: Centre Internacional de Metodes Numerics en Enginyeria (Spain)

Partners: JOTNE (No.), SINTEF (No.), Fraunhofer IGD (D), ATOS (SP), Univ. Edinburgh (UK)

Inria contact: Toan Nguyen, Bruno Raffin

Abstract: VELaSSCo aims at developing a new concept of integrated end-user visual analysis methods with advanced management and post-processing algorithms for engineering modelling applications, scalable for real-time petabyte level simulations [59]. The interface will enable real-time interrogation of simulation data, generating key information for analysis. Main concerns have to do with handling of large amounts of data of a very specific kind intrinsically linked to geometrical properties; how to store, access, simplify and manipulate billion of records to extract the relevant information; how to represent information in a feasible and flexible way; and how to visualise and interactively inspect the huge quantity of information they produce taking into account end-user's needs. VELaSSCo achieves this by putting together experts with relevant background in Big Data handling, advanced visualisation, engineering simulations, and a User Panel including research centres, SMEs and companies form key European industrial sectors such as aerospace, household products, chemical, pharmaceutical and civil engineering.

8.3. International Initiatives

8.3.1. Inria International Labs

8.3.1.1. JLESC

Title: Joint Laboratory for Extreme-Scale-Computing.

International Partners:

University of Illinois at Urbana Champaign (USA)

Argonne National Laboratory (USA),

Barcelona Supercomputing Center (Spain),

Jülich Supercomputing Centre (Germany)

Riken Advanced Institute for Computational Science (Japan)

Start year: 2009

See also: https://jlesc.github.io/

The purpose of the Joint Laboratory for Extreme Scale Computing is to be an international, virtual organization whose goal is to enhance the ability of member organizations and investigators to make the bridge between Petascale and Extreme computing. The JLESC organizes a workshop every 6 months DataMove participates to. DataMove developed several collaborations related to in situ processing with Tom Peterka group (ANL) , the Argo exascale operating system with Swann Perarnau (ANL).

8.3.1.2. ANOMALIES@EXASCALE

Title: Anomalies Detection and Handling towards Exascale Platforms

International Partner:

University of Chicago (United States) - Argonne National Laboratory (ANL)

Start year: 2014. End year: 2016.

See also: http://anomalies.imag.fr

The Anomalies@exascale project intends to prospect new scheduling solutions for very large parallel computing platforms. In particular, we consider the new problems related to fault tolerance raising with the developments of exascale platforms. We expect to define new ways to detect both execution failures and more transient performance anomalies. Information gathered from the detectors will then be taken into account by schedulers to implement corrective measures. PI: Frederic Wagner

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

8.3.2.1. ExaSE

Title: Exascale Computing Scheduling and Energy

International Partners:

UFRGS, PUC Minas and UPS (Brazil)

Duration: 2014 - 2016

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

The main scientific context of this project is high performance computing on Exascale systems: large-scale machines with billions of processing cores and complex hierarchical structures. This project intends to explore the relationship between scheduling algorithms and techniques and the energy constraints present on such exascale systems. PI: Jean-Marc Vincent (Polaris)

8.3.3. Participation in Other International Programs

8.3.3.1. LICIA

Title: International Laboratory in High Performance and Ubiquitous Computing

International Partner (Institution - Laboratory - Researcher):

UFRGS (Brazil)

Duration: 2011 - 2018

See also: http://licia-lab.org/

The LICIA is an Internacional Laboratory and High Performance and Ubiquitous Computing born in 2011 from the common desire of members of Informatics Institute of the Federal University of Rio Grande do Sul and of Laboratoire d'Informatique de Grenoble to enhance and develop their scientific partnership that started by the end of the 1970. LICIA is an Internacional Associated Lab of the CNRS, a public french research institution. It has support from several brazilian and french research funding agencies, such as CNRS, Inria, ANR, European Union (from the french side) and CAPES, CNPq, FAPERGS (from the Brazilian side). DataMove is deeply involved in the animation of LICIA. Bruno Raffin is LICIA associate director.

8.3.3.2. CAPES/COFECUB StarShip

Title: Scalable Tools and Algorithms para Resilient, Scalable, Hybrid Interactive Processing

International Partner (Institution - Laboratory - Researcher):

UFRGS (Brazil)

Duration: 2013 - 2016

PI: Bruno Raffin (DataMove) and Alexandre Carissimi (UFRGS)

8.4. International Research Visitors

8.4.1. Internships

PhD in progress: Marcos Amaris Gonzalez, Performance Evaluation for GPU, USP (Sao Paulo, Brasil). 1 year "sandwich" visit. Local adviser: Denis Trystram

8.4.2. Visits to International Teams

- Pierre François Dutot. Six month stay at University of Hawaii at Manoa (Sept. 2016 - Jan. 2017)

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

- Euro-Par, Grenoble, August 2016: General chair and local organization.
- HCW'2016 (25th IEEE Heterogeneous Computing Workshop), Hyderabad, May 2016a: General Chair

9.1.1.2. Member of the Organizing Committees

- EGPGV (Eurographics Symposium on Parallel Rendering and Visualization): President of the steering committee.

9.1.2. Scientific Events Selection

9.1.2.1. Chair of Conference Program Committees

Euro-Par, Grenoble, August 2016: Topic chair.

9.1.2.2. Member of the Conference Program Committees

ISAV 2016, November 2016, Salt Lake City, USA

2nd IEEE BidDataSecurity, April 8-10 2016, New York, USA

IPDPS 2016 (27th IEEE International Parallel & Distributed Processing Symposium), May 23-27 2016, Chicago, USA

CloudTech, My 24-26 2016, Marrakech, Marocco

COMPAS, July 5-8 2016, Lorient, France

PMAA'16 (10th internat. workshop on Parallel Matrix Algorithms and Applications), July 6-8 2016, Bordeaux, France

ISPDC (15th Internat Symposium on Parallel and Distributed Computing), July 8-10 2016, Fuzhou, China

EuroMPI, September 25-28 2016, Edinburgh, Scotland, UK

28th SBAC-PAD, October 26-28 2016, Los Angeles, USA,

Edu-HPC (Workshop on Education for High-Performance Computing), November 2016, Salt Lake city, USA

CloudCom, December 12-15 2016, Luxemburg

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

Associate Editor of the Parallel Computing journal PARCO.

Member of the Editorial Board of JPDC.

Member of the Editorial Board of Computational Methods in Science and Technology.

Member of the Editorial Board of ARIMA (revue africaine de recherche en informatique et maths appliquées).

Member of the Editorial Board of IEEE Trans. Parallel and Distributed Systems TPDS.

9.1.4. Scientific Expertise

ANR project evaluation expert

Nederlands e-science center expert

9.1.5. Research Administration

Executive committee member of Mathematics and Computer Science Council of Univ. Grenoble-Alpes (Membre du directoire du Conseil du Pôle MSTIC de l'UGA)

Mathematics and Computer Science Council of Univ. Grenoble-Alpes Members (Membre du Conseil du Pôle MSTIC de l'UGA)

Steering commitee of Grid'5000

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master: Denis Trystram is responsible of the first year (M1) of the international Master of Science in Informatics at Grenoble (MOSIG-M1).

Master: D. Trystram, P.-F. Dutot, "Complexity, approximation theory and randomization" master course (M2) at Univ. Grenoble-Alpes

Master: Pierre-François Dutot. 226 hours per year. Licence (first and second year) at IUT2/UPMF (Institut Universitaire Technologique de Univ. Grenoble-Alpes) and 9 hours Master M2R-ISC Informatique-Systèmes-Communication at Univ. Grenoble-Alpes.

Master: Grégory Mounié. 242 hours per year. Master (M1/2nd year and M2/3rd year) at Engineering school ENSIMAG, Grenoble-INP.

Master: Bruno Raffin. 28 hours per year. Parallel System. International Master of Science in Informatics at Grenoble (MOSIG-M2).

Master: Olivier Richard. 222 hours per year. Master at Engineering school Polytech-Grenoble, Univ. Grenoble-Alpes.

Master: Denis Trystram. 200 hours per year in average, mainly at first level of Engineering School ENSIMAG, Grenoble-INP.

Master: Frédéric Wagner. 220 hours per year. Engineering school ENSIMAG, Grenoble-INP (M1/2nd year and M2/3rd year) (190h), Master DESS/M2-P SCCI Security (30h).

9.2.2. Supervision

PhD: David Glesser, Energy Aware Resource Management for HPC, Univ. Grenoble-Alpes. Defended November 2016. Advisers: Denis Trystram and Yianis Georgiou (ATOS/BULL)

PhD : Marwa Sridi, Un modèle de structure de données Cache-aware pour un parallélisme et un l'équilibrage dynamique de la charge, Univ Grenoble-Alpes. Defended April 2016. Advisers: Bruno Raffin, Vincent Faucher (CEA) and Thierry Gautier.

PhD in progress : Julio Toss, Parallel Algorithms and Data Structures for Physically Based Simulation of Deformable Objects, Univ. Grenoble-Alpes and UFRGS (co-tutelle). Started October 2013. Advisers: Bruno Raffin and Joao Comba (UFRGS).

PhD in progress : Estelle Dirand, Integration of High-Performance Data Analytics and IOs for Molecular Dynamics on Exascale Computer, Univ. Grenoble-Alpes. Started January 2016. Advisers: Bruno Raffin and Laurent Colombet (CEA).

PhD in progress: Michael Mercier, Resource Management and Job Scheduling in HPC–Cloud environments towards the Big Data era, Univ. Grenoble Alpes. Started October 2016. Advisers: Olivier Richard and Bruno Raffin.

PhD in progress: Raphaël Bleuse, Affinity Scheduling, Univ. Grenoble-Alpes. Started October 2013. Adviser: Denis Trystram and Gregory Mounié.

PhD in progress: Millian Poquet, Energy consumption optimization for high performance computing, Univ. Grenoble-Alpes. Started October 2014. Advisers: Denis Trystram and Pierre-François Dutot

PhD in progress: Valentin Reis, Machine Learning for resource management, Univ. Grenoble-Alpes. Started October 2015. Advisers: Denis Trystram and Eric Gaussier

PhD in progress: Abhinav Srivastav, Multi-objective Scheduling, Univ. Grenoble-Alpes. Started October 2015. Advisers: Denis Trystram and Oded Maler

PhD in progress: Alessandro Kraemer, Scheduling in the Cloud, Univ Grenoble-Alpes and UFPR (co-tutelle). Started October 2014. Advisers: Olivier Richard and Denis Trystram.

PhD in progress: Fernando Machado Mendonca, Locality Aware Scheduling, Univ. Grenoble-Alpes, Advisers: Frederic Wagner and Denis Trystram.

PhD in progress: Mohammed Khatiri, Tasks scheduling on heterogeneous Multicore, Univ. Grenoble-Alpes and University Mohammed First (co-tutelle), Advisers: Denis Trystram, El Mostafa DAOUDI (University Mohammed First, Oujda, Maroc)

9.2.3. Juries

PhD Defense of François Lehericey, 20th of September 2016. Jury Member. Ray Tracing Based Collision Detection: A quest for Performance. Université Bretagne Loire.

PhD Defense of Rémy Dautriche, 20th of October 2016. Jury President. Multi-scale Interaction Techniques for the Interactive Visualization of Execution Traces. Univ Grenoble-Alpes.

PhD Defense of Xiaohu Wu, 16th of February 2016. Reviewer. University of Nice.

PhD Defense of Ziad Sultan, 17th of June 2016. Jury President. Parallel Generic and Adaptive Exacte Linear Algebra. Univ. Grenoble-Alpes

9.3. Popularization

In conjonction with the Polaris team, the team (Seniors and PhDs) participates to several "computer science with hands" events, notably the "Fête de la science", every year, but also some visits of classes from high school of the area along the year at Inria Rhône-Alpes.

Talk at the ISN conference organized by Inria, dedicated to present the computer science to teachers of High School

10. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] D. GLESSER.*Road to exascale: Improving scheduling performances and reducing energy consumption with the help of end-users*, Univ. Grenoble Alpes, October 2016, https://hal.inria.fr/tel-01425620.

[2] M. SRIDI.*Cache Aware Dynamics Data Layout for Efficient Shared Memory Parallelisation*, Université de Grenoble Alpes, April 2016, https://hal.archives-ouvertes.fr/tel-01430501.

Articles in International Peer-Reviewed Journal

[3] K. JANSEN, D. TRYSTRAM.*Scheduling parallel jobs on heterogeneous platforms*, in "Electronic Notes in Discrete Mathematics", 2016, vol. 55, p. 9–12 [*DOI :* 10.1016/J.ENDM.2016.10.003], https://hal.archives-ouvertes.fr/hal-01427256.

Articles in Non Peer-Reviewed Journal

[4] J. TOSS, J. COMBA, B. RAFFIN.*Parallel Voronoi Computation for Physics-Based Simulations*, in "Computing in Science and Engineering", May 2016, vol. 18, n° 3, 88 [*DOI :* 10.1109/MCSE.2016.52], https://hal.inria.fr/hal-01317549.

International Conferences with Proceedings

[5] K. ALESSANDRO, C. MAZIERO, O. RICHARD.*Reducing the Number of Response Time SLO Violations by a Cloud-HPC Convergence Scheduler*, in "2nd International Conference on Cloud Computing Technologies and Applications (CloudTech'16)", Marrakech, Morocco, May 2016, https://hal.inria.fr/hal-01432583.

[6] P.-F. DUTOT, M. MERCIER, M. POQUET, O. RICHARD.*Batsim: a Realistic Language-Independent Resources and Jobs Management Systems Simulator*, in "20th Workshop on Job Scheduling Strategies for Parallel Processing", Chicago, United States, May 2016, https://hal.archives-ouvertes.fr/hal-01333471.

[7] G. LUCARELLI, N. KIM THANG, A. SRIVASTAV, D. TRYSTRAM.*Online Non-preemptive Scheduling in a Resource Augmentation Model based on Duality*, in "European Symposium on Algorithms (ESA 2016)", Aarhus, Denmark, August 2016, vol. 57, n° 63, p. 1-17 [*DOI :* 10.4230/LIPICS.ESA.2016.63], http://hal.univ-grenoble-alpes.fr/hal-01334219.

[8] G. LUCARELLI, A. SRIVASTAV, D. TRYSTRAM.*From Preemptive to Non-preemptive Scheduling Using Rejections*, in "22nd International Computing and Combinatorics Conference (COCOON 2016)", Ho Chi Minh Ville, Vietnam, August 2016, vol. 9797, p. 510-519 [*DOI :* 10.1007/978-3-319-42634-1_41], http://hal.univ-grenoble-alpes.fr/hal-01371023.

[9] Y. NGOKO, D. TRYSTRAM, V. REIS, C. CÉRIN.*An Automatic Tuning System for Solving NP-Hard Problems in Clouds*, in "IPDPSW 2016 - IEEE International Parallel and Distributed Processing Symposium Workshops", Chicago, United States, May 2016, p. 1443–1452 [*DOI :* 10.1109/IPDPSW.2016.68], https://hal.archives-ouvertes.fr/hal-01427255.

[10] M. SRIDI, B. RAFFIN, V. FAUCHER.*Cache Aware Dynamics Data Layout for Efficient Shared Memory Parallelisation of EUROPLEXUS*, in "International Conference on Computational Science (ICCS)", San Diego, United States, Procedia Computer Science, June 2016, vol. 80, p. 1083 - 1092 [*DOI :* 10.1016/J.PROCS.2016.05.413], https://hal.archives-ouvertes.fr/hal-01420005.

[11] T. TERRAZ, B. RAFFIN, A. RIBES, Y. FOURNIER.*In Situ Statistical Analysis for Parametric Studies*, in "In Situ Infrastructures for Enabling Extreme-scale Analysis and Visualization (ISAV2016)", Salt Lake City, United States, November 2016, https://hal.archives-ouvertes.fr/hal-01383860.

Conferences without Proceedings

[12] P.-F. DUTOT, E. SAULE, A. SRIVASTAV, D. TRYSTRAM.*Online Non-Preemptive Scheduling to Optimize Max Stretch on a Single Machine*, in "22nd International Computing and Combinatorics Conference (COCOON 2016)", Ho-Chi-Minh-Ville, Vietnam, August 2016, http://hal.univ-grenoble-alpes.fr/hal-01309052.

Research Reports

[13] R. BLEUSE, S. HUNOLD, S. KEDAD-SIDHOUM, F. MONNA, G. MOUNIÉ, D. TRYSTRAM.*Scheduling Independent Moldable Tasks on Multi-Cores with GPUs*, Inria Grenoble Rhône-Alpes, Université de Grenoble, January 2016, n° RR-8850, https://hal.archives-ouvertes.fr/hal-01263100.

[14] B. OMIDVAR-TEHRANI, S. AMER-YAHIA, P.-F. DUTOT, D. TRYSTRAM.*Multi-Objective Group Discovery on the Social Web (Technical Report)*, LIG, April 2016, n° RR-LIG-052, Les rapports de recherche du LIG - ISSN: 2105-0422, https://hal.archives-ouvertes.fr/hal-01297763.

Other Publications

[15] M. AMARIS, G. LUCARELLI, C. MOMMESSIN, D. TRYSTRAM.*Generic algorithms for scheduling applications on hybrid multi-core machines*, December 2016, working paper or preprint, https://hal.inria.fr/hal-01420798.

Team DICE

Data on the internet at the Core of the Economy

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Security and Confidentiality

Table of contents

Team DICE

Creation of the Team: 2013 February 01, end of the Team: 2016 December 31

Keywords:

Computer Science and Digital Science:

1.2. - Networks
1.2.4. - QoS, performance evaluation
1.2.9. - Social Networks
2.1.10. - Domain-specific languages
2.6.2. - Middleware
3. - Data and knowledge
3.1.8. - Big data (production, storage, transfer)
3.2.2. - Knowledge extraction, cleaning
3.5. - Social networks
3.5.2. - Recommendation systems
5.1.1. - Engineering of interactive systems
5.2. - Data visualization

Other Research Topics and Application Domains:

6.3. - Network functions
6.3.3. - Network Management
6.3.4. - Social Networks
8. - Smart Cities and Territories
8.2. - Connected city
8.5. - Smart society
8.5.1. - Participative democracy
8.5.3. - Collaborative economy
9.5. - Humanities
9.5.3. - Economy, Finance
9.5.9. - Political sciences

1. Members

Research Scientist

Stephane Grumbach [Team leader, Inria, Senior Researcher, HDR]

Faculty Member

Stephane Frenot [INSA Lyon, Associate Professor, HDR]

Technical Staff

Auguste Caen [Inria, until Oct 2016]
Damien Reimert [INSA Lyon]

PhD Students

Etienne Brodu [INSA Lyon, Atos, granted by CIFRE, until Jun 2016]
Robert Riemann [Inria]

Post-Doctoral Fellow

Aurelien Faravelon [Inria]

Administrative Assistant

Sylvie Boyer [Inria]

Other

Billel Lasledj [Inria, until Apr 2016]

2. Overall Objectives

2.1. Overall Objectives

The DICE team has been created in February 2013 as an "action exploratoire" of Inria to initiate multidisciplinary research on the economy of data resulting from the digital revolution and its impact on all sectors of our society including its political organization.

With the growth of Web 2.0 systems, social data has become a fundamental resource of the economy, much like raw materials. A resource, which is as essential as crude oil, and on which our societies now fully rely. Data is harvested and transformed by industries that grow at an unprecedented pace. Digital corporations offer extremely valuable services, which attract hundreds of millions of users. These corporations generate ecosystems, which become as essential as public utilities and support millions of developers. The new utilities also challenge societies by making obsolete fundamental aspects of their organization, and by generating new imbalances at global scale. At the heart of these changes, is the new capacity to intermediate on two-sided markets, purely in the cloud, that is without having any presence in the physical world were the interactions are taking place.

The objective of DICE is to study the complex dependencies between technological, social and economic systems of the digital age, and to propose technical contributions as well as socio-political analyses. We aim to further investigate the impact of the digital revolution on political systems, anticipated by the French philosopher Michel Serres as expressed in Inria's 2020 Plan. *"if the vast volume of global data [· · ·] were to become accessible to as many people as possible [· · ·], such an event would be liable to put political institutions and the sciences that study them on a new path, perhaps more quickly than we expect."* Michel Serres also insists on the role of computer scientists in studying this revolution and its social impact.

Our contributions target both technical and theoretical aspects of the economy of intermediation platforms. Such platforms are digital intermediaries between users and services. They work on a global scale.

Our aim is threefold:

- We study from technological as well as social, economic, political, and geopolitical points of view, the new ecosystems emerging from the services offered by platforms based on mediating social data, which are reshaping the very form of our organizations;
- We propose technological solutions that answer some of the challenges faced by our societies, such as the concentration of data, the resulting asymmetry of information, and the subsidiarity of computation, that could contribute to better distribute the knowledge among stakeholders;
- We contribute to improve the knowledge of the information society and its implications among specialists as well as non specialists, in the public opinion as well as at the political level.

3. Research Program

3.1. Introduction

Our goal is to address technological issues as well as investigate their impact on society. We believe that addressing both directions simultaneously is essential. More precisely, we focus on the following two objectives:

- Technologies for global intermediation platforms, at reach for unbounded number of users;
- Trans-disciplinary investigations on the global impact of the new intermediation means.

We focus on intermediation platforms, for their increasingly fundamental role in our societies. Intermediation platforms are online systems which offer services to their users, which are well-tuned with their expectation, thanks to the knowledge the platform has accumulated on usage. Search engines and social networks are fundamental examples of intermediation platforms. More generally, intermediation platforms intermediate between producers of services and consumers of services in two-sided markets, with generally one side subsidizing the other. Intermediation will generalise beyond people to things, such as producers or consumers of energy for instance. The capacity to intermediate "in the cloud" with no presence in the physical world in which the market is deployed, by working purely on data with algorithms and in particular learning techniques, is at the heart of the revolution which reshapes our societies.

Platforms ensure a gatekeeping function, always in direct contact with their users, providing them with the most relevant information or contact. They also generate an ecosystem. To do so, platforms allow existing industries as well as new applications proposed by developers to build new services on top of their API. Their impact goes far beyond the Web, while they disrupt step by step all sectors of the economy, transportation, press, education, to name a few.

So far as computer science is concerned, we focus on the technologies used for intermediation, which are at the basis of the largest existing online systems. For the transdisciplinary questions, we focus mostly on the new equilibria that is resulting from the evolution of power balances due mostly to intermediation platforms.

3.2. Intermediation technologies

DICE focuses on intermediation platforms because of the central role they play in the emerging economy.

Intermediation platforms connect users to one another, or users to services with a very high accuracy. They rely on both technological and social innovations. These innovations were unthinkable only a decade ago, when platforms such as Facebook started. They allow communication and interaction between billions of users, gathered in the same digital space, both producers and consumers of data and services. State-of-the-art intermediation platforms include Facebook, Google, Twitter, GitHub, as well as Wikipedia, StackOverflow or Quora. These systems share a common design and their market penetration follows the same pattern. They are built around an initial minimal viable product based on a somehow naive low-tech implementation, which evolves after a few years of improvement to Web giants. Their domination now contributes to standardize the web industry, that means in particular:

- Gatekeeping, a direct relation with users together with services satisfying users' needs;
- Continuous data flows mapped to users' profiles;
- Search engines associating, in a relevant manner, producers, consumers and services.

These common characteristics lead to new software architectural standards, which are shared by all these systems, and used in the peripheral services developed in the ecosystem on top of their API:

- Authentication systems: openId, OAuth, ...
- Object graphs: opengraph, follower/followee scheme, ...
- DataFlow engines: Twitter storm, Google millwheel, ...
- Databases: noSql, keyValues stores, ...
- Application development: javascript, dart, MEAN (Mongo, Express, Angular, Node),...

These architectural components impact the whole digital world. DICE targets systems that use standard architecture services but preserve some aspects we consider as disruptive ones: *data concentration, data symmetry* and *computational subsidiarity*. Our current research activity includes the following directions:

- Peer-to-peer design for preserving users' primary data;
- Third parties based organic systems providing subsidiary data computation hosted at peer sites;
- In-Browser applications that impact mobile device and demonstrate instantaneous usability;
- Flow-based computing enabling a stream based exchange of information between peers at runtime.

3.3. Economy of intermediation

The recent neologism *uberization* coined after the name of *Uber*, a young intermediation platform, may summarize the effects of the digital revolution. This revolution is impacting all sectors of our societies such as organizations, education, energy, transportation and health, to name a few. This revolution results in a serie of what Schumpeter calls *creative destruction*. As traditional sectors disappear, new ones are created. Our societies, which did not anticipate the depth of the changes, have to struggle to adapt to the pace of the development of the industry. Legal reforms in various important sectors including taxation are at stake. Some countries, more reactive than others, are clearly leading the changes, exploiting the benefits for businesses and the capacity to generate information and value, while others are trying to catch up with the global trends.

Data form the bricks of the information society, and their flows between users and services constitute the blood of the industry. We focus in DICE on the strategic role of data in this revolution, and in particular on the systems that harvest the data and concentrate it. In particular, we focus on *intermediation platforms*. Doing so, we investigate the issues they raise and the disruptions they entail.

We are especially interested in the global political impact of intermediation platforms. The settlement of the *right to be forgotten* in Europe, for instance, examplifies the new roles platforms are playing: they are both targets of complaints from institutions and mandatory partners in the governance of the world in the digital era. Indeed, they deeply revolutionize the relations between governments and citizens. If privacy is the focus of considerable attention, together with the state surveillance, in Europe in particular, it is only one aspect of the new knowledge made available. Social media produce considerable knowledge not only on individuals, but on populations as well, their economic fate, their political orientation, etc. On the other hand, open data from governments allow citizens to monitor the action of their governments, as well as to contribute to it. The digital revolution, with the capacity to access information in ways unthinkable in the recent past, modifies completely the balance of powers between citizens, states and corporations.

We investigate the digital world, and more precisely the power relations, from an interdisciplinary perspective. We simultaneously quantify power relations by studying data flows and the rise of intermediation platforms and produce an economical, political and ethical analysis of this new state of affairs. Namely, we show that areas such as the US or China dominate the digital world when others, such as Europe, do not succeed in proposing widely used intermediation platforms. This situation generates several conflicts between countries and companies and prevents *weak* countries from promoting their values and policies.

A new trend is emerging in the humanities, around in particular the digital studies, which promote the cooperation between computer scientists and specialists of social sciences. Among them, the Berkman center for Internet and Society in Harvard, the Medialab at MIT, or the Web Science Institute in the UK have gained strong visibility. They address positive as well as negative externalities of IT for societies, that is the new potentials offered as well as their risks. The Center for Information Technology Research in the Interest of Society in Berkeley also addresses fundamental political impacts on democracy, which can be enhanced by open data as well as another philosophy of political power as currently implemented in the State of California for instance. The Open Data Institute in the UK is also a leading center for political issues in Europe. France should catch up on these research trends, at the intersection of different scientific fields.

4. Application Domains

4.1. Two-Sided Market

Intermediation platforms operate in two-sided markets, that is in environments with two types of actors, producers of good or services on one side, and consumers on the other side. Intermediaries play a fundamental role by allowing the connection of both thypes of actors. If intermediaries already existed in the pre-digital era — banks constitute a historical example of intermediaries — it is really only the advent of digital technologies which boosts the development of intermediation. A large number of activity sectors fall in such a framework, including transportation, press, education, health, etc. We decided to focus on some of them in greater details for their particular relevance.

4.2. Education platforms

Education institutions are at stake because of the new technologies that not only change the access to knowledge, and therefore the traditional euilibrium between teachers and students, but also provide new means to produce knowledge, and share studying experiences.

Our objective is to develop a platform - called Jumplyn - that offers disruptive services for students, helps them produce their work, connects them to other students in the same area, and preserves their contribution online. The platforms targets students. It also aims at offering services on the other side of the education market, i.e. to institutions, by allowing them to organise the work of their students, as well as their evaluation. Jumplyn is accessible online and, as other platforms, evolves continuously.

4.3. Decentralised Voting

Online voting systems are controversial. They are advocated for their simplicity, which could contribute to enhance participation, but criticised for their failure to ensure the same properties as traditional voting systems. We propose an alternative path to online voting relying on decentralised systems with no concentration of data. A patent is under evaluation for the BitBallot protocol.

4.4. City Administration

The team is actively participating to the Inria International Project Lab IPL CityLab on smart cities. We work also with the metropole of Lyon, and its Chief Data Officer in particular, to better understand the equilibrium between online plateforms and the public administration, and the policy regarding data and its accessibility to other parties.

4.5. Metrics for digital economy

While economic metrics based on trade of goods and services, as well as financial exchanges are well-established, exchanges of data, and more generally transborder activities on platforms are not included in standard economic measurements. Defining such metrics both theoretically and practically with means to evaluate them is of great relevance in economy, and beyond.

5. New Software and Platforms

5.1. BitBallot

FUNCTIONAL DESCRIPTION

The BitBallot voting protocol is designed to target large scale communities. The protocol allows users to share only restricted amounts of their data and computation with central platforms as well as other peers. Convinced by the need of new election mechanisms, to support emerging forms of more continuous democracy, we are developing BitBallot, to allow elections to be organized independently of any central authority. The protocol guarantees the following properties, anonymity of the data sources, non interruptible run-time, global access to results, and non predictability of results through partial communication spying.

- Contact: Stéphane Grumbach, Ste´phane Frénot, Damien Reimert, Robert Riemann

5.2. C3PO

FUNCTIONAL DESCRIPTION

Social networks put together individuals with common interests and/or existing real-life relationships so that they can produce and share information. There is a strong interest of individuals towards those networks. They rely on a stable, centralized network infrastructure and a user will always be provided with the same services no matter what their current context is. By contrast, the C3PO project aims at promoting “spontaneous and ephemeral social networks” (SESN), built on top of a peer-to-peer distributed architecture leveraging ad-hoc mobile networks and the resources and services offered by mobile devices. As with traditional social networks, SESN can put together nomad individuals based on their affinities and common interests so that they can collaboratively work on tasks as part of a SESN.

- Contact: Ste´phane Frénot, Damien Reimert

5.3. Jumplyn

Jumplyn is a student project delivery platform. It offers a service based on three features: the ongoing management of the project, resources recommendation, and enhancement of the activity. Like any intermediation platform, it speaks directly to its users, students, and puts them in relation to relevant information.

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- Contact: Ste´phane Frénot, Ste´phane Grumbach
- URL: http://www.jumplyn.com

6. New Results

6.1. Intermediation platforms

Our study of the geopolitics of intermediation aims at grasping the balance of power between platforms, as well as between states - in their relation to platforms - and between platforms and states. We have extended our studies with insights from law in [1] and economics in [2]. We have tuned the metrics we already had in order to better grasp the economic weight of intermediation economy. As we did so, we improved our understanding of the social weight of intermediation platforms and the legal issues which they raise.

Our focus has turned to the analysis of public and private policies and their relation to the development of intermediation platforms. In [3], we study a set of cases ranging from the Safe Harbour to the right to be forgotten. Using the "coalition framework" as our analysis framework, we identify the actors influencing policy-making and potential reasons for the success of failure of policies. Such failures include forbidding innovation or preventing public bodies from stepping up their digital capabilities.

Our work has been intrinsically interdisciplinary, the main result of our work is a global modal of intermediation platforms and their economy, presented in [6]. This model helps to understand the current issues raised by the ubderization for instance.

6.2. Development of platforms

Dice team designs software architectures for intermediation platforms. C3PO and BitBallot targets spontaneous and ephemeral social networks whereas Jumplyn focuses on pure central based system. All these architectures share a common JavaScript layout both at the client and the server sides. In the research context we validate state-of-the art technologies promoted by web leaders such as Google AngularJS, Facebook ReactJS and many others such as Netflix, Wallmart, or the Linux foundation for node.js. The Web environment raises many big issues since all equipments are basically connected to the Internet and the balance between end-user equipment cost and processing power is still a work in progress. Our main research track in such context is to find proper software toolkits hiding Web complexity. We mainly focus on time jitter, cornerstone of Web development, since it implies both end-user and network TCP indecisions. Due to this jitter combination the Web programming model has mutated toward the promises paradigm. It is a complex event based development model provided without external API help. It handles future execution whether successful or not, in a time jittered context. AngularJS, ReactJS, CoffeeScript, NodeJS, MongoDB, ElasticSearch are all time jitter compliant technologies designed for the Web constrains and revolutionising the way we build intermediation platforms.

In C3PO, we tested application in real conditions during the marathon of Vannes and the semi-marathon of Beaune. A few hundred users have downloaded and use the application. The returns on this one are rather positive. [4].

Our joint work with Worldline explores the promises paradigm model to enable automation extraction of independent micro-service. These micro-services called fluxion [9], from the contraction of flow and functions, may be dynamically and transparently moved over a cluster of servers. Our novelty resides in the fact that the original code is not redesigned for the cluster architecture. Fluxion are extracted from the initial code, and an equivalence is maintained between the initially promissified code and the fluxionized one. Code has two facets, a promise one, used to express software services and a fluxion one, used to express software bottlenecks [5].

Eventually our work with Jumplyn explores complex centralised social network. We want to design a software system to later support our technical research hot topics. The target theme is a software platform that helps students handle their projects. University depends more and more on external resources to teach students. Theses resources are both known by students and their teachers, and the pace and range of explored technologies leads to difficulties in teaching state-of-the-art subjects. The more dedicated a professor needs to be in his research activity, the more broad knowledge he has to teach. For instance 20 years ago one could cope software development teaching with one or two programming languages. Nowadays, a single code involves more then four programming languages to be fully understood. This technology spreading issue stands still in many teaching domains, since past technologies are still actives and future one are promising. We build Jumplyn to cope with this unbalanced game. To help student improving their project and avoid working with obsolete technologies, and to help teacher face the universal and inexpensive availability of knowledge. Jumplyn is a complex JavaScript development stack that collects resources for improving student work and providing services to help them from day to day activities. The current stack integrates the following technologies : MaterialDesign, AngularJS, CoffeeScript, NodeJs, MongoDb, ElasticSearch. Managing and developing software service above this stack is a complex research issue for a small sized development team. We do not have any publication on Jumplyn since our first goal is to build a support intermediation platform to study classical issues such as recommendation or web crawling, scraping and indexation with our own sources of raw data.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

Worldline Wordline is a leader in B2B applications development, and is in the front line to provide new technical solution in the Web 2.0 era. We have a CIFRE partnership contract on the study of flow based architectures both at the data centers and at the Web browser level.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. IXXI

The Dice team is hosted in the Rhône-Alpes Institute for Complex Systems, IXXI, located in Ecole Normale Supérieure de Lyon. IXXI is promoting trans-disciplinary research, in particular with social sciences, thus facilitating the establishment of connections with researchers in fields such as economics, history, law, etc.

8.1.2. ARC 6 "Innovative Services for Social Networks"

DICE is involved in a regional project of the Rhoˆne-Alpes region, ARC6 "Innovative Services for Social Networks", with Telecom Saint Etienne.

8.2. National Initiatives

8.2.1. ANR

DICE is involved in an ANR project, which started at the end of 2013

- C3PO, on Collaborative Creation of Contents and Publishing using Opportunistic networks, with LT2C Telecom Saint-Etienne, INSA LYON, IRISA, ChronoCourse, et Ecole des Mines de Nantes.

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

DICE is involved in the CSA project "Big data roadmap and cross-disciplinarY community for addressing socieTal Externalities (BYTE)", Objective ICT-2013.4.2 Scalable data analytics (c) Societal externalities of Big Data roadmap.

8.4. International Initiatives

8.4.1. Inria International Labs

Dice is involved in IPL CityLab@Inria which studies ICT solutions for smart cities. Dice takes part in the Platforms and City Governance theme. Dice focuses on analysing and forecasting the role of intermediation platforms in the governance.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. Member of the Organizing Committees

- Ste´phane Frénot, French Tech, représentant de la COMUE de Lyon
- Ste´phane Grumbach, ANR, Comite´ de Pilotage Scientifique du De´fi 8 « Socie´te´s innovantes »
- Ste´phane Grumbach, scientific committee Global Forum
- Ste´phane Grumbach, scientific committee Colle`ge des Bernardins, Journalisme et bien commun a` l'heure des algorithmes

9.1.2. Scientific Events Selection

9.1.2.1. Chair of Conference Program Committees

Stéphane Grumbach has been chair of the following conferences:

- From data on ecosystems to ecosystems of data, Seminar in cooperation between ENS and EPFL, Lausanne, 21 October 2016
- Seminar Intermediation and Smartness, Anthropocene Curriculum, The Technosphere Issue, Haus der Kulturen der Welt, Berlin, 15-23 April 2016

9.1.3. Invited Talks

Stéphane Grumbach has given the following talks:

- Panel The Transatlantic Data War, obama2016: L'héritage Obama. Tensions et reconfigurations après la présidentielle, Paris, 12-14 déc. 2016
- Panel L'impact des algorithmes sur les media et la culture, Entretiens Jacques Cartier, Lyon 21 novembre 2016
- The Datasphere, in control of ecosystems, The 136th RIHN seminar, Research Institute for Humanity and Nature, Kyoto, 18 November 2016
- Digital Platforms, Europe Asia, Diverging Spaces?, The Relevance of Area Studies for the Sciences and Public Policy, DIJ, Tokyo, 14-15 November 2016
- Platforms vs Administrations, The mutation of data driven government, , ECNU, Shanghai, 9 November 2016
- Panel The Data Revolution, Global Forum, Digitalization: the global transformation, Eindhoven, 19-20 September 2016
- Innovation, pouvoir et territoires, Summer School Cespec 2016, (IX Edizione) Futuri. Immaginare il mondo di domani, Cuneo-Savigliano-Alba-Mondovì, 13-17 settembre 2016
- Révolutions dans la culture et la transmission des savoirs à l'heure du numérique, TUBA'X-PERTS, Lyon, 9 juin 2016
- Conférence "Grand Témoins" : le BIG DATA, Grand rendez-vous de la Métropole, Lyon, 23 mars 2016 video
- Géopolitique du numérique : enjeux des plateformes globales pour la région, LeLabIdF, ThinkLab de la Région Île-de-France, Paris, 17 mars 2016
- Intelligence artificielle, le pouvoir aux machines ? Collège des Bernardins, Paris, 11 février 2016

9.1.4. Research Administration

Ste´phane Grumbach is director of IXXI, the complex Systems Institute.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master : Stéphane Grumbach, Guerre, climat et enjeux de l'Anthropocène, 2h, M1, ENS de Lyon, France

Master : Stéphane Grumbach, La révolution numérique et les difficultés d'ajustement des administrations françaises, 2h, M1, ENTPE, France

Master : Stéphane Grumbach, Réseaux sociaux et Nouveaux Outils de Communication, 2h, M1, INSA Lyon, France

Master : Damien Reimert, - Bitcoin, 24h, M1, INSA de Lyon, France

Master : Damien Reimert, Javascript, 43h, M1, Télécom St-Étienne, France

Licence : Damien Reimert, Développement Mobile, 39h, L3, Télécom St-Étienne, France

Licence : Aurélien Faravelon, HTML5 CSS3 Javascript, 24h, L3, IUT 2 Grenoble, France

Master : Aurélien Faravelon, Economie de l'intermediation, 2h, M2, Ecole centrale de Lyon, France

Licence : Robert Riemann, INSA, Algorithmique et programmation 1, 27HETD, L1, INSA Lyon, France

9.2.2. Supervision

PhD : Etienne Brody, DataFlow compilation from JavaScript, INSA Lyon, 21 Juin, Stéphane Frénot

PhD in progress : Robert Riemann, systemes de vote decentralise´s, sept 2014, Ste´phane Grumbach

9.3. Popularization

Aurélien Faravelon: 12/05/2016, Débats Citoyens, Musée Galo Romain de Lyon

Robert Riemann: 28/12/2016, Chaos Communication Congress/We fix the Net assembly, Hambourg

10. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journal

[1] J.-S. BERGÉ, S. GRUMBACH.*La Sphère des Données : Objet du Droit International et Européen*, in "Journal du droit international (Clunet)", 2016, https://hal.inria.fr/hal-01359798.

[2] A. FARAVELON, S. FRÉNOT, S. GRUMBACH.*Chasing data in the Intermediation Era: Economy and Security at stakes*, in "IEEE Security and Privacy Magazine", January 2016, https://hal.inria.fr/hal-01107365.

International Conferences with Proceedings

[3] A. FARAVELON, S. GRUMBACH.*The Complexity of Public and Private Policies for Big Data*, in "22nd ICE/IEEE ITMC International Technology Management Conference", Trondheim, Norway, IEEE, June 2016, https://hal.archives-ouvertes.fr/hal-01404281.

Conferences without Proceedings

[4] A. BOUTET, S. FRÉNOT, F. LAFOREST, P. LAUNAY, N. LE SOMMER, Y. MAHÉO, D. REIMERT.*C3PO: A Network and Application Framework for Spontaneous and Ephemeral Social Networks.: [this paper ha been published in WISE2015 conference]*, in "Ubiquité et mobilité 2016", Lorient, France, July 2016, https://hal.archives-ouvertes.fr/hal-01384311.

[5] E. BRODU, S. FRÉNOT, F. OBLÉ.*Transforming Javascript Event-Loop Into a Pipeline*, in "SAC", Pisa, Italy, April 2016 [*DOI :* 10.1145/2851613.2851745], https://hal.archives-ouvertes.fr/hal-01238895.

[6] A. FARAVELON, S. GRUMBACH.*Platforms as Governments*, in "The Internet, Policy & Politics Conferences", Oxford, France, September 2016, https://hal.archives-ouvertes.fr/hal-01404295.

Scientific Popularization

[7] S. GRUMBACH, P. VALDURIEZ.*Les données en question*, in "Interstices", March 2016, https://hal.inria.fr/hal-01350453.

Project-Team DRACULA

Multi-scale modelling of cell dynamics : application to hematopoiesis

IN COLLABORATION WITH: Institut Camille Jordan

IN PARTNERSHIP WITH:
CNRS

Université Claude Bernard (Lyon 1)

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Modeling and Control for Life Sciences

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Project-Team DRACULA

Creation of the Team: 2010 January 01, updated into Project-Team: 2011 January 01

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6.1.2. - Stochastic Modeling (SPDE, SDE)
6.1.3. - Discrete Modeling (multi-agent, people centered)
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2.2.5. - Immune system diseases
2.2.6. - Neurodegenerative diseases

1. Members

Research Scientists

Mostafa Adimy [Team leader, Inria, Senior Researcher, HDR]
Samuel Bernard [CNRS, Researcher]
Fabien Crauste [CNRS, Researcher, HDR]
Olivier Gandrillon [CNRS, Senior Researcher, HDR]
Thomas Lepoutre [Inria, Researcher]
Vitaly Volpert [CNRS, Senior Researcher, HDR]

Faculty Members

Philippe Michel [Ecole Centrale de Lyon, Associate Professor]
Laurent Pujo Menjouet [Univ. Lyon I, Associate Professor]
Léon Tine [Univ. Lyon I, Associate Professor]
Celine Vial [Univ. Lyon I, Associate Professor, started September 2015, HDR]

PhD Students

Loïc Barbarroux [Ecole Centrale de Lyon, French ministry scholarship, started October 2013]
Apollos Besse [Univ. Lyon I, French ministry scholarship, started October 2014]

Arnaud Bonnaffoux [ENS Lyon, granted by CIFRE, started November 2015]
Anass Bouchnita [Univ. Lyon I, French ministry scholarship, started October 2014]
Loïs Boullu [Univ. Lyon I, Canadian scholarship, started October 2014]
Aurélien Canet [Univ. Lyon I, granted by Labex Milyon and the start up Neolys Diagnostics, started January 2016]
Abdennasser Chekroun [Univ. Lyon I, Algerian government scholarship, started October 2012 until March 2016]
Flavien Duparc [Univ. Lyon I, French ministry scholarship, started October 2014]
Ronan Duchesne [ENS Lyon, started February 2016]
Tatiana Galochkina [Univ. Lyon I and Moscow, French-Russian scholarship, started October 2014]
Simon Girel [Univ. Lyon I, granted by Labex Milyon, started September 2015]
Ulysse Herbach [Univ. Lyon I, French ministry scholarship, started October 2015]
Marine Jacquier [Univ. Lyon I, French ministry scholarship, started October 2012 until February 2016]

Post-Doctoral Fellows

Pauline Mazzocco [Univ. Lyon I, until September 2016]
Xuefeng Gao [Inria, until October 2016]

Visiting Scientist

Abdelkader Lakmeche [Univ. Sidi Bel Abbés, Algeria, until August 2016, HDR]

Administrative Assistant

Caroline Lothe [Inria]

Others

Raphael Bournhonesque [Univ. Lyon I, M2 student, until May 2016]
Nicolas Corthorn Errazuriz [Inria, M2 student, until Mar 2016]
Manon Muntaner [Univ. Lyon I, M1 student, started April 2016 until July 2016]
Angélique Perrillat [Univ. Lyon I, M2 student, started March 2016 until August 2016]

2. Overall Objectives

2.1. Presentation

Dracula is a joint research team between Inria, University of Lyon 1 (UCBL) and CNRS (ICJ, UMR 5208 and CGMC UMR 5534). It was created in January 2011.

The Dracula project is devoted to multi-scale modeling in biology with applications to normal and pathological hematopoiesis (blood cell production). Multi-scale modeling implies simultaneous modeling of intra-cellular networks (molecular level), of cell behavior (cellular level), of the dynamics of cell populations (organ or tissue) with the control by other organs (organism) (see Figure 1). Such modeling represents one of the major challenges in modern science due to its importance and because of the complexity of biological phenomena and of the presence of very different scales.

Hematopoiesis is a complex process that begins with primitive hematopoietic stem cells and results in formation of mature cells: red blood cells, white cells and platelets. Blood cells are produced in the bone marrow, from where mature cells are released into the blood stream. Hematopoiesis is based on a balance between cell proliferation (including self-renewal), differentiation and apoptosis (programmed cell death). The choice between these three possibilities is determined by intra-cellular regulatory networks and by numerous control mechanisms in the bone marrow (see Figure 2) or carried out by other organs. Intra-cellular regulatory networks are complex biochemical reactions involving proteins, enzymes and signalling molecules. Thus, hematopoiesis is a complex process which has a vital importance for the organism. Its malfunctioning can result in numerous blood diseases including leukemia.

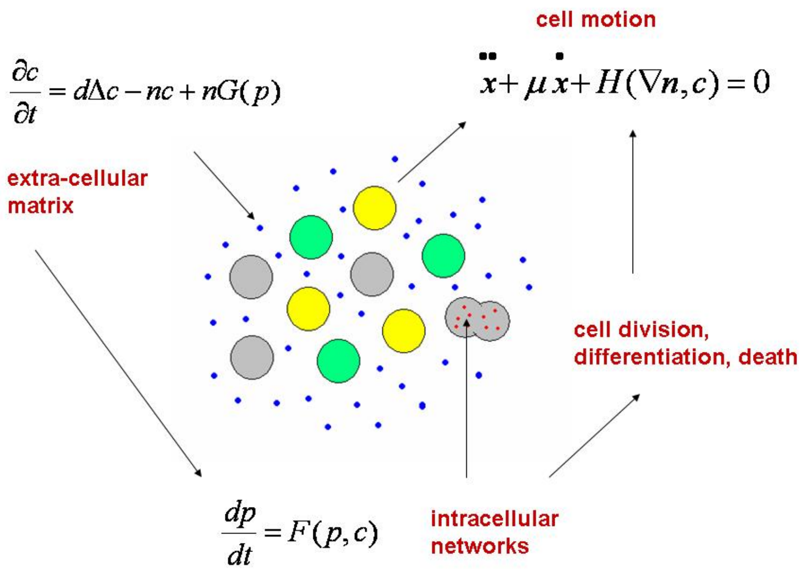

Figure 1. Schema of multi-scale models of cell dynamics: DPD-PDE-ODE models.

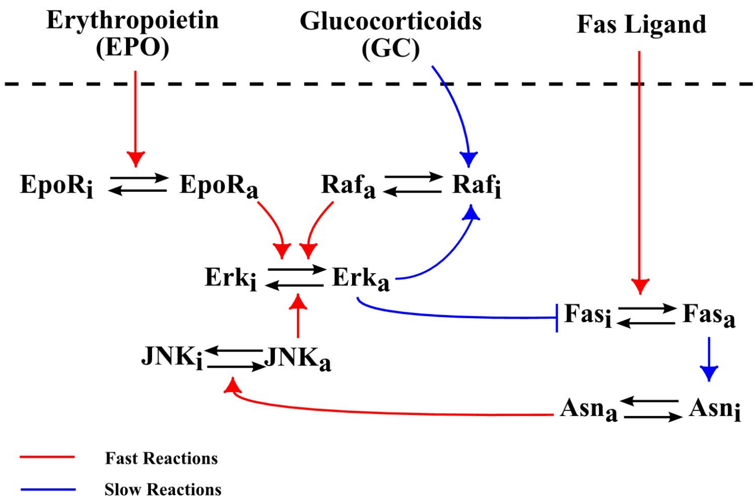

Figure 2. A schematic description of the intra-cellular molecular events that are relevant for decision making in an erythroid progenitor. The non active form of the protein is labeled i, the active form a. Blue lines indicate transcriptional regulation, red lines indicate biochemical regulation.

Multi-scale modeling in hematopoiesis holds a great potential. A variety of techniques exists to deal with this problem. However, the complexity of the system poses new difficulties and leads to the development of new tools. The expected results of this study are numerous. On one hand, it will shed new light on the different physiological mechanisms that converge toward the continuous regeneration of blood cells, for example: the behavior of hematopoietic stem cells under stress conditions, the understanding of deregulation of erythropoiesis (the process of red blood cell production) under drag treatments (this can lead to lack of red blood cells (anemia), or a surplus of red blood cells), the understanding of immune response process under the control of T-cell activation and memory cell generation, in order to adapt infection prevention strategies.

On the other hand, the modeling methods developed here for hematopoiesis are relevant to study other complex biological systems. We pay a special attention on developing methods that are not restricted to hematopoiesis. In parallel with hematopoiesis modeling, most of members of Dracula keep on working on modeling of other biological phenomena, for example: tumor cells, prion disease, adaptive dynamics, atherosclerosis, and so on. Approaches developed in the present project are very likely relevant in these fields too.

An important part of our researches is in close collaboration with biologists and physicians in order to stay in close contact with the biological and medical goals. The presence, within the project, of a biologist (Olivier Gandrillon) that has acquired over the years the know-how required for interacting with mathematicians is probably one of the main asset of the project. He participates actively in many tasks of our program, especially involving description of biological process, and he is "consultant" for other biological aspects, in the other parts of the project.

2.2. Keywords

Multi-scale modeling; Mathematical Biology; Computational Biology; Hematopoiesis modeling; Erythropoiesis modeling; Leukemia modeling; Immune response modeling; Regulatory networks; Partial differential equations; Delay differential equations; Agent-based modeling; Dynamical systems.

2.3. Objectives

Our aim in this project is the development of modern tools of multi-scale modeling in biological phenomena (and in particular, for hematopoiesis). For the last four years, we have fixed the following objectives:

- Multi-scale modeling will be carried out on the basis of coupled DPD-PDE-ODE models, where dissipative particle dynamics (DPD) will be used in order to describe individual cells and relatively small cell populations, partial differential equations (PDE) will be used to describe concentrations of bio-chemical substances in the extra-cellular matrix, and ordinary differential equations (ODE, deterministic or stochastic) for intra-cellular regulatory networks (Figure 1).
- A new software "Cell dynamics" will be created in order to study these models numerically.
- Partial differential equations (PDE) will also be used to describe cell populations considered as continuous medium. We will study reaction-diffusion-convection equations with or without hydrodynamics, transport equations (hyperbolic PDEs) in which the structure can be age, size, maturity, protein concentration, etc. In some particular cases, transport equations will be reduced to delay differential equations (DDE) which are less difficult to investigate analytically.
- Numerical simulations will be compared with analytical studies of simplified test cases and model examples.
- Numerical simulations will also be compared to the "Cell dynamics" approach.
- Multi-scale models of hematopoiesis will be used to study normal situation or homeostasis where different cell types are in equilibrium with each other. This equilibrium is determined by intra-cellular regulatory networks and by numerous feedbacks by cell populations and other organs.
- Development and dynamics of blood diseases will be modeled taking into account disequilibrium of regulatory networks or feedbacks. On the other hand, we will model various approaches to treatment of these diseases (chemotherapy, chronotherapy). We will compare then the results with available biological and clinical information.

3. Research Program

3.1. Cell dynamics

We model dynamics of cell populations with two approaches, dissipative particle dynamics (DPD) and partial differential equations (PDE) of continuum mechanics. DPD is a relatively new method developed from molecular dynamics approach largely used in statistical physics. Particles in DPD do not necessarily correspond to atoms or molecules as in molecular dynamics. These can be mesoscopic particles. Thus, we describe in this approach a system of particles. In the simplest case where each particle is a sphere, they are characterized by their positions and velocities. The motion of particles is determined by Newton's second law (see Figure 1).

In our case, particles correspond to biological cells. The specific feature of this case in comparison with the conventional DPD is that cells can divide (proliferation), change their type (differentiation) and die by apoptosis or necrosis. Moreover, they interact with each other and with the extra-cellular matrix not only mechanically but also chemically. They can exchange signals, they can be influenced by various substances (growth factors, hormones, nutrients) coming from the extra-cellular matrix and, eventually, from other organs.

Distribution of the concentrations of bio-chemical substances in the extra-cellular matrix will be described by the diffusion equation with or without convective terms and with source and/or sink terms describing their production or consumption by cells. Thus we arrive to a coupled DPD-PDE model.

Cell behaviour (proliferation, differentiation, apoptosis) is determined by intra-cellular regulatory networks, which can be influenced by external signals. Intra-cellular regulatory networks (proteins controlling the cell cycle) can be described by systems of ordinary differential equations (ODE). Hence we obtain DPD-PDE-ODE models describing different levels of cell dynamics (see Figure 1). It is important to emphasize that the ODE systems are associated to each cell and they can depend on the cell environment (extra-cellular matrix and surrounding cells).

3.2. From particle dynamics to continuum mechanics

DPD is well adapted to describe biological cells. However, it is a very time consuming method which becomes difficult to use if the number of particles exceeds the order of 10^5-10^6 (unless distributed computing is used). On the other hand, PDEs of continuum mechanics are essentially more efficient for numerical simulations. Moreover, they can be studied by analytical methods which have a crucial importance for the understanding of relatively simple test cases. Thus we need to address the question about the relation between DPD and PDE. The difficulty follows already from the fact that molecular dynamics with the Lennard-Jones potential can describe very different media, including fluids (compressible, incompressible, non-Newtonian, and so on) and solids (elastic, elasto-plastic, and so on). Introduction of dissipative terms in the DPD models can help to justify the transition to a continuous medium because each medium has a specific to it law of dissipation. Our first results [33] show the correspondence between a DPD model and Darcy's law describing fluid motion in a porous medium. However, we cannot expect a rigorous justification in the general case and we will have to carry out numerical comparison of the two approaches.

An interesting approach is related to hybrid models where PDEs of continuum mechanics are considered in the most part of the domain, where we do not need a microscopical description, while DPD in some particular regions are required to consider individual cells.

3.3. PDE models

If we consider cell populations as a continuous medium, then cell concentrations can be described by reaction-diffusion systems of equations with convective terms. The diffusion terms correspond to a random cell motion and the reaction terms to cell proliferation, differentiation and death. These are more traditional models [36] with properties that depend on the particular problem under consideration and with many open questions, both from the point of view of their mathematical properties and for applications. In particular we are interested in the spreading of cell populations which describes the development of leukemia in the bone marrow and many other biological phenomena (solid tumors, morphogenesis, atherosclerosis, and so on). From the mathematical point of view, these are reaction-diffusion waves, intensively studied in relation with various biological problems. We will continue our studies of wave speed, stability, nonlinear dynamics and pattern formation. From the mathematical point of view, these are elliptic and parabolic problems in bounded or unbounded domains, and integro-differential equations. We will investigate the properties of the corresponding linear and nonlinear operators (Fredholm property, solvability conditions, spectrum, and so on). Theoretical investigations of reaction-diffusion-convection models will be accompanied by numerical simulations and will be applied to study hematopoiesis.

Hyperbolic problems are also of importance when describing cell population dynamics ([42], [46]), and they proved effective in hematopoiesis modelling ([28], [29], [31]). They are structured transport partial differential equations, in which the structure is a characteristic of the considered population, for instance age, size, maturity, protein concentration, etc. The transport, or movement in the structure space, simulates the progression of the structure variable, growth, maturation, protein synthesis, etc. Several questions are still open in the study of transport PDE, yet we will continue our analysis of these equations by focusing in particular on the asymptotic behaviour of the system (stability, bifurcation, oscillations) and numerical simulations of nonlocal transport PDE.

The use of age structure often leads to a reduction (by integration over the age variable) to nonlocal problems [46]. The nonlocality can be either in the structure variable or in the time variable [28]. In particular, when coefficients of an age-structured PDE are not supposed to depend on the age variable, this reduction leads to delay differential equations.

3.4. Delay differential Equations

Delay differential equations (DDEs) are particularly useful for situations where the processes are controlled through feedback loops acting after a certain time. For example, in the evolution of cell populations the transmission of control signals can be related to some processes as division, differentiation, maturation, apoptosis, etc. Because these processes can take a certain time, the system depends on an essential way of its past state, and can be modelled by DDEs.

We explain hereafter how delays can appear in hematopoietic models. Based on biological aspects, we can divide hematopoietic cell populations into many compartments. We basically consider two different cell populations, one composed with immature cells, and the other one made of mature cells. Immature cells are separated in many stages (primitive stem cells, progenitors and precursors, for example) and each stage is composed with two sub-populations, resting (G0) and proliferating cells. On the opposite, mature cells are known to proliferate without going into the resting compartment. Usually, to describe the dynamic of these multi-compartment cell populations, transport equations (hyperbolic PDEs) are used. Structure variables are age and discrete maturity. In each proliferating compartment, cell count is controlled by apoptosis (programmed cell death), and in the other compartments, cells can be eliminated only by necrosis (accidental cell death). Transitions between the compartments are modelled through boundary conditions. In order to reduce the complexity of the system and due to some lack of information, no dependence of the coefficients on cell age is assumed. Hence, the system can be integrated over the age variable and thus, by using the method of characteristics and the boundary conditions, the model reduces to a system of DDEs, with several delays.

Leaving all continuous structures, DDEs appear well adapted to us to describe the dynamics of cell populations. They offer good tools to study the behaviour of the systems. The main investigation of DDEs are the effect of perturbations of the parameters, as cell cycle duration, apoptosis, differentiation, self-renewal, and re-introduction from quiescent to proliferating phase, on the behaviour of the system, in relation for instance with some hematological disorders [38].

4. Application Domains

4.1. Normal hematopoiesis

4.1.1. Introduction

Modelling normal hematopoiesis will allow us to explore the dynamical appearance of the various cell types, originating from the stem cell compartment, through the bone marrow development up to the blood stream. The differentiated cell types will both fulfill physiological functions, and play a key role on the feedback control on homeostasis (balance of the system) in their own lineages. We will describe the hematopoiesis from three different points of view:

- The initial cell type, the hematopoietic stem cell (HSC);
- The lineage choice question;
- Three differentiated lineages that are responsible for specific function, namely oxygen transport, immune response and coagulation.

The basic mechanisms of our modelling approach are as follows:

- Any cell type can have two possibilities at each time step: to divide or to die.
- At any division step, the cell can either give rise to two daughter cells which are identical to the mother cell (self-renewal) or that are more advanced in their differentiation.

All these processes will be first modelled at the cellular level. In parallel, we will develop models of intra-cellular molecular networks (as some proteins controlling the cell cycle) influencing this decision making process, so as to be able to describe both micro-to-macro effects (molecules influencing the global cell behaviour) as well as macro-to-micro effects (like the global state of the cell population influencing the molecular behaviour).

4.1.2. Hematopoietic stem cells (HSC)

Although widely studied by biologists, HSC are still poorly understood and many questions remain open: How fast and how frequently do they divide? How many of them are in the bone marrow and where? How is their behaviour modified under stress conditions such as blood loss or transfusion?

Our modelling approach will be based on two methods: deterministic and stochastic differential equations with delays (discrete and distributed), on one hand, and the DPD method using the individual based modelling on the other hand. The differential equation models based on the work initiated by Mackey [39] will describe the HSC compartment in normal conditions and the behaviour of these cells under some stress. The DPD method, as a complementary approach, will emphasize the spatial regulation of stem cell behaviour, and we will focus our attention to give a possible answer regarding their location in the bone marrow and the roles of the niche, their number in the system, their possible role under stress (that is their reaction under the different feedback controls).

4.1.3. Blood cell functions

(i) O2 transport: red lineage

O_2 transport is provided by red blood cells (RBC) also called erythrocytes. Many different stages of maturity (including progenitors, precursors, reticulocytes and erythrocytes) are necessary to achieve the complete formation of RBC. These latter are then released in the blood stream where they transport oxygen. The whole process is tightly dependent on a robust well-balanced equilibrium called homeostasis.

It has been shown in the 1990's that apoptosis is regulated by EPO, a growth factor released by the kidneys under hypoxia. But also, under severe stress (like an important blood loss) some other molecules known as glucocorticoids can be released leading to an increase of the self-renewing rate for each generation. This led to the formulation of a first model, demonstrating the role of self-renewal.

The study of the red blood cell lineage will involve different scale levels, from the molecular one, with the effects of the hormones on the surface and internal parts of the cell, the cell contacts in each stage of RBC formation, and the red branch population in its whole with all the interactions taken into account (see Figure 3) in normal and stress conditions.

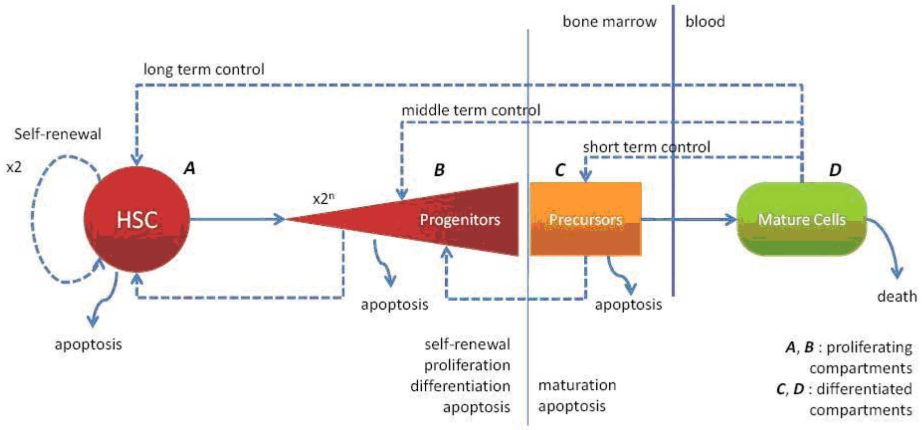

Figure 3. Scheme of Erythropoiesis Modelling ([27]). Without considering explicitly growth factor mediated regulation, all controls (proliferation, self-renewal, differentiation, apoptosis) are mediated by cell populations (dashed arrows). Mature cells can either regulate immature (HSC, progenitors) or almost mature (precursors) cells, precursors may act on progenitor dynamics, etc..

In order to couple the cellular behaviour to explicit molecular events, we will describe the events through a molecular network that is based upon the work of [44]. A first version of this model is shown in Figure 2.

(ii) Immune response

We will focus on the production of T-cells during an immune response. This represents an important activity of the lymphoid branch, part of leucopoiesis (white blood cell production). Several models of the myeloid branch of leucopoiesis have been investigated in the frame of specific diseases (for instance cyclical neutropenia ([38], [32]), chronic myelogenous leukemia [40]).

Time evolution of T-cell counts during an infection is well known: following the antigen presentation, the number of cells quickly increases (expansion), then decreases more slowly (contraction) and stabilizes around a value higher than the initial value. Memory cells have been produced, and will allow a faster response when encountering the antigen for a second time. Mechanisms that regulate this behaviour are however not well known.

A recent collaboration just started with immunologists (J. Marvel, Ch. Arpin) from the INSERM U851 in Lyon, who provide experimental data that are essential to assess the significance of models, based on strongly nonlinear ordinary differential equations, that can be proposed for T-cell production (Figure 4). By considering molecular events leading to cell activation when encountering a virus, we will propose a multi-scale model of the immune response.

(iii) Coagulation: platelet lineage

Thrombopoiesis, the process of production and regulation of platelets, is similar to erythropoiesis although important differences are observed. These two processes have an immature progenitor (MEP) in common. Platelets are involved in blood coagulation, and can be the source of blood diseases (thrombopenia, thrombocytosis). Their production is mainly regulated by thrombopoietin (TPO), a growth factor similar to EPO.

It is important to mention that very few experimental data exist in the literature, and mathematical modelling of thrombopoiesis did not attract so much attention in the past 20 years. However, collaboration with some leading hematologists in this domain will allow us to get updated and new data regarding this process.

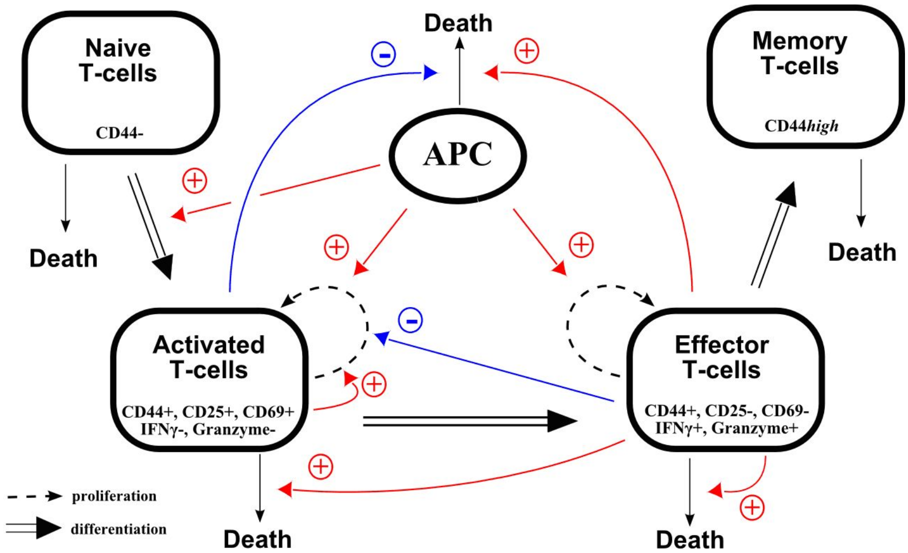

Figure 4. Model of the immune response resulting in the generation of CD8 memory T cells. The response starts with a viral infection resulting in the presentation of viral antigens through antigen presenting cells (APC) to naive T-cells. These latter, once activated, differentiate into activated cells which, under specific feedback loops will either die, differentiate into effector cells or self-renew. Differentiation of effector cells (killer cells) will result in the production of memory cells.

Deterministic models, in the form of structured transport partial differential equations, will be proposed to describe platelet dynamics, through the description of HSC, megakaryocytic progenitor and megacaryocyte (platelet precursor) compartments. Circulating TPO, regulated by platelets, will induce feedback loops in thrombopoiesis, and we will investigate the dynamics of platelet production and emergence of platelet-related diseases.

4.2. Pathological hematopoiesis

The knowledge of hematopoiesis and related diseases has evolved to become a great deal in the past years, and Mackey's previous models (ref. [30]) do not allow us to correctly answer current questions that are clearly oriented toward the investigation of cell signalling pathways. These models nevertheless bring relevant ideas about the essential features of such modelling. It is also noteworthy that even though models of hematopoiesis have existed for quite a long time, their application to questions of explanation and prediction of hematopoiesis dynamics that are encountered in the clinic is still not sufficiently frequent, even though much progress has been achieved in the cooperation between hematologists and mathematicians [41]. This is in the optic of testable experimental predictions that the multi-scale model for pathological hematopoiesis will be developed. For instance, we will concentrate on myeloid leukemias (CML and AML) and their treatment.

4.2.1. Leukemia Modelling

(i) Chronic Myeloid Leukemia

The strong tyrosine kinase activity of the BCR-ABL protein is the basis for the main cell effects that are observed in CML: significant proliferation, anti-apoptotic effect, disruption of stroma adhesion properties, genomic instability. This explains the presence in CML blood of a very important number of cells belonging to the myeloid lineage, at all stages of maturation.

We will consider models based on ordinary differential equations for the action of the main intra- and extra-cellular proteins involved in CML (as BCR-ABL protein), and of transport equations (with or without delay, physiologically structured or not to represent healthy and leukemic cell populations, take into account many interactions between proteins (especially BCR-ABL), cells (anti-apoptotic effect, etc.), and their environment (disruption of stroma adhesion properties, for example). Transport pertains thus to cells from one compartment (or a group of compartments) to another compartment, with a determined speed of aging or maturation. These compartments may be detailed or not: the less mature are stem cells, then progenitor cells, etc.

(ii) Acute Myeloid Leukemia

The natural history of CML leads to its transformation ("blast crisis") in acute myeloid leukemia (AML), following supplementary genetic alterations that produce a maturation arrest (myeloid in $3/4$ of cases, lymphoid in $1/4$ of cases, confirming the insult to pluripotent stem cells), leading to an accumulation of immature cells in the bone marrow and in the general circulation, resulting in deep medullary impairment and fast fatal outcome, in spite of chemotherapy. This phenomenon is the same as the one observed in de novo AML, i.e., AML without a previous chronic phase.

The different modelling methods of AML will be similar to the ones described for CML, with some exceptions: the appearance of BCR-ABL mutations, which are not relevant in the case of AML, the appearance of a gene (spi-1) involved in the differentiation arrest, and constitutive activation of EPO receptor or Kit activating mutations promote proliferation and survival. This explains the accumulation of immature cells in the bone marrow and in the blood stream.

4.2.2. Treatment

As far as treatment of pathological hematopoiesis is concerned, two main strategies currently exist that aim at slowing down or eliminating damaged cell proliferation. The first of these strategies consists in launching the apoptotic process during the cell division cycle. This process is activated, for example when the cell is unable to repair damages, e.g., after exposure to cytostatic drugs. A typical example is apoptosis induced by chemotherapy-induced DNA damage: The damage is recognised by the cell, which then activates the sentinel protein p53 ("guardian of the genome") that arrests the cell cycle to allow, if possible, damage repair. If the latter is unrecoverable, then p53 activates the endogenous apoptotic processes.

The second strategy aims at pushing damaged cells toward the differentiation that has been stopped in the course of their genetic mutation. Since a few years back, a new approach has been developed around the strategy of differentiation therapy. This therapy relies on molecules (growth factors and specific cytokines) that are able to re-initialise the cell differentiation programs that have been modified during malignant transformation. The cancer that is most concerned by the development of this differentiation therapy is AML whose malignant cells present highly undifferentiated features and the ones that present a translocation responsible for the differentiation (PML/RAR of the promyelocytic form, AML1/ETO and CBFbeta/MyH11, involving Core Binding Factors alpha and beta).

Mathematical models based on ordinary differential equations will be developed to describe the action of drugs (in the two cases mentioned above). They will take into account interactions between drugs and their environment. Our goal will be the optimization of possible synergies between drugs acting on distinct cellular targets, and the control of resistances to these treatments as well as their toxicities.

Curative and palliative strategies must take into account the dynamics of healthy and leukemic hematopoietic cells at multiple scales. In time, from optimal scheduling of combination therapy (hours) to avoiding the development of resistances and relapse (months to years). In space, from the stem cell niche to circulating blood. In organization, from gene and signalling networks (JAK/STAT, BCR-ABL) to cell populations and cytokine regulation (EPO, CSFs). Several recent qualitative models have provided insight in the complex dynamics of the disease and the response to treatments. Many of these models focus on the control or regulation processes that promote homeostasis or oscillatory behavior in cell number. However, as A. Morley points out, "once the control-systems features of hematopoiesis are accepted, the ability to construct a model that shows oscillatory behavior, even if the model incorporates the latest advances in hematopoietic cell biology, really adds little new knowledge. Rather, the challenge to modellers would seem to be to provide detailed predictions for the input-output characteristics of the different parts of the various control systems so that these predictions can be tested by experimental hematologists and a truly quantitative description of hematopoiesis can emerge".

We propose for instance, to use models in the form of structured transport partial differential equations (with or without delay, physiologically structured or not) to represent the competition between target, resistant and healthy cell populations. The resulting models to describe the dynamic of these cell populations under the action of drugs are multi-scale systems of the form (Hyperbolic PDE)-ODE or DDE-ODE. For instance, we will develop mathematical models of chronotherapy and pharmacotherapy for CML and AML.

5. New Software and Platforms

5.1. CelDyn

KEYWORDS: Modeling - Bioinformatics - Biology
FUNCTIONAL DESCRIPTION

Software "Celdyn" is developed in order to model cell population dynamics for biological applications. Cells are represented either as soft spheres or they can have more complex structure. Cells can divide, move, interact with each other or with the surrounding medium. Different cell types can be introduced. When cells divide, the types of daughter cells are specified. A user interface is developed.

- Participants: Nikolai Bessonov, Vitaly Volpert, Alen Tosenberger and Laurent Pujo-Menjouet
- Contact: Vitaly Volpert

6. New Results

6.1. Mathematical modeling of memory CD8 T cell ontogeny and quantitative predictions

Primary immune responses generate both short-term effector and long-term protective memory cells from naive CD8 T cells. The delineation of the genealogy linking those cell types has been complicated by the lack of molecular markers allowing to discriminate effector from memory cells at the peak of the response. Coupling transcriptomics and phenotypic analyses, and in collaboration with immunologists from Lyon (Jacqueline Marvel's team, Centre International de Recherche en Infectiologie), we identified a novel marker combination that allows to track nascent memory cells within the effector phase [13]. We then used mathematical models based upon our previous description of the dynamics of T cell immune response ([35], [45]) to investigate potential differentiation pathways. We thereby could describe the dynamics of population-size evolutions to test potential progeny links and we could demonstrate that most cells follow a linear naive-early effector-late effector-memory pathway. Of interest for vaccine design, our mathematical model also allows long-term prediction of memory cell numbers from early experimental measurements. Alltogether, our work thus provides a phenotypic means to identify effector and memory cells, as well as a mathematical framework to investigate the ontology of their generation and to predict the outcome of immunization regimens (vaccines) in terms of memory cell numbers generated.

6.2. Multiscale model of the CD8 T cell immune response

We presented in [43] the first multiscale model of CD8 T cell activation in a lymph node. We now described in [14] an update of this modeling approach. CD8 T cell dynamics are described using a cellular Potts model (hence cells are discrete interacting objects), whereas intracellular regulation is associated with a continuous system of nonlinear ordinary differential equations. We focused our study on describing the role of Interleukin 2 (IL2) secretion. One major result was the demonstration of the full relevance of a bona fide multiscale description of the process: the observed (all or none) emergent behavior at the cell population scale could not have been straightforwardly deduced from the simple examination of (seemingly tenuous) differences in the cellular or molecular levels in separation.

6.3. Moving the Boundaries of Granulopoiesis Modelling

The human blood cell production system usually remains extremely robust, in terms of cell number or function, with little signs of decline in old age. To achieve robustness, circulating blood cells rely on a formidable production machinery, the hematopoietic system, located in the bone marrow. All circulating blood cells-red blood cells, white blood cells and platelets-are renewed on a daily basis. The hematopoietic system produces an estimated $1e12$ cells per day. This is a significant fraction of the $3.7e13$ cells in an adult. Robustness is partly due to the short time scales at which cell populations are able to return to equilibrium, combined with large cell numbers and renewal rates. White blood cells (WBCs), among which neutrophils are most prevalent, are the body's first line, innate immune system. Upon infection, WBCs are mobilized from the bone marrow, to increase their number in circulation and fight off pathogen within hours. The 26 billion circulating neutrophils in human have a mean residence time of only 11h in the blood. After their release from the bone marrow, they quickly disappear in the peripheral tissues and are destroyed in the spleen, liver and bone marrow. In addition to the high renewal rate of circulating blood cells, a large number of mature neutrophils, ten times or more the circulating number, is kept in a bone marrow reserve, ready for entering circulation. This high renewal rate and mobilization capability, however, come at a cost. The blood system is an easy target for chemotherapeutic drugs, whose main way of acting is by killing proliferating cells. White blood cells and end especially neutrophils, with their fast turnover, are particularly vulnerable to chemotherapy. Chemotherapy can induce neutropenia-a state of low absolute neutrophil count (ANC)-in cancer patients, which puts them at risk of infection. Homeostatic regulation of white blood cells is mainly controlled by the cytokine Granulocye-Colony Stimulating Factor (G-CSF). G-CSF promotes survival of white blood cell precursors and their differentiation into mature cells. The identification of this protein in the 1980's, and the subsequent development of human recombinant forms of G-CSF paved the way to the treatment of chemotherapy-induced neutropenia. G-CSF therapy as also been successful at treating congenital and other forms of neutropenia. Today, G-CSF is used as an adjuvant in several anti-cancer treatment protocols. The aim of the adjuvant therapy is to minimize the length of the neutropenic episodes. However, exogenous G-CSF administration interferes with white blood cell production regulation. What should be a straightforward effect–administer G-CSF to cause the ANC to increase–turns to be more complicated than that. For instance, it was observed that early timing of G-CSF administration could lead to prolonged neutropenic phase. Thus, in order to take advantage of the full potential of G-CSF, a detailed understanding of the physiological interaction between neutrophils and exogenous G-CSF is necessary. In this issue of the Bulletin (see [7]), Craig and colleagues present a physiological model of neutrophil production that includes a detailed modelling of the kinetics of G-CSF.

6.4. Bone marrow infiltration by multiple myeloma causes anemia by reversible disruption of erythropoiesis

Multiple myeloma (MM) infiltrates bone marrow and causes anemia by disrupting erythropoiesis, but the effects of marrow infiltration on anemia are difficult to quantify. Marrow biopsies of newly diagnosed MM patients were analyzed before and after four 28-day cycles of nonerythrotoxic remission induction chemotherapy. Complete blood cell counts and serum paraprotein concentrations were measured at diagnosis and before each chemotherapy cycle. At diagnosis, marrow area infiltrated by myeloma correlated negatively with hemoglobin, erythrocytes, and marrow erythroid cells. After successful chemotherapy, patients with less than 30% myeloma infiltration at diagnosis had no change in these parameters, whereas patients with more than 30% myeloma infiltration at diagnosis increased all three parameters. Clinical data were used to develop mathematical models of the effects of myeloma infiltration on the marrow niches of terminal erythropoiesis, the erythroblastic islands (EBIs) (see [12]). A hybrid discrete-continuous model of erythropoiesis based on EBI structure/function was extended to sections of marrow containing multiple EBIs. In the model, myeloma cells can kill erythroid cells by physically destroying EBIs and by producing proapoptotic cytokines. Following chemotherapy, changes in serum paraproteins as measures of myeloma cells and changes in erythrocyte numbers as measures of marrow erythroid cells allowed modeling of myeloma cell death and erythroid cell recovery, respectively. Simulations of marrow infiltration by myeloma and treatment with nonerythrotoxic chemotherapy demonstrate that myeloma-mediated destruction and subsequent reestablishment of EBIs and expansion of erythroid cell populations in EBIs following chemotherapy provide explanations for anemia development and its therapy-mediated recovery in MM patients.

6.5. Mathematical modelling of hematopoiesis dynamics with growth factor-dependent coefficients

In [4] and [5], we propose and analyze an age-structured partial differential model for hematopoietic stem cell dynamics, in which proliferation, differentiation and apoptosis are regulated by growth factor concentrations. By integrating the age-structured system over the age and using the characteristics method, we reduce it to a delay differential system (with discret delay [4] and distribute delay [5]). We investigate the existence and stability of the steady states of the reduced delay differential system. By constructing a Lyapunov function, the trivial steady state, describing cell's dying out, is proven to be globally asymptotically stable when it is the only equilibrium of the system. The asymptotic stability of the positive steady state, the most biologically meaningful one, is analyzed using the characteristic equation. This study may be helpful in understanding the uncontrolled proliferation of blood cells in some hematological disorders. This study may be helpful in understanding the behavior of hematopoietic cells in some hematological disorders.

6.6. Mathematical modelling of Chronic Myleoid Leukemia (CML)

Firstly, an analysis of a reduced version of our model has been performed by A. Besse et al. (manuscript in revision). It allows to analyze the structure of the steady states and their stability. Typically, the situation is as follows. There are 4 steady states: 0 (unstable) a low one (stable) an intermediate (unstable) and a high (stable).

Secondly, considering another framework of modelling [37], it was observed by A. Besse et al. (see also the thesis of A. Besse) that, under the assumptions of the models, the long term response might be non monotonous with respect to the dose. In words, when the disease load has been reduced enough, it might be more efficient (it is not a question of toxicity) to reduce the dose. This comes from a balance between quiescence induction and apoptosis effects of the drug.

6.7. Hybrid Modelling in Biology

The paper [19] presents a general review on hybrid modelling which is about to become ubiquitous in biological and medical modelling. Hybrid modelling is classically defined as the coupling of a continuous approach with a discrete one, in order to model a complex phenomenon that cannot be described in a standard homogeneous way mainly due to its inherent multiscale nature. In fact, hybrid modelling can be more than that since any types of coupled formalisms qualify as being hybrid. The paper [19], first presents the evolution and current context of this modelling approach. It then proposes a classification of the models through three different types that relate to the nature and level of coupling of the formalisms used.

6.8. Design and study of a new model describing the effect of radiotherapy on healthy cells

This new project started in January 2016 between a start up Neolys Diagnostics, an Inserm team from Lyon and some members of the Dracula team (Léon Matar Tine and Laurent Pujo-Menjouet) (see [11]). We recruited a student to start a PhD (Aurélien Canet) paid for one half by Neolys and the other half by the labex Milyon. The objective of this collaboration is to use deterministic models (as a first step) to describe the dynamics of ATM proteins in the cytoplasm moving to the nucleus. Once there, they recognize and repair damaged DNA (due to nuclear radiations) and to give solid mechanistic explanations of the phenomenological linear quadratic model used until now by biologists and clinicians. Next step is then to use data provided by the Inserm team to calibrate our model and use it for clinical tests by Neolys (to detect radiosensitive persons (3 different groups) and prevent individual from creating cancer induced by nuclear radiations).

6.9. Contribution to the interaction between Alzheimer's disease and prion with the analysis of a mathematical model arising from in vitro experiments

Alzheimer's disease (AD) is a fatal incurable disease leading to progressive neuron destruction. AD is caused in part by the accumulation of $A\beta$ monomers inside the brain, which have the faculty to aggregate into oligomers and fibrils. Oligomers are the most toxic structures as they can interact with neurons via membrane receptors, including PrPc proteins. This interaction leads to the misconformation of $PrPc$ into pathogenic oligomeric prions, $PrPol$. The objective of our collaboration with the Inra team lead by Human Rezaei (Jouy en Josas), is to design and study a brand new model describing in vitro $A\beta$ polymerization process (see [25]). We include interactions between oligomers and $PrPc$ that induces the misconformation of PrPc into PrPol. The model consists of nine equations, including size structured transport equations, ordinary differential equations and delayed differential equations. Our collaboration is only at its beginning and we applied for an ANR grant highlighting this interdisciplinary work.

6.10. Methods of Blood Flow Modelling

The paper [9] is devoted to recent developments in blood flow modelling. It begins with the discussion of blood rheology and its non-Newtonian properties. After that it presents some modelling methods where blood is considered as a heterogeneous fluid composed of plasma and blood cells. Namely, it describes the method of Dissipative Particle Dynamics and presents some results of blood flow modelling. The last part of this paper deals with one-dimensional global models of blood circulation. It explains the main ideas of this approach and presents some examples of its application.

6.11. Anomalous diffusion as an age-structured renewal process

Continuous-time random walks (CTRW) are one of the main mechanisms that are recurrently evoked to explain the emergence of subdiffusion in cells. CTRW were introduced fifty years ago as a generalisation of random walks, where the residence time (the time between two consecutive jumps) is a random variable. If the expectation of the residence time is defined, for instance when it is dirac-distributed or decays exponentially fast, one recovers "normal" Brownian motion. However, when the residence time expectation diverges, the CTRW describes a subdiffusive behavior. The classical approach to CTRW yields a non-Markovian (mean-field) transport equation, which is a serious obstacle when one wants to couple subdiffusion with (bio)chemical reaction. In [8], we took an alternative approach to CTRW that maintains the Markovian property of the transport equation at the price of a supplementary independent variable. We associate each random walker with an age a, that is the time elapsed since its last jump and describe the subdiffusive CTRW using an age-structured partial differential equations with age renewal upon each walker jump. In the spatially-homogeneous (zero-dimensional) case, we follow the evolution in time of the age distribution. An approach inspired by relative entropy techniques allows us to obtain quantitative explicit rates for the convergence of the age distribution to a self-similar profile, which corresponds to convergence to a stationary profile for the rescaled variables. An important difficulty arises from the fact that the equation in self-similar variables is not autonomous and we do not have a specific analytical solution. Therefore, in order to quantify the latter convergence, we estimate attraction to a time-dependent "pseudo-equilibrium", which in turn converges to the stationary profile.

6.12. Doubly nonlocal reaction-diffusion equations and the emergence of species

The paper [6] is devoted to a reaction-diffusion equation with doubly nonlocal nonlinearity arising in various applications in population dynamics. One of the integral terms corresponds to the nonlocal consumption of resources while another one describes reproduction with different phenotypes. Linear stability analysis of the homogeneous in space stationary solution is carried out. Existence of travelling waves is proved in the case of narrow kernels of the integrals. Periodic travelling waves are observed in numerical simulations. Existence of stationary solutions in the form of pulses is shown, and transition from periodic waves to pulses is studied. In the applications to the speciation theory, the results of this work signify that new species can emerge only if they do not have common offsprings. Thus, it is shown how Darwin's definition of species as groups of morphologically similar individuals is related to Mayr's definition as groups of individuals that can breed only among themselves.

6.13. Existence of very weak global solutions to cross diffusion models

The entropy structure has been used in [26] to derived a very general theorem for existence for cross diffusion models. The theory is based on the interplay between the entropy structure which gives some compactness in space (gradient control) and the duality strucutre identified by Michel Pierre for general parabolic systems, which gives integrability. We derive a very general results under very general structural hypothesis (exsitence of an entropy which is compatible with reaction terms and relevance of the duality strucutre). The key is the construction of implicit solutions of the semi discete version (time is discretized) which happens to verify all the strucutres and are very regular. Moreover, we give a simple condition for mutliple case (more than 3 species) for building examples with an entropy structure based on the detailed balance structure proposed in [34].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

The industrial connections of the Dracula team have been made through the "Modeling of the immune response" project. Contacts have been established with both large pharmaceutical companies (Sanofi-Pasteur and Merial) and SMEs (AltraBio and The Cosmo Company). The now finished ANR PrediVac project included the two aforementioned SMEs and therefore strengthened the ties between Dracula and its industrial local ecosystem. The same consortium applied to ANR grants on close research topics in 2016. Furthermore, the ties with The Cosmo Company have been strenghened through a joint CIFRE PhD (see below).

7.2. Bilateral Grants with Industry

A recent cooperation has been initiated with the start up “Neolys Diagnostics” about radiotherapy effects on healthy cells and tumor cells. A PhD student, Aurélien Canet, has started his doctorate studies in January 2016 paid for one half by the start up and for the other half by the labex Milyon. Aurélien Canet is co-supervized by Larry Bodgi (from Neolys), Nicolas Foray (from Inserm) and Laurent Pujo-Menjouet.

7.3. Bilateral Grants with Industry

Celine Vial is scientific responsible of a contract with the European Consortium Eurokin and in collaboration with IFP “Energies nouvelles” on the topic: “Design experiments, sensibility and uncertainty analysis and kriging”. The delivrable: “How accurate is my model?” Report by Celine Vial (80 pages).

8. Partnerships and Cooperations

8.1. Regional Initiatives

In the context of the chair of applied mathematics “OQUAIDO”, driven by Olivier Roustand (Mines de St Etienne), Celine Vial is the scientific responsible of a contract with the BRGM (Orléans) 2016-2018: “Study of a submergence problem: identify the critical offshore conditions for coastal flooding”.

8.2. National Initiatives

8.2.1. ANR

Collaboration in other projects

- ANR RPIB PrediVac "Innovative modeling tools for the prediction of CD8 T cell based vaccine efficacy", 2013-2016 (jeune): http://www.agence-nationale-recherche.fr/?Projet=ANR-12-RPIB-0011. Partners: U1111 Inserm (J. Marvel, coordinator), Dracula, Altrabio (small company), The Cosmo Company (small company). Members are Fabien Crauste and Olivier Gandrillon.
- Thomas Lepoutre is a member of the ANR KIBORD (head L. Desvillettes) dedicated to “kinetic and related models in biology". 2014-2017: https://www.ljll.math.upmc.fr/kibord/.
- Thomas Lepoutre is a member of the ERC MESOPROBIO (head V. Calvez) dedicated to "Mesoscopic models for propagation in biology". 2015-2020: https://erc.europa.eu/projects-and-results/erc-funded-projects/mesoprobio.
- Olivier Gandrillon participates in the ANR (Investissement d’Avenir) Iceberg (head Gregory Batt (Inria)) "From population models to model populations: single cell observation, modeling, and control of gene expression". 2011-2017: https://contraintes.inria.fr/~batt/iceberg/home.html.
- Celine Vial participates in the ANR PEPITO (head M. Henner) dedicated to “Design of Experiment for the Industry of transportation and Optimization”. 2014-2018: http://www.agence-nationale-recherche.fr/?Project=ANR-14-CE23-0011.

8.2.2. Other projects

- Inria ADT : SiMuScale "Simulations Multi-Échelles de Populations Cellulaires", 2014-2016.
  Participants: Samuel Bernard [Coordinator], Fabien Crauste, Olivier Gandrillon, David Parsons.
- Association France Alzheimer Sciences Médicales 2014-2015 : PAMELA "Prion et Alzheimer : Modélisation et Expérimentation d'une Liaison Agressive", 2014-2015. Partners: UR0892 VIM (Virologie et Immunologie Moléculaires), INRA Domaine de Vilvert, Jouy-en-Josas.
  Participants: Mostafa Adimy, Samuel Bernard, Thomas Lepoutre, Laurent Pujo-Menjouet [Coordinator], Léon Tine.

8.3. International Initiatives

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

8.3.1.1. Modelling leukemia

Title: Modeling quiescence and drug resistance in Chronic Myeloid Leukemia

International Partner (Institution - Laboratory - Researcher):

University of Maryland (United States) - Center for Scientific Computation and Mathematical Modeling (CSCAMM) - Levy Doron

Start year: 2013

See also: http://dracula.univ-lyon1.fr/modelling_leukemia.php

Leukemia is the most famous disease of the blood cell formation process (hematopoiesis). Chronic myeloid leukemia results in a uncontrolled proliferation of abnormal blood cells. As the hematopoiesis involves stem cells (not accessible to observations), mathematical modeling is here a great tool to test hypothesis. We will join the expertise of Inria team DRACULA specialized on the modeling of blood cell formation and the Center for Scientific Computation and Applied Mathematical Modeling (CSCAMM, University of Maryland, College Park). The theoretical and modeling experience of team DRACULA and the numerical expertise combined with the links with experimentalists of members of CSCAMM will allow us to study deeply evolution of leukemia. We will especially focus on the behavior of leukemic stem cells and their possibility of becoming quiescent (dormant). Then we will study (using the knowledge obtained on leukemic stem cells) the phenomenon of drug resistance and its propagation over time and finally the mechanisms of multidrug resistance.

8.4. International Research Visitors

8.4.1. Visits to International Teams

8.4.1.1. Research Stays Abroad

Mostafa Adimy has been invited for three months (September-December) to “Fundação Getulio Vargas (FGV)” of Rio de Janeiro. He gave a course of 45 hours to students of Master of the School of Applied Mathematics (EMAp): “Reaction-diffusion and age-structured equations with application to biological populations”. A collaboration has been started with FGV on mathematical modeling of human transmissible diseases.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. Member of the Organizing Committees

- International conference “LyonSysBio” (Lyon Systems Biology), Lyon (France), 17 - 18 November 2016 (http://lyonsysbio2016.sciencesconf.org/?lang=en). Co-organizers: Fabien Crauste and Olivier Gandrillon.
- Regular SeMoVi Rhone-Alpes seminar in biological modeling (http://www.biosyl.org/news/semovi), 5 seminars organized in 2016, with one international lecturer each time. Co-organizer : Olivier Grandrillon and Fabien Crauste.
- Minisymposium: “Polymer dynamics models and applications to neurodegenerative disease”, the 11th AIMS Conference on Dynamical Systems, Differential Equations and Applications, 01 - 05 July 2016, Orlando, Florida, USA (http://www.aimsciences.org/conferences/2016/). Co-organizers: Laurent Pujo-Menjouet and Leon Tine.
- Summer School in Probability and PDE for Biology, July 2016 (held at the CIRM) http://scientific-events.weebly.com/1426.html. Co-organizers: Thomas Lepoutre.
- Workshop on complex systems of reaction-diffusion (https://www.ljll.math.upmc.fr/kibord/workshop_march_2016.html). Co-organizers: Thomas Lepoutre.

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

- International conference "LyonSysBio" (Lyon Systems Biology), Lyon (France), 17 - 18 November 2016 (http://lyonsysbio2016.sciencesconf.org/?lang=en). Co-organizers : Fabien Crauste and Olivier Gandrillon.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- Fabien Crauste: Computational and Mathematical Methods in Medicine (HPG).
- Laurent Pujo-Menjouet: Journal for theoretical Biology; Mathematical Modelling of Natural Phenomena.
- Mostafa Adimy: Journal of Nonlinear Systems and Applications; Chinese Journal of Mathematics.
- Olivier Gandrillon: BMC research Notes.

9.1.3.2. Reviewer - Reviewing Activities

- Fabien Crauste: Bulletin of Mathematical Biology; Discrete and Continuous Dynamical Systems Series B; Funkcialaj Ekvacioj (Functional Equations); Journal of Mathematical Biology; Journal of Biological Systems; Systems and Control Letters.
- Laurent Pujo-Menjeout: Journal of Mathematical Biology.
- Celine Vial: Comptes Rendus Mathematique (CRAS).
- Mostafa Adimy: Mathematical Methods in the Applied Sciences; Zeitschrift fuer Angewandte Mathematik und Physik (ZAMP)

9.1.4. Invited Talks

- Fabien Crauste: Workshop “French-Spanish Workshop on Evolution Problems”, Valladolid (Spain), May 16-17.

- Laurant Pujo-Menjouet: Marseille Monthly seminar Aix-Marseille Université, Institut de Mathématiques de Marseille (I2M).
- Mostafa Adimy: Workshop "French-Spanish Workshop on Evolution Problems", Valladolid (Spain), May 16-17.
- Mostafa Adimy: Workshop "Modelling the Dissemination and Control of Arboviroses", Polytechnic School, San Lorenzo (Paraguay), October 5-8.

9.1.5. Scientific Expertise

- Celine Vial: Member of CNU 26; Member of a comity for "Maître de conférences" Pierre et Marie Curie university.
- Celine Vial: Member of the jury of the agregation of mathematic in Tunisia.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

- Master: Fabien Crauste, Population Dynamics, 15h ETD, M2, UCBL, Lyon. Laurent:
- Licence: Laurent Pujo-Menjout, Bio-mathématiques et Modélisation, 10h ETD, L3, UCBL, Lyon.
- Licence: Laurent Pujo-Menjout, Analyse numérique, 72h ETD, L3, UCBL, Lyon.
- Licence: Laurent Pujo-Menjout, Equations différentielles et aux dérivées partielles, 72h ETD, L3, UCBL, Lyon.
- Licence: Laurent Pujo-Menjout, Analyse I : les réels et les fonctions, 72h ETD, L1, UCBL, Lyon.
- Licence: Laurent Pujo-Menjout, Mathématiques Appliquées - Equations Différentielles, 18h ETD, L2, UCBL, Lyon.
- Licence: Laurent Pujo-Menjout, Equations Différentielles ordinanires and Modélisation, 54h ETD, L3, INSA, Lyon.
- Master: Laurent Pujo-Menjout, Modélisation en biologie et médecine, 7.5h ETD, M1, UCBL, Lyon.
- Master: Laurent Pujo-Menjout, Systèmes dynamiques, 78h ETD, M1, UCBL, Lyon.
- Master: Laurent Pujo-Menjout, Gestion de projet en ingénierie mathématique, 3h ETD, M1, UCBL, Lyon.
- Master: Laurent Pujo-Menjout, Equations aux Différences, 29h ETD, M1, INSA, Lyon.
- Master: Mostafa Adimy, Reaction-diffusion and age-structured equations with application to biological populations, 45h ETD, M2, School of Applied Mathematics (EMAp), FGV, Rio de Janeiro, Brazil.

9.2.2. Supervision

- PhD: Abdennasser Chekroun, "Équations différentielles et aux différences à retard pour des modèles de dynamique des cellules souches hématopoïétiques", Université Lyon, until March 2016, encadrant: Mostafa Adimy.
- PhD: Marine Jacquier, "Mathematical modeling of the hormonal regulation of food intake and body weight : applications to caloric restriction and leptin resistance", Université de Lyon, until February 2016, encadrants: Fabien Crauste, Mostafa Adimy and Hedi Soula.
- PhD in progress: Simon Girel, "Multiscale modelling of the immune response", Université Lyon, since September 2015, encadrant: Fabien Crauste.
- PhD in progress: Aurélien Canet, "Contribution à l'étude de la quantification de la réponse d'une tumeur solide après un traitement par radiothérapie", Université Lyon, since January 2016, encadrants: Larry Bodgi, Nicolas Foray and Laurent Pujo-Menjouet.

- PhD in progress : Loïs Boullu, Modélisation de la mégacaryopoïèse et applications aux maladies liées â la production des plaquettes, Université Lyon 1, October 2014, Laurent Pujo-Menjouet and Jacques Bélair (co-tutelle avec l'Université de Montréal).
- PhD in progress: Manaf Ahmed, "Probabilistic and statistical study of the spatiotemporal dependence; application to environment", since october 2013, encadrants: C. Vial, V. Maume-Deschamps and P. Ribereau.
- PhD in progress: Mélina Ribaud, "Robustness in multi-objective optimization for the design of rotating machine", since september 2015, encadrants: C. Vial, C. Helbert and F. Gillot.
- PhD in progress : Loïc Barbarroux, modélisation mathématique de la réponse immunitaire chez un individu en vue d'optimiser des stratégies de vaccination, Université de Lyon 1, since October 2013, Mostafa Adimy and Phillipe Michel.
- PhD in progress : Apollos Besse, The role of tumor-immune interaction in combined treatments for chronic myeloid leukemia, Université Lyon 1, since October 2014, Samuel Bernard and Thomas Lepoutre.
- PhD in progress : Alvaro Mateso Gonzales, Models for anomalous diffusion, ENS Lyon, since October 2014, Thomas Lepoutre, Hugues Berry and Vincent Calvez (Alvaro is not member of Dracula team).
- PhD in progress : Flavien Duparc, Etude d'un modèle mathématiques de régulation de l'hémoglobine chez les patients dialysés, Université Lyon 1, since October 2014, Mostafa Adimy and Laurent Pujo-Menjouet.
- PhD in progress : Ulysse Herbach, Modèles graphiques probabilistes pour l'inférence de réseaux de gènes, Université Lyon 1, since October 2015, Olivier Gandrillon, Thibault Espinasse (ICJ) and Anne-Laure Fougères (ICJ).
- PhD in progress : Arnaud Bonnafoux, Vers une inférence automatique de réseaux de gènes dynamiques à partir de « mégadonnées » temporelles discrètes acquises sur cellules uniques, Université Lyon 1, since November 2015, Olivier Gandrillon (CIFRE with the COSMO company).
- HDR: Laurent Pujo-Menjouet, "Étude de modèles mathématiques issus de la biologie du cycle cellulaire et de la dynamique des protéines", Université Lyon, Decembre 2016.

9.2.3. Juries

- Mostafa Adimy was reviewer and member of the PhD of Benjamin Conti (Université d'Aix Marseille), "Équations de réaction-diffusion dans un environnement périodique en temps Applications en médecine".
- Mostafa Adimy was member of the PhD of Abdennasser Chekroun (Université de Lyon 1), "Contribution à l'analyse mathématique d'équations aux dérivées partielles structurées en âge et en espace modélisant une dynamique de population cellulaire".
- Mostafa Adimy was member of the PhD of Youssef Bourfia (Université de Marrakech and Université Pierre et Marie-Curie), "Modélisation et Analyse de Modèles en Dynamique Cellulaire avec Applications à des Problèmes Liés aux Cancers".
- Mostafa Adimy was member of the HDR of Laurent Pujo-Menjouet (Université de Lyon 1), "Etude de modèles mathématiques issus de la biologie du cycle cellulaire et de la dynamique des protéines".
- Fabien Craute was reviewer and member of the PhD of Ana Jarne Munoz (Université de Bordeaux), "Modeling the effect of exogenous Interleukin 7 in HIV patients under antiretroviral therapy with low immune reconstitution".
- Fabien Craute was reviewer and member of the PhD of David Granjon (Université Pierre et Marie Curie et Université de Lausanne), "Modeling of Calcium Homeostasis in the Rat and its perturbations".

- Celine Vial was member of the PhD of Zahraa Salloum (Université de Lyon 1), “Maximum de vraisemblance empirique pour la détection de changements dans un modèle avec un nombre faible ou très grand de variables”.

9.3. Popularization

- Fabien Crauste : Conference “Grippe saisonnière, épidémie, pandémie : quel apport des mathématiques ?” Université Ouverte, Bibliothèque de Lyon, March 30, 2016.
- Laurent Pujo-Menjouet : Conference “Mathématiques et relations amoureuses : les jeux de l’amour et sans le hasard ?” Université Ouverte, Bibliothèque de Lyon, February 3, 2016.

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Publications of the year

Doctoral Dissertations and Habilitation Theses

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[2] M. JACQUIER.*Mathematical modeling of the hormonal regulation of food intake and body weight : applications to caloric restriction and leptin resistance*, Université de Lyon, February 2016, https://tel.archives-ouvertes.fr/tel-01273347.

[3] L. PUJO-MENJOUET.*Study of mathematical models arising from the biology of the cell cycle and the protein dynamics*, Université Claude Bernard Lyon 1 - Institut Camille Jordan, December 2016, Habilitation à diriger des recherches, https://hal.inria.fr/tel-01411371.

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Project-Team ERABLE

European Research team in Algorithms and Biology, formaL and Experimental

IN COLLABORATION WITH: Laboratoire de Biométrie et Biologie Evolutive (LBBE)

IN PARTNERSHIP WITH:
Centrum Wiskunde & Informatica

Institut national des sciences appliquées de Lyon

Université Claude Bernard (Lyon 1)

Université de Rome la Sapienza

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Computational Biology

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

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ERABLE is a European Inria team gathering French researchers together with researchers in Italy under the banner of the Sapienza University of Rome and researchers in the Netherlands under the banner of the CWI.

1. Members

Research Scientists

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Fabrice Vavre [CNRS, Senior Researcher, HDR]
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Scheila Mucha [Capes-Cofecub, Brazilian Sandwich PhD for one year until June 2015, renewed 6 months more from October 2015 funded by ERABLE, supervised by Arnaldo Zaha, Federal University of Rio Grande do Sul, Brazil]
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2. Overall Objectives

2.1. Overall Objectives

Cells are seen as the basic structural, functional and biological units of all living systems. They represent the smallest units of life that can replicate independently, and are often referred to as the building blocks of life. Living organisms are then classified into unicellular ones – this is the case of most bacteria and archea – or multicellular – this is the case of animals and plants. Actually, multicellular organisms, such as for instance human, may be seen as composed of native (human) cells, but also of extraneous cells represented by the diverse bacteria living inside the organism. The proportion in the number of the latter in relation to the number of native cells is believed to be high: this is for example of 90% in humans. Multicellular organisms have thus been described also as “superorganisms with an internal ecosystem of diverse symbiotic microbiota and parasites” (Nicholson *et al.*, Nat Biotechnol, 22(10):1268-1274, 2004)) where symbiotic means that the extraneous unicellular organisms (cells) live a close, and in this case, long-term relation both with the multicellular organisms they inhabit and among themselves. On the other hand, bacteria sometimes group into colonies of genetically identical individuals which may acquire both the ability to adhere together and to become specialised for different tasks. An example of this is the cyanobacterium *Anabaena sphaerica* who may group to form filaments of differentiated cells, some – the heterocysts –specialised for nitrogen fixation while the others are capable of photosynthesis. Such filaments have been seen as first examples of multicellular patterning.

At its extreme, one could then see life as one collection, or a collection of collections of genetically identical or distinct self-replicating cells who interact, sometimes closely and for long periods of evolutionary time, with same or distinct functional objectives. The interaction may be at equilibrium, meaning that it is beneficial or neutral to all, or it may be unstable meaning that the interaction may be or become at some time beneficial only to some and detrimental to other cells or collections of cells. The interaction may involve other living systems, or systems that have been described as being at the edge of life such as viruses, or else genetic or inorganic material such as, respectively, transposable elements and chemical compounds.

The application goal of ERABLE is, through the use of mathematical models and algorithms, to better understand such close and often persistent interactions, with a longer term objective of becoming able in some cases to suggest the means of controlling for or of re-establishing equilibrium in an interacting community by acting on its environment or on its players, how they play and who plays. This goal requires to identify who are the partners in a closely interacting community, who is interacting with whom, how and by which means. Any model is a simplification of reality, but once selected, the algorithms to explore such model should address questions that are precisely defined and, whenever possible, be exact in the answer as well as exhaustive when more than one exists in order to guarantee an accurate interpretation of the results within the given model.

This fits well the mathematical and computational expertise of the team, and drives the methodological goal of ERABLE which is to substantially and systematically contribute to the field of exact enumeration algorithms for problems that most often will be hard in terms of their complexity, and as such to also contribute to the field of combinatorics in as much as this may help in enlarging the scope of application of exact methods.

The key objective is, by constantly crossing ideas from different models and types of approaches, to look for and to infer "patterns", as simple and general as possible, either at the level of the biological application or in terms of methodology. This objective drives which biological systems are considered, and also which models and in which order, going from simple discrete ones first on to more complex continuous models later if necessary and possible.

3. Research Program

3.1. Two main goals

ERABLE has two main goals, one related to biology and the other to methodology (algorithms, combinatorics, statistics). In relation to biology, the main goal of ERABLE is to contribute, through the use of mathematical models and algorithms, to a better understanding of close and often persistent interactions between "collections of genetically identical or distinct self-replicating cells" which will correspond to organisms/species or to actual cells. The first will cover the case of what has been called symbiosis, meaning when the interaction involves different species, while the second will cover the case of a (cancerous) tumour which may be seen as a collection of cells which suddenly disrupts its interaction with the other (collections of) cells in an organism by starting to grow uncontrollably.

Such interactions are being explored initially at the molecular level. Although we rely as much as possible on already available data, we intend to also continue contributing to the identification and analysis of the main genomic and systemic (regulatory, metabolic, signalling) elements involved or impacted by an interaction, and how they are impacted. We started going to the populational and ecological levels by modelling and analysing the way such interactions influence, and are or can be influenced by the ecosystem of which the "collections of cells" are a part. The key steps are:

- identifying the molecular elements based on so-called omics data (genomics, transcriptomics, metabolomics, proteomics, etc.): such elements may be gene/proteins, genetic variations, (DNA/RNA/protein) binding sites, (small and long non coding) RNAs, etc.
- simultaneously inferring and analysing the network that models how these molecular elements are physically and functionally linked together for a given goal, or find themselves associated in a response to some change in the environment;
- modelling and analysing the populational and ecological network formed by the "collections of cells in interaction", meaning modelling a network of networks (previously inferred or as already available in the literature);
- analysing how the behaviour and dynamics of such a network of networks might be controlled by modifying it, including by substracting some of its components from the network or by adding new ones.

In relation to methodology, the main goal is to provide those enabling to address our main biological objective as stated above that lead to the best possible interpretation of the results within a given pre-established model and a well defined question. Ideally, given such a model and question, the method is exact and also exhaustive if more than one answer is possible. Three aspects are thus involved here: establishing the model within which questions can and will be put; clearly defining such questions; exactly answering to them or providing some guarantee on the proximity of the answer given to the "correct" one. We intend to continue contributing to these three aspects:

- at the modelling level, by exploring better models that at a same time are richer in terms of the information they contain (as an example, in the case of metabolism, using hypergraphs as models for it instead of graphs) and are susceptible to an easier treatment:
  - these two objectives (rich models that are at the same time easy to treat) might in many cases be contradictory and our intention is then to contribute to a fuller characterisation of the frontiers between the two;
  - even when feasible, the richer models may lack a full formal characterisation (this is for instance the case of hypergraphs) and our intention is then to contribute to such a characterisation;
- at the question level, by providing clear formalisations of those that will be raised by our biological concerns;
- at the answer level:
  - to extend the area of application of exact algorithms by: (i) a better exploration of the combinatorial properties of the models, (ii) the development of more efficient data structures, (iii) a smarter traversal of the space of solutions when more than one exists;
  - when exact algorithms are not possible, or when there is uncertainty in the input data to an algorithm, to improve the quality of the results given by a deeper exploration of the links between different algorithmic approaches: combinatorial, randomised, stochastic.

3.2. Different research axes

The goals of the team are biological and methodological, the two being intrinsically linked. Any division into axes along one or the other aspect or a combination of both is thus somewhat artificial. Our choice is based more on the biological questions as these are a main (but not unique) driver for the methodological developments. However, since another main objective is to contribute to the fields of exact enumeration algorithms and of combinatorics, we also defined an axis that is exclusively oriented towards some of the more theoretical aspects of such objective in as much as these can be abstracted from the biological motivation. This will concern improving theory and deeply exploring the links between different algorithmic approaches: combinatorial, randomised, stochastic. The first four axes thus fall in the first category, and the fifth one in the second. As concerns the first four axes, the model organisms or systems chosen will be those studied by the biologists among our permanent members or among our close collaborators. Currently these include the following cases:

- Arthropods, notably insects, and their parasites;
- Symbiont-harbouring trypanosomatids and trypanosomas more in general;
- The bacterial communities inside the respiratory tract of mammals (swine, bovine);
- Human in general, and the human microbiota in particular also for its possible relation to cancer.

Notice however that: (1) new model organisms or systems may be considered as the opportunity for new collaborations appears, indeed such collaborations will be actively searched for; and (2) we will always attempt to explore mathematical and computational models and to develop algorithmic methods that are as much as possible generic.

Axis 1: Identifying the molecular elements

Intra and inter-cellular interactions involve molecular elements whose identification is crucial to understand what governs, and also what might enable to control such interactions. For the sake of clarity, the elements may be classified in two main classes, one corresponding to the elements that allow the interactions to happen by moving around or across the cells, and another that are the genomic regions where contact is established. Examples of the first are non coding RNAs, proteins, and mobile genetic elements such as (DNA) transposons, retro-transposons, insertion sequences, etc. Examples of the second are DNA/RNA/protein binding sites and targets. Furthermore, both types (effectors and targets) are subject to variation across individuals of a population, or even within a single (diploid) individual. Identification of these variations is yet another topic that we wish to cover. Variations are understood in the broad sense and cover single nucleotide polymorphisms (SNPs), copy-number variants (CNVs), repeats other than mobile elements, genomic rearrangements (deletions, duplications, insertions, inversions, translocations) and alternative splicings (ASs). All three classes of identification problems (effectors, targets, variations) may be put under the general umbrella of genomic functional annotation.

Axis 2: Inferring and analysing the networks of molecular elements

As increasingly more data about the interaction of molecular elements (among which those described above) becomes available, these should then be modelled in a subsequent step in the form of genetic, metabolic, protein-protein interaction and signalling networks. This raises two main classes of problems. The first is to accurately infer such networks. Reconstructing, by analogy, the metabolic network of an organism is often considered, rightly or wrongly, to be easier than inferring a gene regulatory network, also because in the latter case, identifying all the elements participating in the network is in itself a complex and far from solved issue, as we saw in Axis 1. Moreover, the difficulty varies depending on whether only the structure or also the dynamics of the network is of interest, assuming that the latter may be studied (kinetics data are often missing even with the increasingly more sophisticated and performing technologies we have nowadays). A more complete picture of the functioning of a cell would further require that ever more layers of network and molecular profile data, when available, are integrated together, which raises the problem of how to model together information that is heterogeneous at different levels. Modelling together metabolic and gene regulation for instance is already a hard problem given that the two happen at very different time-scales: fast for metabolic regulation, slow for gene regulation.

Even assuming such a network, integrated or “simple”, has been inferred for a given organism or set of organisms, the second problem is then to develop the appropriate mathematical models and methods to extract further biological information from such networks. The difficulty of this differs of course again depending on whether only the structure of the network is of interest, or also its dynamics. We are addressing various questions related to one or the other of the above aspects – inference and analysis.

Axis 3: Modelling and analysing a network of individuals, or a network of individuals’ networks

As mentioned, at its extreme, life can be seen as one collection, or a collection of collections of genetically identical or distinct self-replicating cells who interact, sometimes closely and for long periods of evolutionary time, with a same or with distinct functional objectives. One striking example is human, who is composed of cells which are both native and extraneous; in fact, a surprising 90% is believed to belong to the second category, mostly bacteria, including one which lost its identity to become a “mere” human organelle, the mitochondrion. Bacteria on the other hand group into colonies of genetically identical individuals which may sometimes acquire the ability to become specialised for different tasks. Which is the “individual”, a single bacterium or a group thereof is difficult to say. To understand human or bacteria, or to understand any other organism, it appears therefore essential to better comprehend the interactions in which they are involved. Methodologically speaking, we must therefore move towards modelling and analysing not a single individual anymore but a network of individuals. Ultimately, we should move towards investigating a network of individuals’ networks. Moreover, since organisms interact not only with others but also with their abiotic environment, there is a need to model full ecosystems, at a static but also at a dynamic level, that is by taking into account the fact that individuals or populations move in space. Our intention at a longer term is to address all such different levels. We started with the molecular and static one that we are treating from different perspectives for a large number of species at the genomic level (Baudet *et al.*, Syst Biol, 64(3), 2015) and for a small number at the network level (Cottret *et al.*, PLoS Comput Biol, 6(9), 2010). We intend in a near future to slowly move towards a populational and ecological approach that is dynamic in both time and space.

Axis 4: Going towards control
What was described in the Axes 2 and 3 above concerned modelling and analysing a molecular network, or network of networks, but not attempting to control the network at either level for bio-technological, environmental or health purposes.

In the bio-technological case, the objective can be briefly described as involving the manipulation of a species, in general a bacterium, in order for it to produce more of a given chemical compound it already synthetises (for instance, ethanol) but not in enough quantity, or to produce a metabolite it normally is not able to synthetise. The motivation for transplanting its production in a bacterium is, again, to be able to make it more effective.

As concerns control for environmental or health purposes, this could be achieved at least in some cases by manipulating the symbionts with which an organism, insect pest for instance, or humans leave. In the environmental case, this has gone under the name of "biological control" (see for instance Flint & Dreistat, "Natural Enemies Handbook: The Illustrated Guide to Biological Pest Control", University of California Press, 1998) and involves the use of "natural enemies" of a pest organism. This idea has a long history: the ancient Chinese, observing that ants were effective predators of many citrus pests, decided to increase the ants population by displacing their nests from the surrounding habitats and placing them inside their orchards to protect them. More recently, there has been growing evidence that some endosymbiotic bacteria, that is bacteria that live within the cells of their hosts, could become efficient biocontrol agents. This is in particular the case of *Wolbachia*, a bacterium much studied in ERABLE (Ahantarig & Kittayapong, J Appl Entomology, 135(7):479-486, 2011).

The connection between disease and the disruption of homeostatic interactions between the host and its microbiota is on the other hand now well established. Microbiota-targeted therapies involve altering the community composition by eliminating individual strains of a single species (for example, with antibiotics) or replacing the entire community with a new intact microbiota. Secondary infections linked to antibiotic use provide however a cautionary tale of the possible consequences of perturbing a microbial species network.

Besides the biotechnological aspects on which we are already working in the context of two European projects (BacHBerry, and to a lesser extent, MicroWine), our main goal in this case is to try to formalise such type of control. There are two objectives here. One is methodological and concerns attempting to provide a single formal framework for the diverse ways of controlling a network, or a network of networks. Our attention has concentrated initially on metabolism, and will at a mid to longer term include regulation. Our intention notably as concerns the incorporation of regulation is to collaborate with other Inria teams, most notably IBIS with whom we are already in discussion. The second objective is biological and concerns control for environmental and health purposes. The originality we are seeking in this case is to attempt such control not by eliminating species, which is done mainly through the use of antibiotics that may then create resistance, a phenomenon that is becoming a major clinical and public health problem, but by manipulating the species or their environment, or by changing the composition of the community by adding or displacing some other species in such a way that new equilibria may be reached which enable all the species living in a same niche to survive. The idea is not new: the areas of prebiotics (non-digestible food ingredients that stimulate the growth and/or activity of bacteria in the digestive system in beneficial ways) and probiotics (micro-organisms claimed to provide benefits when consumed) indeed cover similar concerns in relation to health. Other novel approaches propose to work at the level of bacterial communication (quorum sensing) to control for pathogenicity (Rutherford & Bassler, Cold Spring Harbor Perspectives in Medicine, 2012). Small RNAs in particular are believed to play an important role in quorum sensing.

Axis 5: Cross-fertilising different computational approaches
In computer science and in optimisation, different approaches and techniques have been proposed to cope with hardness results. It is clear that none of them is dominant: there are classes of problems for which approach A is better than approach B, and vice-versa. Moreover, there is no satisfactory understanding of the conditions that favour one approach with respect to another one.

As an example, the team that gave birth to ERABLE, BAMBOO, had expertise more in the area of combinatorial algorithms for strings (sequences), trees and graphs. Many such algorithms addressed an enumeration problem: given a certain description of the object(s) searched for or definition of a function to be optimised, the method was supposed to list all the solutions. In many real life situations, notably in biology, a majority of the problems treated, of whatever kind, enumeration or else, are however hard. Although combinatorics remains crucial to better understand the structure of such problems and delimit the conditions that could render them easy or at least tractable in practice, often other types of approaches have to be attempted.

Although all approaches may be valid and valuable, in many cases one only is explored. More in general, there appears to be relatively little cross-talk and cross-fertilisation being attempted between these different approaches. Guided by problems from computational biology, the goal of this axis is to add to the growing insights on how well such problems can be solved theoretically.

4. Application Domains

4.1. Biology

The main area of application of ERABLE is biology understood in its more general sense, with a special focus on symbiosis and on intracellular interactions.

5. New Software and Platforms

5.1. AcypiCyc

FUNCTIONAL DESCRIPTION

Database of the metabolic network of *Acyrthosiphon pisum*.

- Participants: Patrice Baa Puyoule, Hubert Charles, Stefano Colella, Ludovic Cottret, Marie-France Sagot, Augusto Vellozo and Amélie Veron
- Contact: Hubert Charles
- URL: http://acypicyc.cycadsys.org/

5.2. AlViE

FUNCTIONAL DESCRIPTION

ALVIE is a post-mortem algorithm visualisation Java environment, which is based on the interesting event paradigm. The current distribution of ALVIE includes more than forty visualisations. Almost all visualisations include the representation of the corresponding algorithm C-like pseudo-code. The ALVIE distribution allows a programmer to develop new algorithms with their corresponding visualisation: the included Java class library, indeed, makes the creation of a visualisation quite an easy task (once the interesting events have been identified).

- Participants: Pierluigi Crescenzi, Giorgio Gambosi, Roberto Grossi, Carlo Nocentini, Tommaso Papini, Walter Verdese
- Contact: Pierluigi Crescenzi
- URL: http://javamm.sourceforge.net/piluc/software/alvie.html

5.3. Cassis

FUNCTIONAL DESCRIPTION

Algorithm for precisely detecting genomic rearrangement breakpoints.

- Participants: Christian Baudet, Christian Gautier, Claire Lemaitre, Marie-France Sagot, Eric Tannier
- Contact: Christian Baudet (not Inria), Claire Lemaitre (Inria GenScale), Marie-France Sagot (Inria ERABLE)
- URL: http://pbil.univ-lyon1.fr/software/Cassis/

5.4. Cidane

FUNCTIONAL DESCRIPTION

CIDANE is a novel framework for genome-based transcript reconstruction and quantification from RNA-seq reads.

- Participants: Stefan Canzar, Sandra Andreotti, David Weese, Kurt Reinert, Gunnar Klau
- Contact: Stefan Canzar (not Inria)
- URL: http://ccb.jhu.edu/software/cidane/

5.5. Coala

FUNCTIONAL DESCRIPTION

COALA stands for "CO-evolution Assessment by a Likelihood-free Approach". It is thus a likelihood-free method for the co-phylogeny reconstruction problem which is based on an Approximative Bayesian Computation (ABC).

- Participants: Christian Baudet, Pierluigi Crescenzi, Beatrice Donati, Christian Gautier, Catherine Matias, Marie-France Sagot, Blerina Sinaimeri
- Contact: Christian Baudet (not Inria), Marie-France Sagot and Blerina Sinaimeri
- URL: http://coala.gforge.inria.fr/

5.6. CophyTrees

FUNCTIONAL DESCRIPTION

COPHYTREES is a visualiser for host-parasite and gene-species trees evolution.

- Participants: Laurent Bulteau
- Contact: Laurent Bulteau (not Inria), Blerina Sinaimeri (for Inria ERABLE)
- URL: http://eucalypt.gforge.inria.fr/viewer.html

5.7. C3Part & Isofun

FUNCTIONAL DESCRIPTION

The C3PART / ISOFUN package implements a generic approach to the local alignment of two or more graphs representing biological data, such as genomes, metabolic pathways or protein-protein interactions, in order to infer a functional coupling between them. It is based on the notion of "common connected components" between graphs.

- Participants: Frédéric Boyer, Yves-Pol Deniélou, Anne Morgat, Marie-France Sagot and Alain Viari
- Contact: Alain Viari
- URL: http://www.inrialpes.fr/helix/people/viari/lxgraph/index.html

5.8. CycADS

FUNCTIONAL DESCRIPTION

Cyc annotation database system.

- Participants: Patrice Baa Puyoule, Hubert Charles, Stefano Colella, Ludovic Cottret, Marie-France Sagot and Augusto Vellozo
- Contact: Hubert Charles
- URL: http://www.cycadsys.org/

5.9. Dinghy

FUNCTIONAL DESCRIPTION

DINGHY is a visualisation program for network pathways of up to 150 reactions.

- Participants: Laurent Bulteau, Alice Julien-Laferrière, Delphine Parrot
- Contact: Laurent Bulteau (not Inria), Alice Julien-Laferrière, Delphine Parrot (not Inria), Marie-France Sagot (for Inria ERABLE)
- URL: http://dinghy.gforge.inria.fr/

5.10. Eucalypt

FUNCTIONAL DESCRIPTION

EUCALYPT stands for "EnUmerator of Co-evolutionary Associations in PoLYnomial-Time delay". It is an algorithm for enumerating all optimal (possibly time-unfeasible) mappings of a parasite tree unto a host tree.

- Participants: Christian Baudet, Pierluigi Crescenzi, Beatrice Donati, Marie-France Sagot, Blerina Sinaimeri
- Contact: Christian Baudet (not Inria), Beatrice Donati (not Inria), and Marie-France Sagot (Inria ERABLE)
- URL: http://eucalypt.gforge.inria.fr/index.html

5.11. Gobbolino & Touché

FUNCTIONAL DESCRIPTION

GOBBOLINO and TOUCHÉ were designed to solve the metabolic stories problem, which consists in finding all maximal directed acyclic subgraphs of a directed graph G whose sources and targets belong to a subset of the nodes of G, called the black nodes. Biologically, stories correspond to alternative metabolic pathways that may explain some stress that affected the metabolites corresponding to the black nodes by changing their concentration (measured by metabolomics experiments).

- Participants: Vicente Acuña, Etienne Birmelé, Ludovic Cottret, Pierluigi Crescenzi, Fabien Jourdan, Vincent Lacroix, Alberto Marchetti-Spaccamela, Andrea Marino, Paulo Vieira Milreu, Marie-France Sagot, Leen Stougie
- Contact: Paulo Vieira Milreu (not Inria), Marie-France Sagot (Inria ERABLE)
- URL: http://gforge.inria.fr/projects/gobbolino

5.12. HapCol

FUNCTIONAL DESCRIPTION

A fast and memory-efficient DP approach for haplotype assembly from long reads that works until 25x coverage, solves a constrained minimum error correction problem exactly.

- Participants: Paola Bonizzoni, Riccardo Dondi, Gunnar Klau, Yuri Pirola, Nadia Pisanti, Simone Zaccaria
- Contact: Gunnar Klau, Nadia Pisanti, Paola Bonizzoni (not Inria)
- URL: http://hapcol.algolab.eu/

5.13. KisSNP & DiscoSNP

FUNCTIONAL DESCRIPTION

Algorithm for identifying SNPs without a reference genome by comparing raw reads. KISSNP has now given birth to DISCOSNP in a work involving V. Lacroix from ERABLE and the GenScale Inria Team at Rennes (contact: pierre.peterlongo@inria.fr).

- Participants: Vincent Lacroix, Pierre Peterlongo
- Contact: Pierre Peterlongo (EPI GenScale)
- URL: http://colibread.inria.fr/software/discosnp/

5.14. KisSplice

FUNCTIONAL DESCRIPTION

Enables to analyse RNA-seq data with or without a reference genome. It is an exact local transcriptome assembler, which can identify SNPs, indels and alternative splicing events. It can deal with an arbitrary number of biological conditions, and will quantify each variant in each condition.

- Participants: Lilia Brinza, Alice Julien-Laferrière, Janice Kielbassa, Vincent Lacroix, Leandro Ishi Soares de Lima, Camille Marchet, Vincent Miele, Gustavo Sacomoto
- Contact: Vincent Lacroix
- URL: http://kissplice.prabi.fr/

5.15. kissDE

FUNCTIONAL DESCRIPTION

KISSDE is an R Package enabling to test if a variant (genomic variant or splice variant) is enriched in a condition. It takes as input a table of read counts obtained from NGS data pre-processing and gives as output a list of condition specific variants.

- Participants: Clara Benoit-Pilven, Lilia Brinza, Janice Kielbassa, Vincent Lacroix, Camille Marchet and Vincent Miele
- Contact: Vincent Lacroix
- URL: http://kissplice.prabi.fr/tools/kissDE/

5.16. KisSplice2RefTranscriptome

FUNCTIONAL DESCRIPTION

KISSPLICE2REFTRANSCRIPTOME enables to combine the output of KISSPLICE with the output of a full-length transcriptome assembler, thus allowing to predict a functional impact for the positioned SNPs, and to intersect these results with condition-specific SNPs. Overall, starting from RNAseq data only, we obtain a list of condition-specific SNPs stratified by functional impact.

- Participants: Mathilde Boutigny, Vincent Lacroix, Hélène Lopez-Maestre
- Contact: Vincent Lacroix
- URL: http://kissplice.prabi.fr/tools/kiss2rt/

5.17. KisSplice2RefGenome

FUNCTIONAL DESCRIPTION

KISSPLICE (see above) identifies variations in RNAseq data, without a reference genome. In many applications however, a reference genome is available. KISSPLICE2REFGENOME enables to facilitate the interpretation of KISSPLICE's results after mapping them to a reference genome.

- Participants: Alice Julien-Laferrière, Vincent Lacroix, Camille Marchet, Camille Sessegolo
- Contact: Vincent Lacroix
- URL: http://kissplice.prabi.fr/tools/kiss2refgenome/

5.18. Lasagne

FUNCTIONAL DESCRIPTION

LASAGNE is a Java application which allows the user to compute distance measures on graphs by making a clever use either of the breadth-first search or of the Dijkstra algorithm. In particular, the current version of LASAGNE can compute the exact value of the diameter of a graph: the graph can be directed or undirected and it can be weighted or unweighted. Moreover, LASAGNE can compute an approximation of the distance distribution of an undirected unweighted graph. These two features are integrated within a graphical user interface along with other features, such as computing the maximum (strongly) connected component of a graph.

- Participants: Pierluigi Crescenzi, Roberto Grossi, Michel Habib, Claudio Imbrenda, Leonardo Lanzi, Andrea Marino
- Contact: Pierluigi Crescenzi
- URL: http://lasagne-unifi.sourceforge.net/

5.19. MeDuSa

FUNCTIONAL DESCRIPTION

MEDUSA (Multi-Draft based Scaffolder) is an algorithm for genome scaffolding. It exploits information obtained from a set of (draft or closed) genomes from related organisms to determine the correct order and orientation of the contigs.

- Participants: Emmanuelle Bosi, Sara Brunetti, Pierluigi Crescenzi, Beatrice Donati, Renato Fani, Marco Fondi, Marco Galardini, Pietro Lió, Marie-France Sagot,
- Contact: Pierluigi Crescenzi, Marco Fondi (not Inria)
- URL: http://combo.dbe.unifi.it/medusa

5.20. MetExplore

FUNCTIONAL DESCRIPTION

Web server to link metabolomic experiments and genome-scale metabolic networks.

- Participants: Michael Barrett, Hubert Charles, Ludovic Cottret, Fabien Jourdan, Marie-France Sagot, Florence Vinson, David Wildridge
- Contact: Fabien Jourdan (not Inria), Marie-France Sagot
- URL: http://metexplore.toulouse.inra.fr/metexplore/

5.21. Migal

FUNCTIONAL DESCRIPTION

Algorithm for comparing RNA structures.

- Participants: Julien Allali and Marie-France Sagot
- Contact: Marie-France Sagot
- URL: http://www-igm.univ-mlv.fr/~allali/logiciels/index.en.php

5.22. Mirinho

FUNCTIONAL DESCRIPTION

Predicts, at a genome-wide scale, microRNA candidates.

- Participants: Christian Gautier, Cyril Fournier, Christine Gaspin, Susan Higashi, Marie-France Sagot
- Contact: Susan Higashi (not Inria), Marie-France Sagot
- URL: http://mirinho.gforge.inria.fr/

5.23. Motus & MotusWEB

FUNCTIONAL DESCRIPTION

Algorithm for searching and inferring coloured motifs in metabolic networks (web-based version - offers different functionalities from the downloadable version).

- Participants: Ludovic Cottret, Fabien Jourdan, Vincent Lacroix, Odile Rogier and Marie-France Sagot
- Contact: Vincent Lacroix
- URL: http://doua.prabi.fr/software/motus and http://pbil.univ-lyon1.fr/software/motus_web/

5.24. MultiPus

FUNCTIONAL DESCRIPTION

MULTIPUS (for MULTIple species for the synthetic Production of Useful biochemical Substances) is an algorithm that, given a microbial consortium given as input, identifies all optimal sub-consortia to synthetically produce compounds that are either exogenous to it, or are endogenous but where interaction among the species in the sub-consortia could improve the production line.

- Participants: Laurent Bulteau, Alice Julien-Laferrière, Arnaud Mary, Alberto Marchetti-Spaccamela, Delphine Parrot, Marie-France Sagot, Leen Stougie and Susana Vinga
- Contact: Alice Julien-Laferrière, Arnaud Mary, Marie-France Sagot
- URL: http://multipus.gforge.inria.fr/

5.25. PepLine

FUNCTIONAL DESCRIPTION

Pipeline for the high-throughput analysis of proteomic data.

- Participants: Jérôme Garin, Alain Viari
- Contact: Alain Viari
- URL: Available upon request to the contact person

5.26. Pitufo and family

FUNCTIONAL DESCRIPTION

Algorithms to enumerate all minimal sets of precursors of target compounds in a metabolic network.

- Participants: Vicente Acuña Aguayo, Ludovic Cottret, Alberto Marchetti-Spaccamela, Fabio Henrique Viduani Martinez, Paulo Vieira Milreu, Marie-France Sagot, Leen Stougie
- Contact: Paulo Vieira Milreu (not Inria), Marie-France Sagot
- URL: https://sites.google.com/site/pitufosoftware/home

5.27. RepSeek

FUNCTIONAL DESCRIPTION

Finding approximate repeats in large DNA sequences.

- Participants: Guillaume Achaz, Eric Coissac, Alain Viari
- Contact: Guillaume Achaz (not Inria), Alain Viari
- URL: http://wwwabi.snv.jussieu.fr/public/RepSeek/

5.28. Rime

FUNCTIONAL DESCRIPTION

RIME detects long similar fragments occurring at least twice in a set of biological sequences.

- Participants: Maria Federico, Pierre Peterlongo, Nadia Pisanti, Marie-France Sagot
- Contact: Maria Federico (not Inria), Nadia Pisanti, Marie-France Sagot
- URL: https://code.google.com/p/repeat-identification-rime/

5.29. Sasita

FUNCTIONAL DESCRIPTION

SASITA is a software for the exhaustive enumeration of minimal stoichiometrically valid precursor sets in metabolic networks.

- Participants: Vicente Acuña, Ricardo Andrade, Alberto Marchetti-Spaccamela, Marie-France Sagot, Leen Stougie, Martin Wannagat
- Contact: Marie-France Sagot, Ricardo Andrade, Martin Wannagat
- URL: http://sasita.gforge.inria.fr/

5.30. Smile

FUNCTIONAL DESCRIPTION

Motif inference algorithm taking as input a set of biological sequences. A visualiser is currently being developed.

- Participants: Ricardo Andrade (visualiser), Mariana Ferrarini (visualiser), Laurent Marsan, Marie-France Sagot
- Contact: Ricardo Andrade, Marie-France Sagot
- URL: Soon available

5.31. Totoro & Kotoura

FUNCTIONAL DESCRIPTION

We proposed two methods to decipher the reaction changes during a metabolic transient state using measurements of metabolic concentrations. We called these *metabolic hyperstories*.

TOTORO (for TOpological analysis of Transient metabOlic RespOnse) is based on a qualitative measurement of the concentrations in two steady-states to infer the reaction changes that lead to the observed differences in metabolite pools in both conditions. In the currently available release, a pre-processing and a post-processing steps are included. After the post-processing step, the solutions can be visualised using DINGHY.

KOTOURA (for Kantitative analysis Of Transient metabOlic and regUlatory Response And control) infers quantitative changes of the reactions using information on measurement of the metabolite concentrations in two steady-states.

- Participants: Ricardo Andrade, Laurent Bulteau, Louis Duchemin, Alice Julien-Laferrière, Alberto Marchetti-Spaccamela, Arnaud Mary, Vincent Lacroix, Marie-France Sagot, Leen Stougie, Philippe Veber, Susana Vinga
- Contact: Alice Julien-Laferrière, Arnaud Mary, Ricardo Andrade, Marie-France Sagot
- URL: http://hyperstories.gforge.inria.fr/

5.32. WhatsHap and pWhatsHap

FUNCTIONAL DESCRIPTION

WHATSHAP is a DP approach for haplotype assembly from long reads that works until 20x coverage, solves the minimum error correction problem exactly. PWHATSHAP is a parallelisation of the core dynamic programming algorithm of WHATSHAP done by M. Aldinucci, A. Bracciali, T. Marschall, M. Patterson, N. Pisanti, and M. Torquati.

- Participants: Gunnar Klau, Tobias Marschall, Murray Patterson, Nadia Pisanti, Alexander Schönhuth, Leen Stougie, Leo van Iersel
- Contact: Alexander Schönhuth (not Inria), Gunnar Klau, Nadia Pisanti
- URL: https://bitbucket.org/whatshap/whatshap and https://bitbucket.org/whatshap/whatshap/branch/parallel

6. New Results

6.1. General comments

We present in this section the main results obtained in 2016. Some were already in preparation or submitted at the end of 2015. This will be indicated whenever it is the case.

We tried to organise the results following the five main axes of research of the team. Clearly, in some cases, a result obtained overlaps more than one axis. We chose the one that could be seen as the main one concerned by such results.

We did not indicate here the results on more theoretical aspects of computer science if it did not seem for now that they could be relevant in contexts related to computational biology. Actually, we do believe those on rumour spreading (by Pierluigi Crescenzi) [9] or on general network analysis (by Pierluigi Crescenzi or Roberto Grossi) [31], [36], [40], [39], [37], [38], [10], [42] could in the future become relevant for life sciences (biology or ecology). In the other direction, algorithmic ideas that were developed in the context of a problem in life sciences could prove useful for solving more general problems (possibly with other applications). This was the case of some of the ideas explored in previous years to deal with de Bruijn graphs in the context of NGS analysis that led to the team fruitfully collaborating with a group of researchers at the ETH in Switzerland on a problem related to transport systems [34].

Below however, we preferred to only indicate the theoretical results related to problems closely resembling questions that have already been addressed by us in computational biology. Notice that such CS results concern not only cross-fertilising issues among different computational approaches, and we therefore extended the title of this axis for the purpose of presenting such results, for now purely theoretical.

A few other results are not mentioned either in this report, not because the corresponding work is not important, but because it was likewise more specialised, or the work represented a survey.

6.2. Identifying the molecular elements

RNA-seq NGS algorithms and data analysis

SNPs (Single Nucleotide Polymorphisms) are genetic markers whose precise identification is a prerequisite for association studies. Methods to identify them are currently well developed for model species, but rely on the availability of a (good) reference genome, and therefore cannot be applied to non-model species. They are also mostly tailored for whole genome (re-)sequencing experiments, whereas in many cases, transcriptome sequencing can be used as a cheaper alternative which already enables to identify SNPs located in transcribed regions. In a paper accepted this year [18], we proposed the use of a previously developed method, KISSPLICE, that identifies, quantifies and annotates SNPs without any reference genome, using RNA-seq data only. Individuals can be pooled prior to sequencing if not enough material is available from one individual. Using pooled human RNA-seq data, we clarified the precision and recall of our method and discussed them with respect to other methods which use a reference genome or an assembled transcriptome. We then validated experimentally the predictions of our method using RNA-seq data from two non-model species. KISSPLICE can be used for any species to annotate SNPs and predict their impact on the protein sequence. We further enable to test for the association of the identified SNPs with a phenotype of interest.

We participated also in two other works, one computational and the other biological, on alternative splicing in Human.

The first is associated to the ANR Colib'read project in which we were one of the partners. A Colib'read Galaxy tools suite was developed that should enable a broad range of life science researchers to analyse raw NGS data, allows the maximum biological information to be retained in the data, and uses a very low memory footprint [17]. The algorithms implemented in the tools are based on the use of a de Bruijn graph and of a bloom filter. The analyses can be performed in a few hours, using small amounts of memory. Applications using real data further demonstrate the good accuracy of these tools compared to classical approaches.

KISSPLICE was also used in the context of myotonic dystrophy (DM), which is caused by the expression of mutant RNAs containing expanded CUG repeats that sequester muscleblind-like (MBNL) proteins, leading to alternative splicing changes. Cardiac alterations, characterised by conduction delays and arrhythmia, are the second most common cause of death in DM. Using RNA sequencing, the authors of [14] identified novel splicing alterations in DM heart samples, including a switch from adult exon 6B towards fetal exon 6A in the cardiac sodium channel, SCN5A. They found that MBNL1 regulates alternative splicing of SCN5A mRNA and that the splicing variant of SCN5A produced in DM presents a reduced excitability compared to the control adult isoform. Importantly, reproducing splicing alteration of Scn5a in mice is sufficient to promote heart arrhythmia and cardiac-conduction delay, two predominant features of myotonic dystrophy. Misregulation of the alternative splicing of SCN5A may therefore contribute to a subset of the cardiac dysfunctions observed in myotonic dystrophy.

We introduced CIDANE, a novel framework for genome-based transcript reconstruction and quantification from RNA-seq reads [8]. CIDANE assembles transcripts efficiently with significantly higher sensitivity and precision than existing tools. Its algorithmic core not only reconstructs transcripts *ab initio*, but also allows the use of the growing annotation of known splice sites, transcription start and end sites, or full-length transcripts, which are available for most model organisms. CIDANE supports the integrated analysis of RNA-seq and additional gene-boundary data and recovers splice junctions that are invisible to other methods.

Landscape of somatic mutations in breast cancer whole-genome sequences

In the context of the International Cancer Genome Consortium (ICGC), we conducted a whole-genome, exome, RNASeq and methylome characterisation of 560 breast cancers. The results were published this year in three main papers.

The first one describes the general landscape of somatic mutations and rearrangements in all subtypes of breast cancers [21]. This allowed to extend our current repertoire of probable breast cancer drivers to 93 genes. The mutational signature analysis was extended to genome rearrangements as well and revealed six typical rearrangement signatures. Three of them, characterised by tandem duplications or deletions, appear associated with defective homologous- recombination-based DNA repair (BRCA1/2). This analysis highlighted the repertoire of cancer genes and mutational processes operating in human, and represented a progress towards obtaining a comprehensive account of the somatic genetic basis of breast cancer.

This first analysis was then used to link known and novel drivers and mutational signatures to gene expression (transcriptome) of 266 cases [28]. One important and still debated question is to know to what extend somatic aberrations could trigger an immune-response. Our data suggested that substitutions of a particular type could be more effective in doing so than others.

Finally, in the context of ICGC, France was in charge of the analysis of a clinically specific subgroup of breast cancers, called HER2-positive, characterised by the HER2/ERBB2 amplification and over-expression. This is a subgroup for which several efficient targeted therapies (trastuzumab) are now available. However, resistance to treatment has been observed, revealing the underlying diversity of these cancers. An in-depth genomic and transcriptomic characterisation of 64 HER2-positive breast tumour was carried out. We delineated four subgroups, based on the expression data, each of them with distinctive genomic features in terms of somatic mutations, copy-number changes or structural variations [12]. The results suggested that, despite being clinically delineated by a specific gene amplification, HER2-positive tumours actually melt into the luminal-basal breast cancer spectrum rather, probably following their "cell-of-origin" fate and suggesting that the ERBB2 amplification is an embedded event in the natural history of these tumours. Finally, WGS data allowed us to gain more information about the amplification process itself and brought some indications about how (and maybe when) it arose. Whole genome paired-end sequencing provides two important experimental clues to this purpose: a) high dynamics and resolution analysis of copy numbers, and b) ability to pinpoint large scale structural rearrangements by using clipping and abnormal mapping of read pairs. We could show that, in several cases, the observed sequence of copy numbers as well as the orientation of clipped reads was consistent with a breakage-fusion-bridge folding mechanism (BFB). However, the observation of long distance and inter-chromosomal rearrangements further showed that the amplification is a complex event (or sequence of events), likely involving several amplicons on the same or different chromosomes and several intertwined mechanisms. Indeed one of the features of HER2+ tumours is the ubiquitous presence of firestorms, corresponding to multiple closely spaced amplicons on highly rearranged chromosomal arms. It is therefore tempting to combine two mechanisms to explain the complex amplification patterns observed: chromothripsis, which will generate a mosaic of fragments (but no amplification per se), followed by a BFB amplification of chromosomal arm(s). This work was done at the “Plateforme Bioinformatique Gilles Thomas” located at Centre Léon Bérard (Lyon).

Sequence comparison

Sequence comparison is a fundamental step in many important computational biology tasks, in particular the reconstruction of genomes, a first key step before being able to identify the molecular elements present in them.

Traditional algorithms for measuring approximation in sequence comparison are based on the notions of distance or similarity, and are generally computed through sequence alignment techniques. As circular molecular structures are a common phenomenon in nature, a caveat of the adaptation of alignment techniques for circular sequence comparison is that they are computationally expensive, requiring from super-quadratic to cubic time in the length of the sequences. We introduced a new distance measure based on q-grams, and showed how it can be applied effectively and computed efficiently for circular sequence comparison [15]. Experimental results, using real DNA, RNA, and protein sequences as well as synthetic data, demonstrated orders-of-magnitude superiority of our approach in terms of efficiency, while maintaining an accuracy very competitive in relation to the state of the art.

Data structures for text indexing and string (sequence) comparison

Suffix trees are important data structures for text indexing and string algorithms. For any given string w of length $n = |w|$, a suffix tree for w takes $O(n)$ vertices and links. It is often presented as a compacted version of a suffix trie for w, where the latter is the trie (or digital search tree) built on the suffixes of w. The compaction process replaces each maximal chain of unary vertices with a single arc. For this, the suffix tree requires that the labels of its arcs are substrings encoded as pointers to w (or equivalent information). On the contrary, the arcs of the suffix trie are labeled by single symbols but there can be $\Theta(n^2)$ vertices and links for suffix tries in the worst case because of their unary vertices. It was an interesting question if the suffix trie can be stored using $O(n)$ vertices. We addressed it and thus presented the linear-size suffix trie, which guarantees $O(n)$ vertices [11]. We used a new technique for reducing the number of unary vertices to $O(n)$, that stems from some results on anti-dictionaries. For instance, by using the linear-size suffix trie, we are able to check whether a pattern p of length $m = |p|$ occurs in w in $O(m \log |\Sigma|)$ time and we can find the longest common substring of two strings w_1 and w_2 in $O((|w_1| + |w_2|) \log |\Sigma||)$ time for an alphabet $\Sigma|$.

Haplotype assembly

Haplotype assembly is the computational problem of reconstructing haplotypes in diploid organisms and is of fundamental importance for characterising the effects of single-nucleotide polymorphisms on the expression of phenotypic traits. Haplotype assembly highly benefits from the advent of "future-generation" sequencing technologies and their capability to produce long reads at increasing coverage. Existing methods are not able to deal with such data in a fully satisfactory way, either because accuracy or performances degrade as read length and sequencing coverage increase or because they are based on restrictive assumptions.

By exploiting a feature of future-generation technologies – the uniform distribution of sequencing errors – we designed an exact algorithm, called HAPCOL, that is exponential in the maximum number of corrections for each single-nucleotide polymorphism position and that minimises the overall error-correction score [22]. We performed an experimental analysis, comparing HAPCOL to the current state-of-the-art combinatorial methods both on real and simulated data. On a standard benchmark of real data, we showed that HAPCOL is competitive with state-of-the-art methods, improving the accuracy and the number of phased positions. Furthermore, experiments on realistically simulated datasets revealed that HAPCOL requires significantly less computing resources, especially memory. Thanks to its computational efficiency, HAPCOL can overcome the limits of previous approaches, allowing to phase datasets with higher coverage and without the traditional all-heterozygous assumption.

HAPCOL is based on MEC (Minimum error correction) which is computationally hard to solve. However, some approximation-based or fixed-parameter approaches have been proved capable of obtaining accurate results on real data. In another work [5], we then attempted to expand the current characterisation of the computational complexity of MEC from such approximation and fixed-parameter tractability points of view. We showed that MEC is not approximable within a constant factor, whereas it is approximable within a logarithmic factor in the size of the input. Furthermore, we answered open questions on the fixed-parameter tractability for parameters of classical or practical interest: the total number of corrections and the fragment length. In addition, we presented a direct 2-approximation algorithm for a variant of the problem that has also been applied in the framework of clustering data. Finally, since polyploid genomes, such as those of plants and fishes, are composed of more than two copies of the chromosomes, we introduced a novel formulation of MEC, namely the k-ploid MEC problem, that extends the traditional problem to deal with polyploid genomes. We showed that the novel formulation remains both computationally hard and hard to approximate. Nonetheless, from the parameterised point of view, we proved that the problem is tractable for parameters of practical interest such as the number of haplotypes and the coverage, or the number of haplotypes and the fragment length.

6.3. Inferring and analysing the networks of molecular elements

Metamodules in transcriptomic analysis

The human microbiome plays a key role in health and disease. Thanks to comparative metatranscriptomics, the cellular functions that are deregulated by the microbiome in disease can now be computationally explored. Unlike gene-centric approaches, pathway-based methods provide a systemic view of such functions; however, they typically consider each pathway in isolation and in its entirety. They can therefore overlook the key differences that (i) span multiple pathways, (ii) contain bidirectionally deregulated components, (iii) are confined to a pathway region. To capture these properties, computational methods that reach beyond the scope of predefined pathways are needed.

By integrating an existing module discovery algorithm into comparative metatranscriptomic analysis, we developed METAMODULES, a novel computational framework for automated identification of the key functional differences between health- and disease-associated communities [20]. Using this framework, we recovered significantly deregulated subnetworks that were indeed recognised to be involved in two well-studied, microbiome-mediated oral diseases, such as butanoate production in periodontal disease and metabolism of sugar alcohols in dental caries. More importantly, our results indicated that our method can be used for hypothesis generation based on automated discovery of novel, disease-related functional subnetworks, which would otherwise require extensive and laborious manual assessment.

Metabolic environmental dialog

What an organism needs at least from its environment to produce a set of metabolites, *e.g.* target(s) of interest and/or biomass, has been called a minimal precursor set. Early approaches to enumerate all minimal precursor sets took into account only the topology of the metabolic network (topological precursor sets). Due to cycles and the stoichiometric values of the reactions, it is often not possible to produce the target(s) from a topological precursor set in the sense that there is no feasible flux. Although considering the stoichiometry makes the problem harder, it enables to obtain biologically reasonable precursor sets that we call stoichiometric. Recently a method to enumerate all minimal stoichiometric precursor sets was proposed in the literature. The relationship between topological and stoichiometric precursor sets had however not yet been studied.

Such relationship was explored in a recently accepted paper [3]. In there, we also presented two algorithms that enumerate all minimal stoichiometric precursor sets. The first one is of theoretical interest only and is based on the above mentioned relationship. The second approach solves a series of mixed integer linear programming (MILP) problems. We compared the computed minimal precursor sets to experimentally obtained growth media of several *Escherichia coli* strains using genome-scale metabolic networks.

The results showed that the second approach, called SASITA, efficiently enumerates minimal precursor sets taking stoichiometry into account, and allows for broad *in silico* studies of strains or species interactions that may help to understand *e.g.* pathotype and niche-specific metabolic capabilities.

This work was also part of the PhD of Martin Wannagat, defended in June 2016 [2].

Metabolic hyperstories

In the context of a PhD in the team (whose defence took place in Dec 8, 2016) [1] and using metabolomics data, we focused on inferring the metabolic behaviour of an organism when it is subjected to a change in conditions. In this case, one can infer the reactions impacted when the changes are controlled and known (*e.g.* exposition to toxic compounds, changes in culture conditions). However, understanding how the metabolism of an organism changes of equilibrium is also of interest to infer the processes related for example to a transition between a commensal or beneficial bacterium to a pathogenic one. This question led to two different methods. The first, that we called TOTORO (for TOpological analysis of Transient metabOlic RespOnse), is based on the topology of metabolic networks to infer the reactions involved in a transient state, when an organism goes from one state of growth to another. We proposed a novel definition using the directed hypergraph representation and discussed its application on a dataset of Yeast exposed to cadmium. We showed that this method suggests more complete solutions of the reactions impacted during the metabolic shift. The second method, called KOTOURA (for Kantitative analysis Of Transient metabOlic and regUlatory Response And control), offers a constraint-based perspective in a more quantitative approach. We applied it to a simulated dataset and we are currently trying to infer the possible quantitative responses to mutations with a more complete kinetic model. An image previously used is that condition-specific models provide a snapshot of the metabolism of an organism, whether it is at the evolutionary-time scale or at the scale of a specific environmental condition describing a physiological process. Our idea here is thus to infer the transitions between those snapshots.

Besides the PhD manuscript, two papers are in preparation to present this work. They should be submitted in early 2017. A prototype for the two methods is available at: http://hyperstories.gforge.inria.fr/.

6.4. Modelling and analysing a network of individuals, or a network of individuals' networks

Robustness of the parsimonious reconciliation method in cophylogeny

The currently most used method in cophylogenetic studies is the so-called *phylogenetic tree reconciliation*. In this model, we are given the phylogenetic tree of the hosts H, the one of the symbionts S, and a mapping ϕ from the leaves of S to the leaves of H indicating the known symbiotic relationships among present-day organisms. The common evolutionary history of the hosts and of their symbionts is then explained through a number of macroevolutionary events (four in general). A reconciliation is then a function λ which is an extension of the mapping ϕ between leaves to a mapping that includes all internal nodes and that can be constructed using the different types of events considered. An optimal reconciliation is usually defined in a parsimonious way: a cost is associated to each event and a solution of minimum total cost is searched for.

An important issue in this model is that it makes strong assumptions on the input data which may not be verified in practice. We examine two cases where this situation happens. The first is related to a limitation in the currently available methods for tree reconciliation where the association ϕ of the leaves is for now required to be a function. This is not realistic as a single symbiont species can infect more than one host. For each present-day symbiont involved in a multiple association, one is currently forced to choose a single one. The second case addresses a different type of problem related to the phylogenetic trees of hosts and symbionts. These indeed are assumed to be correct, which may not be the case. In this work, we addressed the problem of correctly rooting a phylogenetic tree.

We thus explored the robustness of the parsimonious tree reconciliation method under "editing" (multiple associations) or "small perturbations" of the input (rooting problem) [29].

An extended version of this paper has been submitted to *IEEE/ACM Transactions on Computational Biology and Bioinformatics*.

Insights on the virulence of swine respiratory tract mycoplasmas through genome-scale metabolic modelling

The respiratory tract of swines is colonised by several bacteria among which are three Mycoplasma species: *Mycoplasma flocculare*, *Mycoplasma hyopneumoniae* and *Mycoplasma hyorhinis*. While colonisation by *M. flocculare* was shown to be virtually asymptomatic, *M. hyopneumoniae* is known to be the causative agent of enzootic pneumonia and *M. hyorhinis* to be present in cases of pneumonia, polyserositis and arthritis. Nonetheless, the elevated genomic resemblance among these three mycoplasmas combined with their different levels of pathogenicity is an indication that they have unknown mechanisms of virulence and differential expression. In 2015, we performed whole-genome metabolic network reconstructions for these three mycoplasmas. The results obtained were then submitted for publication to *BMC Genomics*. The paper has since been published [13].

Maximal chain subgraphs and covers of bipartite graphs motivated by analysis of cytoplasmic incompatibility

In a previous work of the team (Nor *et al.American Naturalist*, 182(1):15-24, 2013; Nor*et al.Information and Computation*, 213:23-32, 2012), we showed that a minimum chain subgraph cover of a given bipartite graph provides a good model for identifying the minimum genetic architecture enabling to explain one type of manipulation, called *cytoplasmic incompatibility*, by some parasite bacteria on their hosts. This phenomenon results in the death of embryos produced in crosses between males carrying the infection and uninfected females. The observed cytoplasmic compatibility relationships, can then be represented by a bipartite graph with males and females in different classes. Moreover, as different minimum (resp. minimal) covers may correspond to solutions that differ in terms of their biological interpretation, the capacity to enumerate all such minimal chain covers becomes crucial.

We recently addressed three related problems that bear some interest for the above problem besides raising interesting theoretical questions [35]. One is the enumeration of all the maximal *edge induced* chain subgraphs of a bipartite graph, for which we provided a polynomial delay algorithm. We gave bounds on the number of maximal chain subgraphs for a bipartite graph and used them to establish the input-sensitive complexity of the enumeration problem. The second problem we treated was the one of finding the minimum number of chain subgraphs needed to cover all the edges a bipartite graph. For this, we provided an exact exponential algorithm with a non trivial complexity. Finally, we approached the problem of enumerating all minimal chain subgraph covers of a bipartite graph and showed that it can be solved in quasi-polynomial time.

An extended version of the conference paper has been submitted to a journal in December 2016.

6.5. Cross-fertilising different computational approaches and other theoretical results

On the Complexity of Quadratic-Time Solvable Problems

Quadratic-time solvable problems may be classified into two classes: problems that are solvable in *truly subquadratic* time (that is, in time $(n^{2-\epsilon})$ for some $\epsilon > 0$) and problems that are not, unless the well known Strong Exponential Time Hypothesis (in short, SETH) is false. We proved that some quadratic-time solvable problems are indeed easier than expected [6]. We provided an algorithm that computes the transitive closure of a directed graph in time $(mn^{\frac{\omega+1}{4}})$, where m denotes the number of edges in the transitive closure and ω is the exponent for matrix multiplication. As a side effect of our analysis, we were able to prove that our algorithm runs in time $(n^{\frac{5}{3}})$ if the transitive closure of the graph is sparse. The same time bounds hold if we want to check whether a graph is transitive, by replacing m with the number of edges in the graph itself. As far as we know, this gives us the fastest algorithm for checking whether a sparse graph is transitive. Finally, we applied our algorithm to the comparability graph recognition problem (which dates back to 1941): also in this case, we obtained the first truly subquadratic algorithm. We then dealt with some hardness results. In particular, we started from an artificial quadratic-time solvable variation of the k-SAT problem and constructed a graph of Karp reductions, proving that a truly subquadratic-time algorithm for any of the problems in the graph falsifies SETH. More specifically, the analysed problems were the following: computing the subset graph, finding dominating sets, computing the betweenness centrality of a vertex, computing the minimum closeness centrality, and computing the hyperbolicity of a pair of vertices. We were also able to include in our framework three proofs that had already appeared in the literature, concerning the problems of distinguishing between split graphs of diameter 2 and diameter 3, of solving the local alignment of strings, and of finding two orthogonal binary vectors inside a collection.

Enumeration of solutions produced by closure operations

In enumeration problems, we are interested in listing a set of elements, which can be of exponential cardinality in the size of the input. The complexity of such problems is thus measured in terms of their input and output sizes. An enumeration algorithm with a complexity polynomial in both sizes is called output polynomial or total polynomial time. Another more precise notion of complexity is related to the *delay*, that is to the time between the production of two consecutive solutions. We are especially interested in problems solvable with a delay polynomial in the input size. These are considered as the tractable problems in enumeration complexity.

We addressed the problem of generating all elements obtained by the saturation of an initial set by some operations [41]. More precisely, we proved that we can generate the closure by polymorphisms of a boolean relation with a polynomial delay. This implies for instance that we can compute with polynomial delay the closure of a family of sets by any set of "set operations" (*e.g.* union, intersection, difference, symmetric difference, etc.). To do so, we proved that for any set of operations $\mathcal{F}$, one can decide in polynomial time whether an element belongs to the closure by $\mathcal{F}$ of a family of sets. When the relation is over a domain larger than two elements, our generic enumeration method fails for some cases since the associated decision problem is NP-hard, and we then provide an alternative algorithm.

6.6. Going towards control

Combinatorial approach for microbial consortia synthetic design

Synthetic biology has boomed since the early 2000s when it started being shown that it was possible to efficiently synthetise compounds of interest in a much more rapid and effective way by using other organisms than those naturally producing them. However, to thus engineer a single organism, often a microbe, to optimise one or a collection of metabolic tasks may lead to difficulties when attempting to obtain a production system that is efficient, or to avoid toxic effects for the recruited microorganism. The idea of using instead a microbial consortium has thus started being developed in the last decade. This was motivated by the fact that such consortia may perform more complicated functions than could single populations and be more robust to environmental fluctuations. Success is however not always guaranteed. In particular, establishing which consortium is best for the production of a given compound or set thereof remains a great challenge. This is the problem we addressed in a paper accepted this year [16].

We thus introduced an initial model and a method, called MULTIPUS, that enable to propose a consortium to synthetically produce compounds that are either exogenous to it, or are endogenous but where the interaction among the species in the consortium could improve the production line. In mathematical terms, given a weighted directed hypergraph $\mathcal{H}$, the problem is to enumerate all directed sub-hypergraphs whose sets of vertices and of hyperarcs are included in those of $\mathcal{H}$, enable to produce the set of targets of interest from a subset of the sources of $\mathcal{H}$, and are of minimum weight. We called this the Directed Steiner Hypertree (DSH) problem.

We showed that the main issue in terms of the complexity of the problem comes from the hyperarcs with multiple source vertices (we called those the *tentacular hyperarcs*), not from the possible multiplicity of the target vertices. This is not the only issue though, and we thus further demonstrated that even when there is only one target that needs to be reached, the problem remains NP-hard. When both parameters, number of tentacular hyperarcs and of targets, are fixed, the problem becomes tractable. We then explored two methods for addressing it. One is a dynamic programming approach, and the other logic programming using ASP (Answer Set Programming). The second was more efficient for now, and the software MULTIPUS is thus based on it.

As initial validations of the model and of the method, we applied it to two case-studies taken from the literature.

This work was also part of the PhD of Alice Julien-Laferrière defended in December 2016 [1].

7. Partnerships and Cooperations

7.1. Regional Initiatives

7.1.1. ICEbErg

- Title: Integrating Co-phylogeny in the analysis of Ecological nEtworks
- Coordinator: B. Sinaimeri and S. Dray
- ERABLE participant(s): B. Sinaimeri
- Type: Inter-departmental project funded by the LBBE (Sept 2016 - Sept 2017)
- Web page: Not available

7.2. National Initiatives

7.2.1. ANR

7.2.1.1. ABS4NGS

- Title: Solutions Algorithmiques, Bioinformatiques et Logicielles pour le Séquençage Haut Débit
- Coordinator: E. Barillot

- ERABLE participant(s): V. Lacroix
- Type: ANR (2012-2016)
- Web page: https://sites.google.com/site/abs4ngs/

7.2.1.2. Colib'read

- Title: Methods for efficient detection and visualization of biological information from non assembled NGS data
- Coordinator: P. Peterlongo
- ERABLE participant(s): V. Lacroix, L. I. S. de Lima, A. Julien-Laferrière, H. Lopez-Maestre, C. Marchet, G. Sacomoto, M.-F. Sagot, B. Sinaimeri
- Type: ANR (2013-2016)
- Web page: http://colibread.inria.fr/

7.2.1.3. ExHyb

- Title: Exploring genomic stability in hybrids
- Coordinator: C. Vieira
- ERABLE participant(s): C. Vieira
- Type: ANR (2014-2018)
- Web page: Not available

7.2.1.4. GraphEn

- Title: Enumération dans les graphes et les hypergraphes : algorithmes et complexité
- Coordinator: D. Kratsch
- ERABLE participant(s): A. Mary
- Type: ANR (2015-2019)
- Web page: http://graphen.isima.fr/

7.2.1.5. IMetSym

- Title: Immune and Metabolic Control in Intracellular Symbiosis of Insects
- Coordinator: A Heddi
- ERABLE participant(s): H. Charles, S. Colella
- Type: ANR Blanc (2014-2017)
- Web page: Not available

7.2.2. Others

Notice that were included here national projects of our members from Italy when these have no other partners than researchers from the same country.

7.2.2.1. Amanda

- Title: Algorithmics for MAssive and Networked DAta
- Coordinator: G. Di Battista (University of Roma 3)
- ERABLE participant(s): R. Grossi, N. Pisanti
- Type: MIUR PRIN, Italian Ministery of Research National Projects (2014-2017)
- Web page: http://www.dia.uniroma3.it/~amanda/

7.2.2.2. Effets de l'environnement sur la stabilité des éléments transposables

- Title: Effets de l'environnement sur la stabilité des éléments transposables
- Coordinator: C. Vieira
- ERABLE participant(s): C. Vieira
- Type: Fondation pour la Recherche Médicale (FRM) (2014-2016)
- Web page: Not available

7.2.2.3. QualiBioConsensus

- Title: Qualité des classements consensuels de données biologiques massives
- Coordinator: S. Cohen-Boulakia
- ERABLE participant(s): L. Bulteau (external collaborator of ERABLE)
- Type: Défi Mastodons (2016)
- Web page: Not available

7.3. European Initiatives

7.3.1. FP7 & H2020 Projects

7.3.1.1. BacHBerry

Title: BACterial Hosts for production of Bioactive phenolics from bERRY fruits
Duration: November 2013 - October 2016
Coordinator: Jochen Förster, DTU Danemark
ERABLE participant(s): R. Andrade, L. Bulteau, A. Julien-Laferrière, V. Lacroix, A. Marchetti-Spaccamela, A. Mary, D. Parrot, M.-F. Sagot, L. Stougie, A. Viari, M. Wannagat
Type: FP7 - KBBE
Web page: http://www.bachberry.eu/

7.3.1.2. MicroWine

- Title: Microbial metagenomics and the modern wine industry
- Duration: January 2015 - January 2019
- Coordinator: Lars Hestbjerg Hansen, University of Copenhagen
- ERABLE participant(s): A. Marchetti-Spaccamela, A. Mary, H. T. Pusa, M.-F. Sagot, L. Stougie
- Type: H2020-MSCA-ETN-2014
- Web page: http://www.microwine.eu/

7.3.2. Collaborations in European Programs, Except FP7 & H2020

7.3.2.1. Combinatorics of co-evolution

- Title: The combinatorics of co-evolution
- Duration: 2015 - 2017
- Coordinator: Katharina Huber, University of Warwick, UK
- ERABLE participant(s): M.-F. Sagot, B. Sinaimeri
- Type: The Royal Society
- Web page: not available

7.3.3. Collaborations with Major European Organisations

By itself, ERABLE is built from what initially were collaborations with some major European Organisations (CWI, Sapienza University of Rome, Universities of Florence and Pisa, Free University of Amsterdam) and now has become a European Inria Team.

7.4. International Initiatives

7.4.1. Inria International Labs

ERABLE participates in a project within the Inria-Chile CIRIC (Communication and Information Research and Innovation Center) titled “Omics Integrative Sciences”. The main objectives of the project are the development and implementation of mathematical and computational methods and the associated computational platforms for the exploration and integration of large sets of heterogeneous omics data and their application to the production of biomarkers and bioidentification systems for important Chilean productive sectors. The project started in 2011 and is coordinated in Chile by Alejandro Maass, Mathomics, University of Chile, Santiago. It is in the context of this project that we are currently hosting Alex di Genova in ERABLE as a PhD sandwich student (for 18 to 24 months). Alex is co-supervised by Alejandro Maass and by Eric Goles from the University Adolfo Ibañez, Santiago, Chile.

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

ALEGRIA

- Title: ALgorithms for ExplorinG the inteRactions Involving Apicomplexa and kinetoplastida
- Duration: 2015 - 2017
- Coordinator: On the Brazilian side, Andréa Rodrigues Ávila; on the French side, Marie-France Sagot
- ERABLE participant(s): M. Ferrarini, L. Ishi Soares de Lima, A. Mary, H. T. Pusa, M.-F. Sagot, M. Wannagat
- Web page: http://team.inria.fr/erable/en/alegria/

7.4.3. Participation in other International Programs

ERABLE is coordinator of a CNRS-UCBL-Inria Laboratoire International Associé (LIA) with the Laboratório Nacional de Computação Científica (LNCC), Petrópolis, Brazil. The LIA has for acronym LIRIO (“Laboratoire International de Recherche en bIOinformatique”) and is coordinated by Ana Tereza Vasconcelos from the LNCC and Marie-France Sagot from BAOBAB-ERABLE. The LIA was created in January 2012 for 4 years, renewable once. A web page for the LIA LIRIO is available at this address: http://team.inria.fr/erable/en/cnrs-lia-laboratoire-international-associe-lirio/.

ERABLE coordinates another project with Brazil. This is a CAPES-COFECUB project titled: “Multidisciplinary Approach to the Study of the Biodiversity, Interactions and Metabolism of the Microbial Ecosystem of Swines”, and its acronym MICO. The coordinators are M.-F. Sagot (France) and A. T. Vasconcelos (LNCC, Brazil) with also the participation of Arnaldo Zaha (Federal University of Rio Grande do Sul, Brazil). The project started in 2013 for 2 years, and was renewed for 2 more years starting from 2015. The main objective of this project is to experimentally and mathematically explore the biodiversity of the bacterial organisms living in the respiratory tract of swines, many of which are pathogenic. This project is strongly linked to the LIA LIRIO. More information on it may be found at this address: http://team.inria.fr/erable/en/cnrs-lia-laboratoire-international-associe-lirio/associated-projects/#CAPES-COFECUB_Microbial_Ecosystem_of_Swines.

ERABLE has a Stic AmSud project that started in 2016 for 2 years. The title of the project is “Methodological Approaches Investigated as Accurately as possible for applications to biology”, and its acronym MAIA. This project involves the following partners: (France) Marie-France Sagot, ERABLE Team, Inria; (Brazil) Roberto Marcondes César Jr, Instituto de Matemática e Estatística, Universidade de São Paulo; and Paulo Vieira Milreu, TecSinapse; (Chile) Vicente Acuña, Centro de Modelamiento Matemático, Santiago; and Gonzalo Ruz, University Adolfo Ibañez, Santiago. One of them, TecSinapse, is an industrial partner. MAIA has two main goals: one methodological that aims to explore how accurately hard problems can be solved theoretically by different approaches – exact, approximate, randomised, heuristic – and combinations thereof, and a second that aims to better understand the extent and the role of interspecific interactions in all main life processes by using the methodological insights gained in the first goal and the algorithms developed as a consequence. A preliminary web page for MAIA is available at this address: http://team.inria.fr/erable/en/projects/maia/.

Finally, we would like to mention the participation of one member of ERABLE (Alain Viari) in the Breast Cancer French Working Group of the International Cancer Genome Consortium (ICGC, https://icgc.org) led by the Institut National du Cancer (INCa, http://www.e-cancer.fr/Professionnels-de-la-recherche/Innovations/Les-progres-de-la-genomique/ICGC-France). This project was initiated by Pr. Gilles Thomas who passed away in 2014. Alain took the head of the bioinformatics platform located at the Centre Léon Bérard. The project aims at the genomic characterisation of 75 HER2-amplified breast cancers by using high-throughput sequencing (whole genome of paired tumour/normal samples and RNAseq of tumour samples). One of the scientific goals is to decipher whether the HER2/ERBB2 amplification is a driver or a passenger event in the course of tumour development.

7.5. International Research Visitors

7.5.1. Visits of International Scientists

In 2016, ERABLE greeted the following International scientists:

- In France: Katharina Huber and Vincent Moulton (University of Warwick, UK), Giuseppe Italiano (Tor Vergata University of Rome, Italy, various visits), Ana Rute Neves and Thomas Janzen (ChR Hansen, Oslo, Danemark), two members of the LIA LIRIO (Arnaldo Zaha from the Federal University of Rio Grande do Sul, and Ana Tereza Vasconcelos from the LNCC, both in Brazil), Susana Vinga and various members of her team (IDMEC-IST Portugal), Tiziana Calamoneri (Sapienza University of Rome).
- In Italy: Costas Iliopoulos and Solon Pissis (King's College, London, UK).

7.5.2. Internships

In 2016, ERABLE greeted the following internship students:

- In France: Audric Cologne, Master 2 (6 months); Irene Ziska, Master Free University Berlin (2 months), Louis Duchemin Master 1 (5 months).

7.5.3. Visits to International Teams

7.5.3.1. Visits

In 2016, members of ERABLE visited the following International teams:

- In France: Giuseppe Italiano (Tor Vergata University of Rome), visit to members of the LIA LIRIO at the LNCC in Brazil, visit to the Department of Computer Science of the University of São Paulo and to members of the TecSinapse company in Brazil, Tiziana Calamoneri (La Sapienza University of Rome), Susana Vinga and members of her team (IDMEC-IST Portugal), Rafaelle Giancarlo (Palermo University, Italy).
- In Italy: Costas Iliopoulos (King's College, London, UK), Luís Russo (INESC-IST, Lisbon, Portugal), Paola Bonizzoni (Milan-Bicocca, Italy), Rafaelle Giancarlo (Palermo University, Italy).

7.5.3.2. Research stays abroad

Gunnar Klau spent 9 months starting from November 2015 at the Center for Computational Molecular Biology at Brown University, USA, visiting notably Benjamin Raphael, Director of the Center.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific events organisation

8.1.1.1. General chair, scientific chair

- Alberto Marchetti-Spaccamela is member of the Steering committee of WG, Workshop on Graph Theoretic Concepts in Computer Science, and of ATMOS, Workshop on Algorithmic Approaches for Transportation Modeling, Optimization, and Systems.
- Marie-France Sagot was from 2010 to 2016 member and from 2014 to 2016 Chair of the Steering Committee of the International Conference *LATIN* (http://www.latintcs.org/). She is member of the Steering Committee of the *European Conference on Computational Biology* (*ECCB*) since 2002 and of the International Symposium on Bioinformatics Research and Applications (ISBRA) since 2008.

8.1.1.2. Member of the organising committees

- Leen Stougie was co-organiser, together with Neil Olver and René Sitters of the 8th Workshop on Flexible Network Design, July 4-8, 2016, Vrije Universiteit, Amsterdam, The Netherlands.

8.1.2. Scientific events selection

8.1.2.1. Member of the conference program committee

- Laurent Bulteau (external collaborator of ERABLE) was a member of the program committee for the following international conferences in 2016: 41st International Symposium on Mathematical Foundations of Computer Science (MFCS 2016) and 11th International Conference on Algorithmic Aspects of Information and Management (AAIM).
- Pierluigi Crescenzi was a member of the program committee for the following international conferences in 2016: 17th Italian Conference on Theoretical Computer Science (ICTCS), 31st IEEE International Parallel & Distributed Processing Symposium (IPDPS).
- Roberto Grossi was a member of the program committee for the following international conferences in 2016: 12th Latin American Theoretical Informatics Symposium (LATIN), 27th International Workshop on Combinatorial Algorithms (IWOCA), 8th International Conference on Fun with Algorithms (FUN).
- Alberto Marchetti-Spaccamela was a member of the program committee for the following international conference in 2016: 15th International Symposium on Experimental Algorithms (SEA).
- Nadia Pisanti was a member of the program committee for the following international conferences in 2016: 10th International Workshop on Algorithms and Computation (WALCOM), 5th International Symposium on Network Enabled Health Informatics, Biomedicine and Bioinformatics (Hi BI BI), 5th RECOMB Satellite Workshop on Computational Cancer Biology (RECOMB-CCB), 16th Workshop on Algorithms in BIoinformatics (WABI), 6th RECOMB Satellite Workshop on Massively Parallel Sequencing (RECOMB-Seq), 12th International Symposium on Bioinformatics Research and Applications (ISBRA), 7th International Conference on Information Technology on Bio- and Medical-Informatics (ITBAM), 6th IEEE International Conference on Computational Advances in Bio and Medical Sciences (ICCABS).
- Marie-France Sagot was a member of the program committee for the following international conferences in 2016: Intelligent Systems for Molecular Biology (ISMB), Prague Stringology Conference 2016, 11th International Conference on Algorithmic Aspects of Information and Management (AAIM), 20th Annual International Conference on Research in Computational Molecular Biology (RECOMB), 14th RECOMB Satellite Workshop on Comparative Genomics (RECOMB-CG), 16th Workshop of Algorithms in Bioinformatics (WABI).
- Leen Stougie was a member of the program committee of the following conferences in 2016: 18th Conference on Integer Programming and Combinatorial Optimization (IPCO), Workshop on Approximation and Online Algorithms (WAOA).

8.1.2.2. Reviewer

Besides the above, various other members of ERABLE have been reviewer for other international conferences, such as SODA etc.

8.1.3. Journal

8.1.3.1. Member of the editorial board

- Pierluigi Crescenzi is member of the Editorial Board of *Journal of Computer and Systems Science* and *Electronic Notes on Theoretical Computer Science*.
- Roberto Grossi is member of the Editorial Board of *Theory of Computing Systems (TOCS)* and *RAIRO – Theoretical Informatics and Applications – Informatique Théorique et Applications*.
- Alberto Marchetti-Spaccamela is member of the Editorial Board of *Theoretical Computer Science* and *Transactions on Algorithms Engineering*.
- Nadia Pisanti is since 2012 member of Editorial Board of *International Journal of Computer Science and Application (IJCSA)*.
- Marie-France Sagot is member of the Editorial Board of *Lecture Notes in Bioinformatics* (subseries of *Lectures Notes in Computer Science*), *Journal of Discrete Algorithms*, *BMC Bioinformatics*, and *BMC Algorithms for Molecular Biology*.
- Leen Stougie is member of the Editorial Board of *Transactions on Algorithms Engineering* since 2010, *Surveys in Operations Research and Management Science* since 2011, and *Journal of Industrial and Management Optimization* since 2013.
- Cristina Vieira is Executive Editor of *Gene*, and since 2014 member of the Editorial Board of *Mobile DNA*.

8.1.3.2. Reviewer for Journals

Members of ERABLE have reviewed papers for the following journals: *Theoretical Computer Science*, *Algorithmica*, *IEEE/ACM Transactions in Computational Biology and Bioinformatics (TCBB)*, *Algorithms for Molecular Biology*, *Scientific Reports*, *Journal of Computational Biology*, *BMC Bioinformatics*, *Computing and Informatics*, *BMC Evolutionary Biology*, *Genetica*, *Gene*, *Genome Biology and Evolution*, *Genetical Research*, *Genome Research*, *Molecular Biology and Evolution*, *Insect Biochemistry and Molecular Biology*, *PLoS Genetics*, *Mutation research*, *mBio*, *Frontiers in Microbiology*, *Infection, genetics and evolution*, *PLoS Biology*.

8.1.4. Invited talks

Clara Benoit-Pilven gave a lecture (Workshop Colib'read, November 7-8, 2016).

Roberto Grossi gave an invited talk (Eleventh International Conference on Algorithmic Aspects in Information and Management (AAIM), Bergamo, Italy, July 18-20, 2016).

Gunnar Klau gave an invited talk (Simon's Institute for the Theory of Computing, Workshop on Network Biology, April 11-15, 2016).

Vincent Lacroix gave a lecture+demonstration (Workshop Colib'read, November 7-8, 2016). He also made an invited presentation in the context of a CNRS training meeting (Formation Bioinformatique pour les NGS Montpellier, March 24, 2016)

Hélène Lopez-Maestre gave a lecture (Workshop Colib'read, November 7-8, 2016).

Nadia Pisanti gave two invited talks (Data Driven Innovation Open Summit, Rome, May 20-21, 2016; Conference Mathematical Foundations in Bioinformatics (MatBio), London, UK, July 20, 2016).

Marie-France Sagot gave two invited talks (German Conference on Bioinformatics (GCB), Berlin, Germany, Sept 12-15, 2016; First Workshop on Enumeration Problems and Applications (WEPA), Aubière, France, Nov 21-22, 2016).

Blerina Sinaimeri gave a talk (University of Palermo, Sept 27, 2016).

Leen Stougie gave two lectures (Graduate School on Methods for Discrete Structures, Free University Berlin, 25 April 2016; 7th Cargese Workshop on Combinatorial Optimization, October 9-14, 2016).

Laura Urbini gave a lecture (Warwick University, Computer Science Department, November 10, 2016).

8.1.5. Leadership within the scientific community

Alberto Marchetti-Spaccamela is Member of the Council of EATCS, the European Association for Theoretical Computer Science.

Leen Stougie was Chairman of the Dutch Network on the Mathematics of Operations Research (Landelijk Netwerk Mathematische Besliskunde (LNMB)) from February 2011 to January 2016. From February 2016, he is Member of the general board of the LNMB. He is also Chairman Program Committee Econometrics and OR, VU Amsterdam and Member of the Board of the research school ABRI-VU, Amsterdam.

Cristina Vieira is director of the GDRE "Comparative genomics" since the latter was renewed in 2010.

Marie-France Sagot and Fabrice Vavre are members of the Steering Committee of the LabEx Ecofect (http://ecofect.universite-lyon.fr/).

8.1.6. Scientific expertise

Marie-France Sagot is member of the Advisory Board of the CWI, Amsterdam, The Netherlands, and chair of the "Commissions Scientifiques Spécialisées" (CSS) of the INRA for the Department of Applied Mathematics and Computer Science. She was also a Panel Member for the ERC.

Fabrice Vavre is member of the Section 29 of the Comité National de la Recherche Scientifique (CoNRS).

8.1.7. Research administration

Hubert Charles is director of the Biosciences Department of the Insa-Lyon.

Alberto Marchetti-Spaccamela is Director of the Department of Computer, Control, and Management Engineering Antonio Ruberti at Sapienza University of Rome, Italy.

Nadia Pisanti is since 2013 member of the Board of the Regional PhD School of Computer Science at the University of Pisa, Italy.

Alain Viari is since 2012 Deputy Scientific Director at Inria responsible for the domain "Digital Health, Biology and Earth". He thus represents Inria at several national instances related to Life Sciences, Health and Environment.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Most of the members of ERABLE are Assistant / Associate or Full Professors and as such have a heavy load of teaching. Depending on the country, this represents between 150 to 192 hours in front of a class plus the additional work of preparing the courses and exams, and of correcting the latter. Many are also responsible for some of the university courses at the undergraduate or graduate levels.

More in detail:

- In France:
  - Hubert Charles is responsible for the Master of Modelling and Bioinformatics (BIM) at the Insa of Lyon. He teaches 192 hours per year in statistics and biology.
  - Pierluigi Crescenzi taught 120h (72h of Programming in Java for the undergraduate program in Computer Science and 48 of Distributed Algorithms for the Master in Computer Science) at the University of Florence.
  - Vincent Lacroix is responsible for several courses both at the University (L2: Bioinformatics, L3: Advanced Bioinformatics, M1: Methods for Genomics, M1: Methods for Transcriptomics, M1: Projects, M2: Bioethics) and at the Insa (M1: Gene Expression). He teaches 192 hours per year in bioinformatics and statistics.
  - Arnaud Mary taught 109+115 hours in 2016 at the University of Lyon 1 (L1: mathematics; L2: bioinformatics; M1: data analysis; M1: computer science).

    - Cristina Vieira is responsible for the Evolutionary Genetics and Genomics academic career of the Master Ecosciences-Microbiology. She was awarded an IUF (Institut Universitaire de France) distinction and teaches genetics 64 hours per year at the University and ENS Lyon.
- In Italy: Nadia Pisanti taught a total of 104 hours (L1: algorithms and programming; M2: algorithms for bioinformatics).
    - Alberto Marchetti-Spaccamela taught 60 hours of Computing Models (undergraduate class) and 30 hours of Privacy in the electronic society (master class) at Sapienza University of Rome.
    - Nadia Pisanti taught 72h (24h of Programming in C for the undergraduate program in Computer Science and 42 of Algorithms for Bioinformatics for the Master in Computer Science) at the University of Pisa.

Inria or CNRS Junior and senior researchers as well as PhD students and postdocs are also involved in teaching. Notably Alice Julien-Laferrière (PhD student) taught 6 hours (Jury PEL 4); Hélène Lopez-Maestre (PhD student) and Laura Urbini (PhD student) taught each 64 hours of Mathematics and Statistics at the Department of Biology (undergraduate students); Blerina Sinaimeri (Junior Inria Researcher) taught 12h in Discrete Mathematics at the Master of Modelling and Bioinformatics (BIM), INSA, University Lyon 1, as well as 24h at the Master 2 in Computer Science at the ENS Lyon; Fabrice Vavre taught 25h on symbiosis (L3, M1, M2, University Lyon 1, ENS Lyon, University of Poitiers).

Roberto Grossi also participated this year to the Olympiads in Informatics.

8.2.2. Supervision

The following are the PhDs defended in ERABLE in 2016.

- Martin Wannagat, University of Lyon 1, June 2016, supervisors: M.-F. Sagot, A. Marchetti-Spaccamela, L. Stougie.
- Alice Julien-Laferrière, University of Lyon 1, December 2016, supervisors: M.-F. Sagot, V. Lacroix, S. Vinga.

8.2.3. Juries

The following are the PhD or HDR juries to which members of ERABLE participated in 2016.

- Gunnar Klau: Reviewer of the PhD of Arnon Mazza, Tel Aviv University, and of the HDR of Pierre Peterlongo, University of Rennes.
- Marie-France Sagot: Reviewer of the PhD of Yoann Dufresne, University of Lille 1, France.
- Blerina Sinaimeri: Reviewer of the PhD of Nilakantha Paudel, University of Rome, Italy.

8.3. Popularisation

Gunnar Klau wrote an article for ERCIM News about Networks in Biology (http://ercim-news.ercim.eu/en104/special/networks-to-the-rescue-from-big-omics-data-to-targeted-hypotheses).

Roberto Grossi participated to the Pisa CoderDojo (https://www.unipi.it/index.php/news/item/7983-toscana-dojocon-2016-una-giornata-per-la-programmazione-digitale).

Marie-France Sagot, together with Roeland Merks from the CWI, co-edited a special Theme for ERCIM News on Tackling Big Data in the Life Sciences (http://ercim-news.ercim.eu/images/stories/EN104/EN104-web.pdf).

Blerina Sinaimeri participated to the “Conférences ISN et enseignement 2016” organised by Inria, 27 April 2016, to "Les journées nationales de l’APMEP: À la lumière des mathématiques", October 2016, and to “Filles et informatique : une équation lumineuse !” (Nov. 28. 2016, Lyon, France).

Fabrice Vavre participated in a television program on Arte, on the topic of “Ces microbes qui nous gouvernent”.

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Other Publications

[43] M. G. FERRARINI, F. M. SIQUEIRA, S. G. MUCHA, T. L. PALAMA, E. E. JOBARD, B. E. HERRMANN, A. T. RIBEIRO DE VASCONCELOS, F. F. TARDY, I. S. SCHRANK, A. ZAHA, M.-F. SAGOT.*Metabolic Investigation of the Mycoplasmas from the Swine Respiratory Tract*, September 2016, JOBIM 2016, Poster [*DOI :* 10.1186/S12864-016-2644-Z], https://hal.inria.fr/hal-01394118.

[44] A. JULIEN-LAFERRIÈRE, L. BULTEAU, D. PARROT, A. MARCHETTI-SPACCAMELA, L. STOUGIE, S. VINGA, A. MARY, M.-F. SAGOT.*MultiPus: Conception de communautés microbiennes pour la production de composés d'intérêt*, June 2016, Jobim, Poster, https://hal.inria.fr/hal-01394119.

Project-Team EXMO

Computer mediated exchange of structured knowledge

IN COLLABORATION WITH: Laboratoire d'Informatique de Grenoble (LIG)

IN PARTNERSHIP WITH:
Université Grenoble Alpes

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Data and Knowledge Representation and Processing

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Project-Team EXMO

Creation of the Project-Team: 2003 July 01, end of the Project-Team: 2016 December 31

Keywords:

Computer Science and Digital Science:

3.1.7. - Open data
3.2.2. - Knowledge extraction, cleaning
3.2.4. - Semantic Web
3.2.5. - Ontologies
8.1. - Knowledge

Other Research Topics and Application Domains:

6.3.1. - Web
9.7. - Knowledge dissemination
9.7.2. - Open data

1. Members

Research Scientist

Jérôme Euzenat [Team leader, Inria, Senior Researcher, HDR]

Faculty Members

Manuel Atencia Arcas [Univ. Grenoble Alpes, Associate Professor]
Jérôme David [Univ. Grenoble Alpes, Associate Professor]

PhD Students

Armen Inants [Inria, until Apr 2016, granted by ANR LINDICLE project]
Adam Sanchez Ayte [Inria, granted by ANR LINDICLE project]

Post-Doctoral Fellow

Tatiana Lesnikova [Inria, until May 2016; Post-Doctoral Fellow since then, granted by ANR LINDICLE project]

Administrative Assistants

Lydie Leon [Inria, from Sep 2016]
Marion Ponsot [Inria, until Sep 2016]

Others

Mashruf Zaman Chowdhury [Inria, Master student, from Feb 2016 until Jun 2016]
Irina Dragoste [Inria, Master student, from Feb 2016 until Aug 2016]
Maroua Gmati [Inria, Master student, from Feb 2016 until Jun 2016]

2. Overall Objectives

2.1. General Objectives

The semantic web blends the communication capabilities of the web with knowledge representation. Expressing formalised knowledge on a computer is useful, not exclusively for the need of the computer, but for communication. The goal of EXMO is the development of theoretical, experimental and software tools for communicating formalised knowledge.

There is no reason why knowledge expressed on the web should be in a single format or by reference to a single vocabulary (or ontology). In order to interoperate, the representations have to be matched and transformed. We build on our experience of alignments as representing the relationships between ontologies. Such alignments may be used for generating knowledge transformations (or any other kind of mediators) used for interoperating or interlinking data. We focus on the design of an alignment infrastructure and on the investigation of alignment properties when they are used for reconciling ontologies or interlinking data.

On a longer term, we study how a semantic web made of interrelated ontologies and datasets evolves and structures itself depending on its use. In particular, we aim at understanding how it influences and is influenced by its use in interpersonal communication.

EXMO's work is naturally applied in all contexts in which ontologies are used for expressing knowledge that has to be communicated. It is more directly focussed on the infrastructure of the semantic web and the web of data.

3. Research Program

3.1. Knowledge representation semantics

We work with semantically defined knowledge representation languages (like description logics, conceptual graphs and object-based languages). Their semantics is usually defined within model theory initially developed for logics. The languages dedicated to the semantic web (RDF and OWL) follow that approach. RDF is a knowledge representation language dedicated to the description of resources; OWL is designed for expressing ontologies: it describes concepts and relations that can be used within RDF.

We consider a language L as a set of syntactically defined expressions (often inductively defined by applying constructors over other expressions). A representation ($o \subseteq L$) is a set of such expressions. It is also called an ontology. An interpretation function (I) is inductively defined over the structure of the language to a structure called interpretation domain (D). This expresses the construction of the "meaning" of an expression in function of its components. A formula is satisfied by an interpretation if it fulfills a condition (in general being interpreted over a particular subset of the domain). A model of a set of expressions is an interpretation satisfying all these expressions. An expression (δ) is then a consequence of a set of expressions (o) if it is satisfied by all of their models (noted $o \models \delta$).

A computer must determine if a particular expression (taken as a query, for instance) is the consequence of a set of axioms (a knowledge base). For that purpose, it uses programs, called provers, that can be based on the processing of a set of inference rules, on the construction of models or on procedural programming. These programs are able to deduce theorems (noted $o \vdash \delta$). They are said to be sound if they only find theorems which are indeed consequences and to be complete if they find all the consequences as theorems. However, depending on the language and its semantics, the decidability, i.e., the ability to create sound and complete provers, is not warranted. Even for decidable languages, the algorithmic complexity of provers may prohibit their exploitation.

To solve this problem a trade-off between the expressivity of the language and the complexity of its provers has to be found. These considerations have led to the definition of languages with limited complexity – like conceptual graphs and object-based representations – or of modular families of languages with associated modular prover algorithms – like description logics.

EXMO mainly considers languages with well-defined semantics (such as RDF and OWL that we contributed to define), and defines the semantics of some languages such as the SPARQL query language and alignment languages, in order to establish the properties of computer manipulations of the representations.

3.2. Ontology matching and alignments

When different representations are used, it is necessary to identify their correspondences. This task is called ontology matching and its result is an alignment [4]. It can be described as follows: given two ontologies, each describing a set of discrete entities (which can be classes, properties, rules, predicates, etc.), find the relationships, if any, holding between these entities.

An alignment between two ontologies o and o' is a set of correspondences $\langle e, e', r\rangle$ such that:

- e and e' are the entities between which a relation is asserted by the correspondence, e.g., formulas, terms, classes, individuals;
- r is the relation asserted to hold between e and e'. This relation can be any relation applying to these entities, e.g., equivalence, subsumption.

In addition, a correspondence may support various types of metadata, in particular measures of the confidence in a correspondence.

Given the semantics of the two ontologies provided by their consequence relation, we define an interpretation of two aligned ontologies as a pair of interpretations $\langle m, m'\rangle$, one for each ontology. Such a pair of interpretations is a model of the aligned ontologies o and o' if and only if each respective interpretation is a model of the ontology and they satisfy all correspondences of the alignment.

This definition is extended to networks of ontologies: a collection of ontologies and associated alignments. A model of such an ontology network is a tuple of local models such that each alignment is valid for the models involved in the tuple. In such a system, alignments play the role of model filters which select the local models that are compatible with all alignments. So, given an ontology network, it is possible to interpret it.

However, given a set of ontologies, it is necessary to find the alignments between them and the semantics does not tell which ones they are. Ontology matching aims at finding these alignments. A variety of methods is used for this task. They perform pairwise comparisons of entities from each of the ontologies and select the most similar pairs. Most matching algorithms provide correspondences between named entities, more rarely between compound terms. The relationships are generally equivalence between these entities. Some systems are able to provide subsumption relations as well as other relations in the support language (like incompatibility or instantiation). Confidence measures are usually given a value between 0 and 1 and are used for expressing preferences between two correspondences.

3.3. Data interlinking

Links are important for the publication of RDF data on the web. We call data interlinking the process of generating links identifying the same resource described in two data sets. Data interlinking parallels ontology matching: from two datasets (d and d') it generates a set of links (also called a link set, L).

We have extended the notion of database keys in a way which is more adapted to the context of description logics and the openness of the semantic web. We have introduced the notion of a link key [4], [1] which is a combination of such keys with alignments. More precisely, a link key is a structure $\langle K^{eq}, K^{in}, C\rangle$ such that:

- K^{eq} is a set of pairs of property expressions;
- K^{in} is a set of pairs of property expressions;
- C is a correspondence between classes.

Such a link key holds if and only if for any pair of resources belonging to the classes in correspondence such that the values of their property in K^{eq} are pairwise equal and the values of those in K^{in} pairwise intersect, the resources are the same.

As can be seen, link key validity is only relying on pairs of objects in two different data sets. We further qualify link keys as weak, plain and strong depending on them satisfying further constraints: a weak link key is only valid on pairs of individuals of different data sets, a plain link key has to apply in addition to pairs of individuals of the same data set as soon as one of them is identified with another individual of the other data set, a strong link key is a link key which is also a key for each data set, it can be though of as a link key which is made of two keys.

Link keys can then be used for finding equal individuals across two data sets and generating the corresponding owl:sameAs links.

4. Application Domains

4.1. Semantic web technologies

The main application context motivating our work is the "semantic web" infrastructure.

Internet technologies support organisations and people in accessing and sharing knowledge, often difficult to access in a documentary form. However, these technologies quickly reach their limits: web site organisation is expensive and full-text search inefficient. Content-based information search is becoming a necessity. Content representation enables computers to manipulate knowledge on a more formal ground and to carry out similarity or generality search. Knowledge representation formalisms are good candidates for expressing content.

The vision of a "semantic web" [17] complements the web, with formal knowledge representation spanning across sites. Taking advantage of this semantic web requires the manipulation of various knowledge representation formats. EXMO concerns are thus central to the semantic web implementation. Our work aims at enhancing content understanding, including the intelligibility of communicated knowledge and formal knowledge transformations.

In addition, EXMO considers more specific uses of semantic web technologies in wider contexts.

5. New Software and Platforms

5.1. Alignment API

SCIENTIFIC DESCRIPTION

Using ontologies is the priviledged way to achieve interoperability among heterogeneous systems within the semantic web. However, as the ontologies underlying two systems are not necessarily compatible, they may in turn need to be reconciled. Ontology reconciliation requires most of the time to find the correspondences between entities (e.g., classes, objects, properties) occuring in ontologies. We call a set of such correspondences an alignment.

We have designed a format for expressing alignments in a uniform way. The goal of this format is to share available alignments on the web. It should help systems using alignments, e.g., mediators, translators, to take advantage of any matching algorithm and it will help matching algorithms to be used in many different tasks. This format is expressed in RDF, so it is freely extensible. We have proposed and implemented an expressive extension called EDOAL [13].

The Alignment API [2] is an API and implementation for expressing and sharing ontology alignments.

FUNCTIONAL DESCRIPTION

The API itself is a Java description of tools for accessing the common format. It defines five main interfaces (OntologyNetwork, Alignment, Cell, Relation and Evaluator).

We provide an implementation for this API which can be used for producing transformations, rules or bridge axioms independently from the algorithm which produced the alignment. The proposed implementation features:

- a base implementation of the interfaces with all useful facilities,
- a library of sample matchers,
- a library of renderers (XSLT, RDF, SKOS, SWRL, OWL, C-OWL, SPARQL, etc.),
- a library of evaluators (various generalisation of precision/recall, precision/recall graphs),
- a flexible test generation framework which allows for generating evaluation datasets,
- a library of wrappers for several ontology APIs,
- parsers for different formats.

To instanciate the API, it is sufficient to refine the base implementation by implementing the align() method. Doing so, the new implementation will benefit from all the services already implemented in the base implementation.
We have developed, on top of the Alignment API, an Alignment server that can be used by remote clients for matching ontologies and for storing and sharing alignments. It is developed as an extensible platform which allows to plug-in new interfaces. The Alignment server can be accessed through HTML, web service (SOAP and REST) and agent communication interfaces.

The Alignment API is used in the Ontology Alignment Evaluation Initiative data and result processing (§6.1.1). It is also used by more than 50 other teams worldwide.

The Alignment API is freely available since december 2003, under the LGPL licence, at http://alignapi.gforge.inria.fr.

- Participants: Jérôme Euzenat, Jérôme David, Armen Inants
- Contact: Jérôme Euzenat
- URL: http://alignapi.gforge.inria.fr/

5.2. OntoSim

SCIENTIFIC DESCRIPTION

There are many reasons for measuring a distance between ontologies. For example, in semantic social networks, when a peer looks for particular information, it could be more appropriate to send queries to peers having closer ontologies because it will be easier to translate them and it is more likely that such a peer has the information of interest.

OntoSim is a library offering similarity and distance measures between ontology entities as well as between ontologies themselves. It materialises our work towards better ontology proximity measures.
FUNCTIONAL DESCRIPTION

OntoSim is a Java API allowing to compute similarities between ontologies. It relies on the Alignment API for ontology loading so it is quite independent of the ontology API used (JENA or OWL API).

OntoSim provides a framework for designing various kinds of similarities. In particular, we differentiated similarities in the ontology space from those in the alignment space. The latter ones make use of available alignments in a network of ontologies while the former only rely on ontology data. OntoSim is provided with 4 entity measures which can be combined using various aggregation schemes (average linkage, Hausdorff, maximum weight coupling, etc.), 2 kinds of vector space measures (boolean and TFIDF), and 4 alignment space measures. It also features original comparison methods such as agreement/disagreement measures. In addition, the framework embeds external similarity libraries which can be combined to our own.

OntoSim is based on an ontology interface allowing for using ontology parsed with different APIs. It is written in JAVA and is available, under the LGPL licence, at http://ontosim.gforge.inria.fr.

- Participants: Jérôme David, Jérôme Euzenat
- Contact: Jérôme David
- URL: http://ontosim.gforge.inria.fr/

6. New Results

6.1. Ontology matching and alignments

6.1.1. Evaluation

Participant: Jérôme Euzenat [Correspondent].

Since 2004, we run the Ontology Alignment Evaluation Initiative (OAEI) which organises evaluation campaigns for assessing the degree of achievement of actual ontology matching algorithms [3].

This year, we used again our generator for generating a new version of benchmarks. The Alignment API was used for manipulating alignments and evaluating results [8].

The participating systems and evaluation results were presented in the 11th Ontology Matching workshop [14], [15], held Kobe (JP). More information on OAEI can be found at http://oaei.ontologymatching.org/.

6.1.2. Algebras of alignment relations

Participants: Manuel Atencia Arcas, Jérôme Euzenat [Correspondent], Armen Inants.

Qualitative calculi are central in qualitative binary constraint satisfaction problems. All these qualitative calculi share an implicit assumption that the universe is homogeneous, i.e., consists of objects of the same kind. However, objects of different kinds may also entertain relations. Many applications discriminate between different kinds of objects. For example, some spatial models discriminate between regions, lines and points, and different relations are used for each kind of objects. In ontology matching, qualitative calculi were shown useful for expressing alignments between only one kind of entities, such as concepts or individuals. However, relations between individuals and concepts, which impose additional constraints, are not exploited.

We introduced modularity in qualitative calculi and provided a methodology for modeling qualitative calculi with heterogeneous universes [5]. It is based on a special class of partition schemes which we call modular. For a qualitative calculus generated by a modular partition scheme, we can define a structure that associates each relation symbol with an abstract domain and codomain from a Boolean lattice of sorts. A module of such a qualitative calculus is a sub-calculus restricted to a given sort, which is obtained through an operation called relativisation to a sort. Of a greater practical interest is the opposite operation, which allows for combining several qualitative calculi into a single calculus. We defined an operation called combination modulo glue, which combines two or more qualitative calculi over different universes, provided some glue relations between these universes. The framework is general enough to support most known qualitative spatio-temporal calculi.

In 2012, we introduced a semantics supporting confidences in correspondences as weights. However, it introduced a discontinuity between weighted and non-weighted interpretations. Moreover, it does not provide a calculus for reasoning with weighted ontology alignments. We introduced a calculus for such alignments [11] provided by an infinite relation-type algebra, the elements of which are weighted taxonomic relations. In addition, it approximates the non-weighted case in a continuous manner.

This work has been part of the PhD of Armen Inants [5] partially funded by the LINDICLE project (§7.1.1).

6.2. Data interlinking

The web of data uses semantic web technologies to publish data on the web in such a way that they can be interpreted and connected together. It is thus important to be able to establish links between these data [7], both for the web of data and for the semantic web that it contributes to feed. We consider this problem from different perspectives.

6.2.1. Interlinking cross-lingual RDF data sets

Participants: Tatiana Lesnikova, Jérôme David [Correspondent], Jérôme Euzenat.

RDF data sets are being published with labels that may be expressed in different languages. Even systems based on graph structure, ultimately rely on anchors based on language fragments. In this context, data interlinking requires specific approaches in order to tackle cross-lingualism. We proposed a general framework for interlinking RDF data in different languages and implemented two approaches: one approach is based on machine translation, the other one takes advantage of multilingual references, such as BabelNet.

This year, we evaluated machine translation for interlinking concepts, i.e., generic entities named with a common noun or term, as opposed to individual entities. In previous work, the evaluated method has been applied on named entities. We conducted two experiments involving different thesauri in different languages. The first experiment involved concepts from the TheSoz multilingual thesaurus in three languages: English, French and German. The second experiment involved concepts from the EuroVoc and AGROVOC thesauri in English and Chinese respectively. We demonstrated that machine translation can be beneficial for cross-lingual thesauri interlining independently of a dataset structure [12].

This work has been part of the PhD of Tatiana Lesnikova [6] developed in the LINDICLE project (§7.1.1).

6.2.2. Uncertainty-sensitive reasoning for inferring sameAs facts in Linked Data

Participants: Manuel Atencia Arcas [Correspondent], Jérôme David.

A major challenge in data interlinking is to design tools that effectively deal with incomplete and noisy data, and exploit uncertain knowledge. We modelled data interlinking as a reasoning problem with uncertainty. For that purpose, we introduced a probabilistic framework for modelling and reasoning over uncertain RDF facts and rules that is based on the semantics of probabilistic Datalog. We have designed an algorithm, ProbFR, based on this framework. Experiments on real-world datasets have shown the usefulness and effectiveness of our approach for data linkage and disambiguation [9].

This work was carried out in collaboration with Mustafa Al-Bakri and Marie-Christine Rousset (LIG).

6.2.3. Tableau extensions for reasoning with link keys

Participants: Manuel Atencia Arcas [Correspondent], Jérôme Euzenat, Maroua Gmati.

Link keys allow for generating links across datasets expressed in different ontologies (see §3.3). But they can also be thought of as axioms in a description logic. As such, they can contribute to infer ABox axioms, such as links, or terminological axioms and other link keys. Yet, no reasoning support existed for link keys. We extended the tableau method designed for ALC to take link keys into account [10]. We showed how this extension enables combining link keys with classical terminological reasoning with and without ABox and TBox and generate non trivial link keys.

7. Partnerships and Cooperations

7.1. National Initiatives

7.1.1. ANR Lindicle

Program: ANR-Blanc international 2

Project acronym: LINDICLE

Project title: Linking data in cross-lingual environment

Duration: January 2013 - December 2016

Coordinator: Inria EXMO/Jérôme David

Participants: Jérôme Euzenat, Manuel Atencia Arcas, Jérôme David, Tatiana Lesnikova, Adam Sanchez Ayte, Armen Inants

Other partners: Tsinghua university (CN)

See also: http://lindicle.inrialpes.fr

Abstract: The LINDICLE project investigates multilingual data interlinking between French, English and Chinese data sources (see §6.2).

7.2. International Initiatives

7.2.1. Informal International Partners

EXMO (and other colleagues from Oxford, Trento, Mannheim, Linköping, Milano, Amsterdam, Galway and the Open university) organises yearly the Ontology alignment evaluation initiative (OAEI).

7.2.2. Participation in Other International Programs

Jérôme Euzenat is benefiting from a special visiting researcher grant from the Brazilian Ciência sem Fronteiras program on "Methodology and algorithms for ontology refinement and matching" (2015-2017). He is working with the team of Fernanda Baião and Kate Revoredo at the Universidade Federal do Estado do Rio de Janeiro (UNIRIO). Together, they investigate methods for evolving ontologies and alignments which involve users and agents. The goal of the project is to design methods and algorithms using theory revision to deal with knowledge evolution in a reliable manner and obtaining better quality alignments.

7.3. International Research Visitors

7.3.1. Visits of International Scientists

- Karima Akli (USTHB, Algiers) visited EXMO in September 2016, working on rough sets for link key extraction.
- Yan Zhang (U. Tsinghua) and Zhichun Wang (Beijing Normal University) visited EXMO in September 2016 in the framework of the Lindicle project, working cross-lingual data interlinking and query-driven ontology matching.

7.3.2. Research Stays Abroad

- Jérôme Euzenat visited the Universidade Federal do Estado do Rio de Janeiro (UNIRIO) for two months in March and November 2016 (see §7.2.2).

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. Member of the Organizing Committees

- Jérôme Euzenat was organiser of the 11th Ontology matching workshop of the 15th ISWC, Kobe (JP), 2016 (with Pavel Shvaiko, Ernesto Jiménez Ruiz, Michele Cheatham, Oktie Hassanzadeh and Ryutaro Ichise),

8.1.2. Scientific Events Selection

8.1.2.1. Member of Conference Program Committees

- Manuel Atencia, Jérôme David and Jérôme Euzenat have been programme committee members of the conference "European conference on artificial intelligence (ECAI)" 2016
- Jérôme Euzenat was programme committee member of the "International conference on Knowledge Representation and Reasoning (KR)" 2016
- Manuel Atencia and Jérôme Euzenat have been programme committee members of the "International semantic web conference (ISWC)" 2016
- Manuel Atencia, Jérôme David and Jérôme Euzenat have been programme committee members of the "European Semantic Web Conference (ESWC)" 2016
- Jérôme Euzenat was programme committee member of the "International Conference on Formal Ontologies for Information Systems (FOIS)" 2016
- Jérôme Euzenat was programme committee member of the "International Conference on Conceptual Structures (ICCS)" 2016
- Jérôme Euzenat was programme committee member of the "International Conference on Web Information Systems and Technologies (WebIST)" 2016

- Tatiana Lesnikova and Jérôme Euzenat have been scientific committee member of the “Language resources and evaluation conference (LREC)” 2016
- Jérôme Euzenat was programme committee member of the “French fundamental artificial intelligence days” (JAIF) 2016
- Jérôme David was programme committee member of the ISWC “Ontology matching” workshop (OM) 2016
- Jérôme David was programme committee member of the EGC workshop on “quality of linked open data” (QLOD) 2016
- Jérôme Euzenat was programme committee member of the ESWC workshop on “Completing and Debugging the Semantic Web (CoDeS)”, 2016.
- Jérôme Euzenat was programme committee member of the ECAI workshop on “Diversity-aware artificial intelligence”, 2016.

8.1.2.2. Reviewer

- Jérôme David and Tatiana Lesnikova have been a reviewer for the 15th “International Semantic Web Conference (ISWC)”, 2016.

8.1.3. Journal

8.1.3.1. Member of the Editorial Boards

- Jérôme Euzenat is member of the editorial board of *Journal of web semantics* (area editor), *Journal on data semantics* and the *Semantic web journal*.

8.1.3.2. Reviewer - Reviewing Activities

- Manuel Atencia has been reviewer for *Semantic web journal* and *ACM transactions on database systems*.
- Jérôme David has been reviewer for *Artificial intelligence review* and *Semantic web journal*.
- Jérôme Euzenat has been reviewer for *IEEE transactions on knowledge and data engineering*, *Knowledge and information systems* and *Artificial intelligence review*.

8.1.4. Invited Talks

- “Extraction de clés de liage de données”, Invited talk, 16e conférence internationale francophone sur l’extraction et la gestion des connaissances (EGC), Reims (FR), 2016-01-21 (Jérôme Euzenat).
- Series of four seminars at UniRio, Rio de Janeiro (BR): “Introduction to ontology matching and alignment” 2016-03-11, “Repairing alignments and cultural evolution” 2016-03-17, “Data link key extraction (and relation with Formal concepts analysis)” 2016-03-22, “(Belief) revision in networks of ontologies” 2016-03-30 (Jérôme Euzenat).
- “Introduction to ontology matching and alignment”, Seminar IBM Research, Rio de Janeiro (BR), 2016-03-23 (Jérôme Euzenat).
- “Semantic web evolution: tectonic quake or gentle drift?”, Invited talk, 12th International Conference on Web Information Systems and Technologies (WebIST), Roma (IT), 2016-04-24 (Jérôme Euzenat).
- “Knowledge change, failure, adaptation, and evolution”, Invited talk, 2nd Joint ontology workshops (JOWO), Annecy (FR), 2016-07-06 (Jérôme Euzenat).
- “Data interlinking with formal concept analysis and link keys”, Invited talk, 13th international conference on concept lattices and applications (CLA), Moskow (RU), 2016-07-19 (Jérôme Euzenat).
- “Fixing knowledge in the distributed age”, Invited tutorial, 10th international conference on scalable uncertainty managament (SUM), Nice (FR), 2016-09-21 (Jérôme Euzenat).

8.1.5. Leadership within the Scientific Community

- Jérôme Euzenat is member of the executive committee and the scientific council of the CNRS Pre-GDR “Artificial intelligence”.

8.1.6. Scientific Expertise

- Jérôme David has been consulting for the start-up Budplace.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

8.2.1.1. Responsibilities

- Jérôme David is coordinator, with Véronique Sansonnet, of the Master “Mathematicques et informatiques appliquées aux sciences humaines et sociales” (Univ. Grenoble Alpes);
- Manuel Atencia is coordinator of option “Web, Informatique et Connaissance” of Master M1 “Mathematicques et informatiques appliquées aux sciences humaines et sociales” (Univ. Grenoble Alpes);
- Jérôme Euzenat is, with Sihem Amer-Yahia, coordinator of the “AI and the web” option of the M2R in computer science and applied mathematics (Univ. Grenoble Alpes).

8.2.1.2. Lectures

Licence: Jérôme David, Algorithmique et programmation par objets, 90h, L2 MIASHS, UGA, France

Licence: Jérôme David, Introduction à Python, Licence ESSIG, 24h, UGA, France

Licence: Manuel Atencia, Technologies du Web, LP ESSIG, 18h, UGA, France

Licence: Manuel Atencia, Introduction aux technologies du Web, 60h, L3 MIASHS, UGA, France

Master: Jérôme David, Programmation Java 2, 45h, M1 MIASHS, UGA, France

Master: Jérôme David, Documents XML, 30h, M1 MIASHS, UGA, France

Master: Manuel Atencia, Langages et technologies du Web 2, 21h, M1 MIASHS, UGA, France

Master: Manuel Atencia, Introduction à la programmation web, 30h, M1 MIASHS, UGA, France

Master: Manuel Atencia, Intelligence Artificielle, 7,5h, M1 MIASHS, UGA, France

Master: Jérôme David, JavaEE, 30h, M2 MIASHS, UGA, France

Master: Jérôme David, Développement Web Mobile, 30h, M2 MIASHS, UGA, France

Master: Manuel Atencia, Web Sémantique, 30h, M2 MIASHS, UGA, France

Master: Jérôme Euzenat, Semantic web: from XML to OWL, 23heqTD, M2R, UGA, France

Post-graduate level: Jérôme Euzenat, “Ontology matching”, 1h30, Tutorial, 13th international conference on concept lattices and applications (CLA), Moskow (RU), 2016

8.2.2. Supervision

8.2.2.1. PhD

- PhD: Armen Inants, “Qualitative calculi with hererogeneous universes”, Univ. Grenoble Alpes, 2016-04-25
- PhD: Tatiana Lesnikova, “RDF data interlinking: evaluation of cross-lingual methods”, Univ. Grenoble Alpes, 2016-05-04

8.2.2.2. Master

- MSc: Mashruf Chowdury, Agreement and disagreement between ontologies, M2R Informatics, Univ. Grenoble Alpes, June 2016
- MSc: Irina Dragoste, Ontology evolution through interaction, M2R Informatics, Univ. Grenoble Alpes, September 2016

- MSc: Maroua Gmati, Reasoning with link keys, M2R Informatics, Univ. Grenoble Alpes, June 2016

8.2.3. Juries

- Jérôme Euzenat has been external examiner of the computer science PhD of Filip Radulovic (Universidad Politécnica de Madrid) "RIDER: a recommendation framework for exploiting evaluation results and user quality requirements" supervised by Asunción Gómez-Pérez, 2016
- Manuel Atencia has been external examiner of the computer science PhD of Daniel Vila Suero (Universidad Politécnica de Madrid) "A framework for ontology-based library data generation, access and exploitation" supervised by Asunción Gómez-Pérez and Jorge Gracia del Rio, 2016
- Jérôme Euzenat has been external examiner of the computer science PhD of Damien Graux (Université Grenoble Alpes) "On the efficient distributed evaluation of SPARQL queries" supervised by Nabil Layaïda and Pierre Genevès, 2016

8.3. Popularization

- Jérôme Euzenat gave a training conference in computer science for high-school teachers on "Language and semantics", Inria, Montbonnot (FR), 2016-02-10

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[6] T. LESNIKOVA.*RDF Data Interlinking : evaluation of Cross-lingual Methods*, Université Grenoble Alpes, May 2016, https://tel.archives-ouvertes.fr/tel-01366030.

Invited Conferences

[7] J. EUZENAT.*Extraction de clés de liage de données (résumé étendu)*, in "16e conférence internationale francophone sur extraction et gestion des connaissances (EGC)", Reims, France, B. CRÉMILLEUX, C. DE RUNZ (editors), Hermann, January 2016, p. 9-12, euzenat2016a, https://hal.inria.fr/hal-01382101.

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[8] M. ACHICHI, M. CHEATHAM, Z. DRAGISIC, J. EUZENAT, D. FARIA, A. FERRARA, G. FLOURIS, I. FUNDULAKI, I. HARROW, V. IVANOVA, E. JIMÉNEZ-RUIZ, E. KUSS, P. LAMBRIX, H. LEOPOLD, H. LI, C. MEILICKE, S. MONTANELLI, C. PESQUITA, T. SAVETA, P. SHVAIKO, A. SPLENDIANI, H. STUCKENSCHMIDT, K. TODOROV, C. TROJAHN DOS SANTOS, O. ZAMAZAL.*Results of the Ontology Alignment Evaluation Initiative 2016*, in "11th ISWC workshop on ontology matching (OM)", Kobe, Japan, No commercial editor., October 2016, p. 73-129, achichi2016a, https://hal.inria.fr/hal-01421833.

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Project-Team IBIS

Modeling, simulation, measurement, and control of bacterial regulatory networks

IN PARTNERSHIP WITH:
CNRS

Université Grenoble Alpes

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Computational Biology

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Project-Team IBIS

Creation of the Project-Team: 2009 January 01

Keywords:

Computer Science and Digital Science:

3.1.1. - Modeling, representation
3.4.5. - Bayesian methods
6.1.1. - Continuous Modeling (PDE, ODE)
6.1.2. - Stochastic Modeling (SPDE, SDE)
6.2.1. - Numerical analysis of PDE and ODE
6.2.3. - Probabilistic methods
6.2.4. - Statistical methods
6.3.1. - Inverse problems
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6.3.3. - Data processing
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Other Research Topics and Application Domains:

1. - Life sciences
1.1.2. - Molecular biology
1.1.5. - Genetics
1.1.6. - Genomics
1.1.9. - Bioinformatics
1.1.10. - Mathematical biology
1.1.11. - Systems biology
1.1.12. - Synthetic biology
4.3.1. - Biofuels

IBIS is bilocated at the Inria Grenoble - Rhône-Alpes research center in Montbonnot and the Laboratoire Interdisciplinaire de Physique (CNRS UMR 5588) in Saint Martin d'Hères.

1. Members

Research Scientists

Hidde de Jong [Team leader, Inria, Senior researcher, HDR]
Eugenio Cinquemani [Inria, Researcher]
Delphine Ropers [Inria, Researcher]

Faculty Members

Johannes Geiselmann [Team co-leader, Université Grenoble Alpes, Professor, HDR]
Stephan Lacour [Université Grenoble Alpes, Associate professor]
Yves Markowicz [Université Grenoble Alpes, Associate professor]
Michel Page [Université Grenoble Alpes, Associate professor]

Technical Staff

Corinne Pinel [CNRS, Assistant engineer]
Ludowic Lancelot [Inria and Université Grenoble Alpes, Laboratory technician]

Célia Boyat [Inria, Laboratory technician, since September 2016]
Yannick Martin [Inria, since June 2016]
Cyril Dutrieux [Inria, since October 2016]

PhD Students

Nils Giordano [ENS/Université Grenoble Alpes, supervisors: Hidde de Jong and Johannes Geiselmann, until September 2016]
Thibault Etienne [INRA/Université de Lyon, supervisors: Muriel Cocaign-Bousquet (INRA Toulouse) and Delphine Ropers, since November 2016]

Visiting Scientists

Alberto Soria-Lopéz [Centro de Investigación y de Estudios Avanzados (Cinestav) of Instituto Politécnico Nacional (IPN), Mexico, June 2016]
Aline Métris [Institute of Food Research, Norwich, UK, from September 2016 until December 2016]

Administrative Assistant

Catherine Bessiere [Inria]

Others

François Rechenmann [Retired Senior Researcher, Inria]
Alex Uchenna Anyaegbunam [MSc student, Université Paris Descartes, from February 2016 until April 2016]
Cindy Bergerat [MSc student, INSA de Rouen, from June 2016 until August 2016]

2. Overall Objectives

2.1. Overview

When confronted with changing environmental conditions, bacteria and other microorganisms have a remarkable capacity to adapt their functioning. The responses of bacteria to changes in their environment are controlled on the molecular level by large and complex networks of biochemical interactions involving genes, mRNAs, proteins, and metabolites. The study of bacterial regulatory networks requires experimental tools for mapping the interaction structure of the networks and measuring the dynamics of cellular processes. In addition, when dealing with such large and complex systems, we need mathematical modeling and computer simulation to integrate available biological data, and understand and predict the dynamics of the system under various physiological and genetic perturbations. The analysis of living systems through the combined application of experimental and computational methods has gathered momentum in recent years under the name of systems biology.

The first aim of the IBIS project-team is to apply such a systems-biology approach to gain a deeper understanding, on the mechanistic level, of the strategies that bacteria have developed to respond to changes in their environment. [0] In particular, we focus on the enterobacterium *Escherichia coli*, for which enormous amounts of genomic, genetic, biochemical and physiological data have accumulated over the past decades. A better understanding of the adaptive capabilities of *E. coli* to nutritional limitations or other environmental changes is an aim in itself, but also a necessary prerequisite for the second and most ambitious aim of the project: interfering with the cellular responses by specific perturbations or by rewiring the underlying regulatory networks. This does not only spawn fundamental research on the control of living matter, but may ultimately also lead to practical applications. Because *E. coli* is easy to manipulate in the laboratory, it serves as a model for many pathogenic bacteria and is widely used in biotechnology, for such diverse applications as the development of vaccines, the mass production of enzymes and other (heterologous) proteins, and the production of biofuels.

[0] The ibis was an object of religious veneration in ancient Egypt, particularly associated with the god Thoth. Thoth was seen, among other things, as a god of the measurement and regulation of events.

The aims of IBIS raise new problems on the interface of biology, applied mathematics, and computer science. In particular, the following objectives have structured the work of the project-team: (1) the analysis of the qualitative dynamics of gene regulatory networks, (2) the inference of gene regulatory networks from time-series data, (3) the analysis of integrated metabolic and regulatory networks, and (4) natural and engineered control of regulatory networks. Although these axes cover most of the work carried out in IBIS, some members have also made contributions to research projects on different topics. Since this usually represents a minor proportion of the overall research effort of the project-team, we will not describe this work in detail in the activity report. The publications resulting from these side-tracks have been included in the bibliography.

The challenges of the research programme of the IBIS team require a wide range of competences on the interface of (experimental) biology, applied mathematics, and computer science (Figure 1). Since no single person can be expected to possess all of these competences, the international trend in systems biology is to join researchers from different disciplines into a single group. In line with this development, the IBIS team is a merger of a microbiology and molecular genetics group on the one hand, and a bioinformatics and mathematical biology group on the other hand. In particular, the IBIS team is composed of members of the group of Johannes Geiselmann, formerly at the Laboratoire Adaptation et Pathogénicité des Microorganismes of the Université Joseph Fourier (UJF, CNRS UMR 5163), and since September 2014 at the Laboratoire Interdisciplinaire de Physique (CNRS UMR 5588), and the members of the network modeling and simulation group formerly part of the HELIX project-team at Inria Grenoble - Rhône-Alpes, a group coordinated by Hidde de Jong. Both groups include researchers and technicians from other institutes, such as CNRS and the Université Pierre Mendès France (UPMF). The two groups have established a fruitful collaboration, which has resulted in more than 60 peer-reviewed publications in journals, conferences, and books since 2000. [0]

Hidde de Jong is the head of the IBIS project-team and Johannes Geiselmann its co-director. The experimental component of IBIS is also part of the Laboratoire Interdisciplinaire de Physique, and Johannes Geiselmann continues to represent this group in the interactions with the laboratory and university administration.

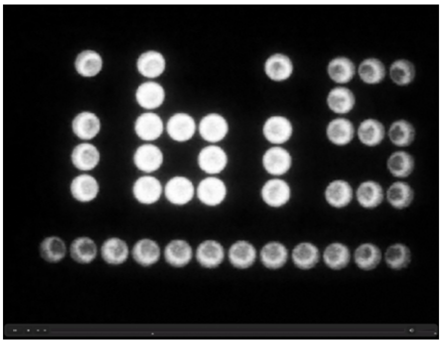


Figure 1. Display of the project-team name on a "bacterial billboard" (see http://team.inria.fr/ibis for the corresponding movie). A microplate containing a minimal medium (with glucose and acetate) is filmed during 36 hours. Wells contain E. coli bacteria which are transformed with a reporter plasmid carrying the luciferase operon (luxCDABE) under control of the acs promoter. This promoter is positively regulated by the CRP-cAMP complex. When bacteria have metabolized all the glucose, the cAMP concentration increases quickly and activates the global regulator CRP which turns on the transcription of the luciferase operon producing the light. The glucose concentration increases from left to right on the microplate, so its consumption takes more time when going up the gradient and the letters appear one after the other. The luciferase protein needs reductive power ($FMNH_2$) to produce light. At the end, when acetate has been depleted, there is no carbon source left in the medium. As a consequence, the reductive power falls and the bacterial billboard switches off. Source: Guillaume Baptist.

[0] See http://team.inria.fr/ibis for a complete list.

3. Research Program

3.1. Analysis of qualitative dynamics of gene regulatory networks

Participants: Hidde de Jong [Correspondent], Michel Page.

The dynamics of gene regulatory networks can be modeled by means of ordinary differential equations (ODEs), describing the rate of synthesis and degradation of the gene products as well as regulatory interactions between gene products and metabolites. In practice, such models are not easy to construct though, as the parameters are often only constrained to within a range spanning several orders of magnitude for most systems of biological interest. Moreover, the models usually consist of a large number of variables, are strongly nonlinear, and include different time-scales, which makes them difficult to handle both mathematically and computationally. This has motivated the interest in qualitative models which, from incomplete knowledge of the system, are able to provide a coarse-grained picture of its dynamics.

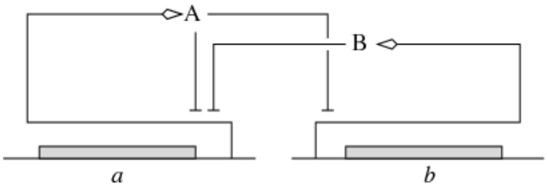
A variety of qualitative modeling formalisms have been introduced over the past decades. Boolean or logical models, which describe gene regulatory and signalling networks as discrete-time finite-state transition systems, are probably most widely used. The dynamics of these systems are governed by logical functions representing the regulatory interactions between the genes and other components of the system. IBIS has focused on a related, hybrid formalism that embeds the logical functions describing regulatory interactions into an ODE formalism, giving rise to so-called piecewise-linear differential equations (PLDEs, Figure 2). The use of logical functions allows the qualitative dynamics of the PLDE models to be analyzed, even in high-dimensional systems. In particular, the qualitative dynamics can be represented by means of a so-called state transition graph, where the states correspond to (hyperrectangular) regions in the state space and transitions between states arise from solutions entering one region from another.

First proposed by Leon Glass and Stuart Kauffman in the early seventies, the mathematical analysis of PLDE models has been the subject of active research for more than four decades. IBIS has made contributions on the mathematical level, in collaboration with the BIOCORE and BIPOP project-teams, notably for solving problems induced by discontinuities in the dynamics of the system at the boundaries between regions, where the logical functions may abruptly switch from one discrete value to another, corresponding to the (in)activation of a gene. In addition, many efforts have gone into the development of the computer tool GENETIC NETWORK ANALYZER (GNA) and its applications to the analysis of the qualitative dynamics of a variety of regulatory networks in microorganisms. Some of the methodological work underlying GNA, notably the development of analysis tools based on temporal logics and model checking, which was carried out with the Inria project-teams CONVEX (ex-VASY) and POP-ART, has implications beyond PLDE models as they apply to logical and other qualitative models as well.

3.2. Inference of gene regulatory networks from time-series data

Participants: Eugenio Cinquemani [Correspondent], Johannes Geiselmann, Hidde de Jong, Cyril Dutrieux, Stephan Lacour, Yannick Martin, Michel Page, Corinne Pinel, Delphine Ropers.

Measurements of the transcriptome of a bacterial cell by means of DNA microarrays, RNA sequencing, and other technologies have yielded huge amounts of data on the state of the transcriptional program in different growth conditions and genetic backgrounds, across different time-points in an experiment. The information on the time-varying state of the cell thus obtained has fueled the development of methods for inferring regulatory interactions between genes. In essence, these methods try to explain the observed variation in the activity of one gene in terms of the variation in activity of other genes. A large number of inference methods have been proposed in the literature and have been successful in a variety of applications, although a number of difficult problems remain.



$$\dot{x}_a = \kappa_a\, s^-(x_a, \theta_a^2)\, s^-(x_b, \theta_b) - \gamma_a\, x_a$$
$$\dot{x}_b = \kappa_b\, s^-(x_a, \theta_a^1) - \gamma_b\, x_b$$
$$s^+(x,\theta) = \begin{cases} 1, & \text{if } x > \theta \\ 0, & \text{if } x < \theta \end{cases}$$
$$s^-(x,\theta) = 1 - s^+(x,\theta)$$

Figure 2. (Left) Example of a gene regulatory network of two genes (a and b), each coding for a regulatory protein (A and B). Protein B inhibits the expression of gene a, while protein A inhibits the expression of gene b and its own gene. (Right) PLDE model corresponding to the network in (a). Protein A is synthesized at a rate κ_a, if and only if the concentration of protein A is below its threshold θ_a^2 ($x_a < \theta_a^2$) and the concentration of protein B below its threshold θ_b ($x_b < \theta_b$). The degradation of protein A occurs at a rate proportional to the concentration of the protein itself ($\gamma_a\, x_a$).

Current reporter gene technologies, based on Green Fluorescent Proteins (GFPs) and other fluorescent and luminescent reporter proteins, provide an excellent means to measure the activity of a gene *in vivo* and in real time (Figure 3). The underlying principle of the technology is to fuse the promoter region and possibly (part of) the coding region of a gene of interest to a reporter gene. The expression of the reporter gene generates a visible signal (fluorescence or luminescence) that is easy to capture and reflects the expression of a gene of interest. The interest of the reporter systems is further enhanced when they are applied in mutant strains or combined with expression vectors that allow the controlled induction of any particular gene, or the degradation of its product, at a precise moment during the time-course of the experiment. This makes it possible to perturb the network dynamics in a variety of ways, thus obtaining precious information for network inference.

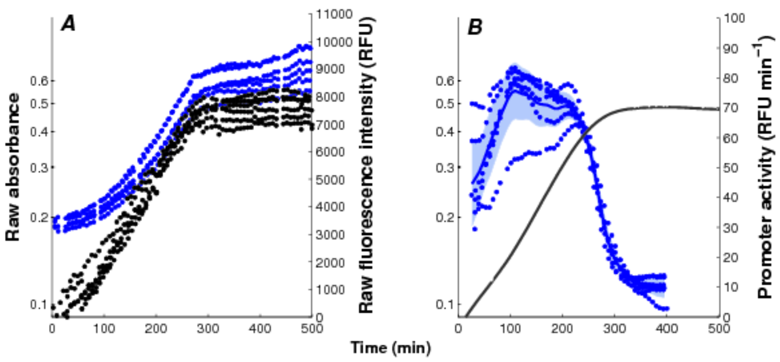


Figure 3. Monitoring of bacterial gene expression in vivo using fluorescent reporter genes (Stefan et al., PLoS Computational Biology, 11(1):e1004028, 2015). The plots show the primary data obtained in a kinetic experiment with E. coli cells, focusing on the expression of the motility gene tar in a mutant background. A: Absorbance (•, black) and fluorescence (•, blue) data, corrected for background intensities, obtained with the ΔcpxR strain transformed with the ptar-gfp reporter plasmid and grown in M9 with glucose. B: Activity of the tar promoter, computed from the primary data. The solid black line corresponds to the mean of 6 replicate absorbance measurements and the shaded blue region to the mean of the promoter activities $\pm$ twice the standard error of the mean.

The specific niche of IBIS in the field of network inference has been the development and application of genome engineering techniques for constructing the reporter and perturbation systems described above, as well as the use of reporter gene data for the reconstruction of gene regulation functions. We have developed an experimental pipeline that resolves most technical difficulties in the generation of reproducible time-series measurements on the population level. The pipeline comes with data analysis software that converts the primary data into measurements of time-varying promoter activities (Sections 5.4 and 5.3). In addition, for measuring gene expression on the single-cell level by means of microfluidics and time-lapse fluorescence microscopy, we have established collaborations with groups in Grenoble and Paris. The data thus obtained can be exploited for the structural and parametric identification of gene regulatory networks, for which methods with a solid mathematical foundation are developed, in collaboration with colleagues at ETH Zürich and EPF Lausanne (Switzerland). The vertical integration of the network inference process, from the construction of the biological material to the data analysis and inference methods, has the advantage that it allows the experimental design to be precisely tuned to the identification requirements.

3.3. Analysis of integrated metabolic and gene regulatory networks

Participants: Eugenio Cinquemani, Hidde de Jong, Thibault Etienne, Johannes Geiselmann, Stephan Lacour, Yves Markowicz, Aline Métris, Michel Page, Corinne Pinel, Delphine Ropers [Correspondent].

The response of bacteria to changes in their environment involves responses on several different levels, from the redistribution of metabolic fluxes and the adjustment of metabolic pools to changes in gene expression. In order to fully understand the mechanisms driving the adaptive response of bacteria, as mentioned above, we need to analyze the interactions between metabolism and gene expression. While often studied in isolation, gene regulatory networks and metabolic networks are closely intertwined. Genes code for enzymes which control metabolic fluxes, while the accumulation or depletion of metabolites may affect the activity of transcription factors and thus the expression of enzyme-encoding genes.

The fundamental principles underlying the interactions between gene expressions and metabolism are far from being understood today. From a biological point of view, the problem is quite challenging, as metabolism and gene expression are dynamic processes evolving on different time-scales and governed by different types of kinetics. Moreover, gene expression and metabolism are measured by different experimental methods generating heterogeneous, and often noisy and incomplete data sets. From a modeling point of view, difficult methodological problems concerned with the reduction and calibration of complex nonlinear models need to be addressed.

Most of the work carried out within the IBIS project-team specifically addressed the analysis of integrated metabolic and gene regulatory networks in the context of *E. coli* carbon metabolism (Figure 4). While an enormous amount of data has accumulated on this model system, the complexity of the regulatory mechanisms and the difficulty to precisely control experimental conditions during growth transitions leave many essential questions open, such as the physiological role and the relative importance of mechanisms on different levels of regulation (transcription factors, metabolic effectors, global physiological parameters, ...). We are interested in the elaboration of novel biological concepts and accompanying mathematical methods to grasp the nature of the interactions between metabolism and gene expression, and thus better understand the overall functioning of the system. Moreover, we have worked on the development of methods for solving what is probably the hardest problem when quantifying the interactions between metabolism and gene expression: the estimation of parameters from hetereogeneous and noisy high-throughput data. These problems are tackled in collaboration with experimental groups at Inra/INSA Toulouse and CEA Grenoble, which have complementary experimental competences (proteomics, metabolomics) and biological expertise.

3.4. Natural and engineered control of growth and gene expression

Participants: Célia Boyat, Eugenio Cinquemani, Cyril Dutrieux, Johannes Geiselmann [Correspondent], Nils Giordano, Hidde de Jong, Stephan Lacour, Ludowic Lancelot, Delphine Ropers, Alberto Soria-Lopéz.

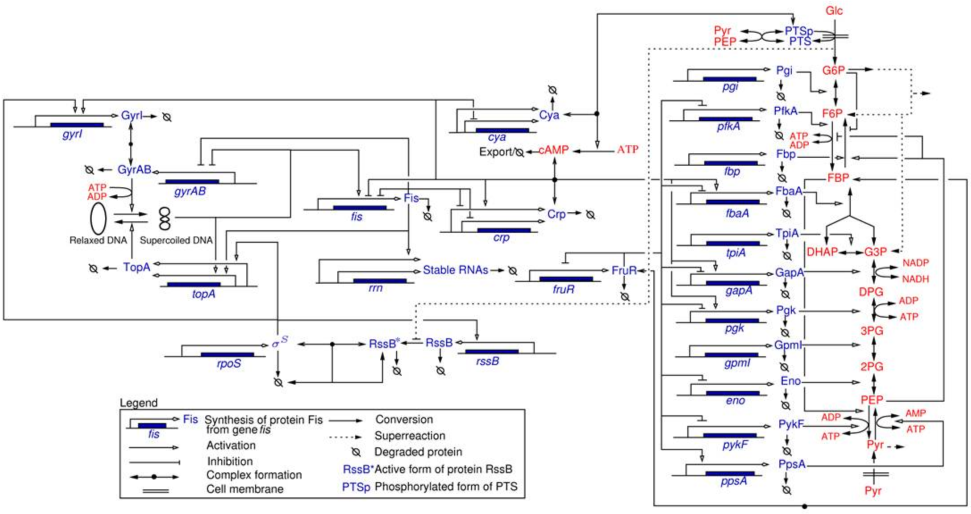


Figure 4. Network of key genes, proteins, and regulatory interactions involved in the carbon assimilation network in E. coli (Baldazzi et al., PLoS Computational Biology, 6(6):e1000812, 2010). The metabolic part includes the glycolysis/gluconeogenesis pathways as well as a simplified description of the PTS system, via the phosphorylated and non-phosphorylated form of its enzymes (represented by PTSp and PTS, respectively). The pentose-phosphate pathway (PPP) is not explicitly described but we take into account that a small pool of G6P escapes the upper part of glycolysis. At the level of the global regulators the network includes the control of the DNA supercoiling level, the accumulation of the sigma factor RpoS and the Crp·cAMP complex, and the regulatory role exerted by the fructose repressor FruR.

The adaptation of bacterial physiology to changes in the environment, involving changes in the growth rate and a reorganization of gene expression, is fundamentally a resource allocation problem. It notably poses the question how microorganisms redistribute their protein synthesis capacity over different cellular functions when confronted with an environmental challenge. Assuming that resource allocation in microorganisms has been optimized through evolution, for example to allow maximal growth in a variety of environments, this question can be fruitfully formulated as an optimal control problem. We have developed such an optimal control perspective, focusing on the dynamical adaptation of growth and gene expression in response to envrionmental changes, in close collaboration with the BIOCORE project-team.

A complementary perspective consists in the use of control-theoretical approaches to modify the functioning of a bacterial cell towards a user-defined objective, by rewiring and selectively perturbing its regulatory networks. The question how regulatory networks in microorganisms can be externally controlled using engineering approaches has a long history in biotechnology and is receiving much attention in the emerging field of synthetic biology. Within a number of on-going projects, IBIS is focusing on two different questions. The first concerns the development of open-loop and closed-loop growth-rate controllers of bacterial cells for both fundamental research and biotechnological applications (Figure 5). Second, we are working on the development of methods for the real-time control of gene expression. These methods are obviously capital for the above-mentioned design of growth-rate controllers, but they have also been applied in the context of a platform for real-time control of gene expression in cell population and single cells, developed by the Inria project-team LIFEWARE, in collaboration with a biophysics group at Université Paris Descartes.

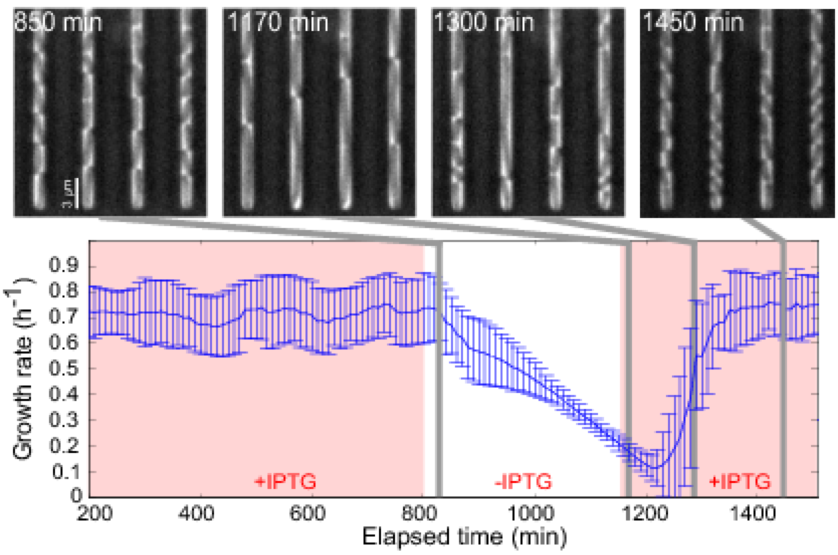


Figure 5. Growth arrest by external control of the gene expression machinery (Izard, Gomez Balderas et al., Molecular Systems Biology, 11:840, 2015). An E. coli strain in which an essential component of the gene expression machinery, the $\beta\beta'$ subunits of RNA polymerase, was put under the control of an externally-supplied inducer (IPTG), was grown in a microfluidics device and phase-contrast images were acquired every 10 min. The cells were grown in minimal medium with glucose, initially in the presence of 1 mM IPTG. 6 h after removing IPTG from the medium, the growth rate slows down and cells are elongated. About 100 min after adding back 1 mM IPTG into the medium, the elongated cells divide and resume normal growth. The growth rates in the plot are the (weighted) mean of the growth rates of 100 individual cells. The error bars correspond to ± one standard deviation. The results of the experiment show that the growth rate of a bacterial can be switched off in a reversible manner by an external inducer, based on the reengineering of the natural control of the expression of RNA polymerase.

4. Highlights of the Year

4.1. Highlights of the Year

A paper based on the PhD thesis of Manon Morin was published in *Molecular Microbiology* this year [14]. Furthermore, two papers appeared in *PLoS Computational Biology*, one by Eugenio Cinquemani and colleagues from the LIFEWARE project-team and the University of Pavia [13], and one describing results from the PhD thesis of Nils Giordano, in collaboration with colleagues from the BIOCORE project-team [12]. Eugenio Cinquemani co-organized the Fifth International Conference on Hybrid Systems Biology (HSB 2016) (http://hsb2016.imag.fr/) in Grenoble.

5. New Software and Platforms

5.1. Genetic Network Analyzer (GNA)

KEYWORDS: Bioinformatics - Gene regulatory networks - Qualitative simulation - Model checking
GENETIC NETWORK ANALYZER (GNA) is a tool for the qualitative modeling and simulation of gene regulatory networks developed in the IBIS project. The input of GNA consists of a model of the regulatory network in the form of a system of piecewise-linear differential equations (PLDEs), supplemented by inequality constraints on the parameters and initial conditions. From this information, GNA generates a state transition graph summarizing the qualitative dynamics of the system. In order to analyze large graphs, GNA allows the user to specify properties of the qualitative dynamics of a network in temporal logic, using high-level query templates, and to verify these properties on the state transition graph by means of standard model-checking tools, either locally installed or accessible through a remote web server. GNA is currently distributed by the company Genostar, but remains freely available for academic research purposes. The current version is GNA 8.7.2. In comparison with the previously distributed versions, GNA 8.7.2 has the following additional functionalities: (1) it supports the editing and visualization of regulatory networks, in an SBGN-compatible format, (2) it semi-automatically generates a prototype model from the network structure, thus accelerating the modeling process, and (3) it allows models to be exported in the SBML Qual standard.

- Participants: Hidde de Jong, Michel Page, François Rechenmann
- Partners: Genostar, Université Grenoble Alpes
- Contact: Hidde de Jong
- URL: http://www-helix.inrialpes.fr/gna

5.2. WellFARE

KEYWORDS: Bioinformatics - Statistics - Data visualization - Data modeling
WELLFARE is a Python library implementing linear inversion methods for the reconstruction of gene expression profiles from fluorescent or luminescent reporter gene data. As input, WELLFARE reads the primary data file produced by a 96-well microplate reader, containing time-series measurements of the absorbance (optical density) as well as the fluorescence and luminescence intensities in each well (if available). Various functions exist to analyze the data, in particular for detecting outliers, subtracting background, estimating growth rates, promoter activities and protein concentrations, visualizing expression profiles, synchronizing replicate profiles, etc. WELLFARE is the computational core of the web application WELLINVERTER.

- Participants: Johannes Geiselmann, Hidde de Jong, Yannick Martin, Michel Page, Delphine Ropers, Valentin Zulkower
- Partners: Université Grenoble Alpes
- Contact: Hidde de Jong
- URL: https://github.com/ibis-inria/wellfare

5.3. WellInverter

KEYWORDS: Bioinformatics - Statistics - Data visualization - Data modeling
WELLINVERTER is a web application that implements linear inversion methods for the reconstruction of gene expression profiles from fluorescent or luminescent reporter gene data. As input, WELLINVERTER reads the primary data file produced by a 96-well microplate reader, containing time-series measurements of the absorbance (optical density) as well as the fluorescence and luminescence intensities in each well (if available). Various modules exist to analyze the data, in particular for detecting outliers, subtracting background, estimating growth rates, promoter activities and protein concentrations, visualizing expression profiles, synchronizing replicate profiles, etc. The computational core of the web application consists of the Python library WELLFARE.

- Participants: Johannes Geiselmann, Hidde de Jong, Yannick Martin, Michel Page, Delphine Ropers, Valentin Zulkower
- Partners: Université Grenoble Alpes
- Contact: Hidde de Jong
- URL: https://team.inria.fr/ibis/wellinverter/

5.4. WellReader

WELLREADER is a program for the analysis of gene expression data obtained by means of fluorescent and luminescent reporter genes. WELLREADER reads data files in an XML format or in a format produced by microplate readers, and allows the user to detect outliers, perform background corrections and spline fits, compute promoter activities and protein concentrations, and compare expression profiles across different conditions. WELLREADER has been written in MATLAB and is available under an LGPL licence, both as source code (M files) and compiled code (platform-specific binary files).

- Participants: Johannes Geiselmann, Hidde de Jong, Michel Page, Delphine Ropers
- Partners: Université Grenoble Alpes
- Contact: Hidde de Jong
- URL: http://ibis.inrialpes.fr/article957.html

6. New Results

6.1. Qualitative modeling of gene regulatory networks in food-borne pathogens

Bacteria are able to respond to a variety of environmental stresses, which poses food safety problems when these bacteria are food-borne pathogens. Addition of salt, one of the most ancient and common way of preserving food, subjects the bacteria to an osmotic stress to which some may survive. However, the molecular mechanisms of adaptation in food-born pathogens are largely unknown. As a first step towards better understanding these adaptation processes on the molecular level, Delphine Ropers and Aline Métris from the Institute for Food Research in Norwich (UK), invited researcher in IBIS this year, have developed a qualitative model of the osmotic stress response in the model bacterium *Escherichia coli* for which more information is available in the literature. The model has allowed to reproduce the behavior of *E. coli* cells adapting to an osmotic stress by including the regulatory mechanisms involved in the process. This work has been published in the *International Journal of Food Microbiology* [15] and in *Data in Brief* [16]. It paves the way to modelling stress responses of other foodborne pathogens like *Salmonella* to stresses relevant for the food industry, for which much less is known.

The tool used for the qualitative modeling and simulation of the regulatory mechanism underlying osmotic stress is GENETIC NETWORK ANALYZER (GNA). This tool describes the dynamics of gene regulatory networks by means of PLDE models, as described in Section 5.1. GNA has been integrated with the other bioinformatics tools distributed by Genostar (http://www.genostar.com/). Version 8.7.2 of GNA was released by IBIS and Genostar this year and has been deposited at the Agence pour la Protection des Programmes (APP). Some bugs have been corrected in the new version and the program has been adapted to the latest versions of Java and the software platform of Genostar. Version 8.7.2 supports the SBML standard and is also capable of exporting its models to the newly-developed standard for qualitative models, SBML Qual. This standard has been elaborated by the community of developers of logical and related modeling tools (CoLoMoTo), in which the GNA developers participate.

6.2. Analysis of fluorescent reporter gene data

The use of fluorescent and luminescent reporter genes allows real-time monitoring of gene expression, both at the level of individual cells and cell populations (Section 3.2). In order to fully exploit this technology, we need methods to rapidly construct reporter genes, both on plasmids and on the chromosome, mathematical models to infer biologically relevant quantities from the primary data, and computer tools to achieve this in an efficient and user-friendly manner. For instance, in a typical microplate experiment, 96 cultures are followed in parallel, over several hours, resulting in 10,000-100,000 measurements of absorbance and fluorescence and luminescence intensities.

Valentin Zulkower, former PhD student in IBIS, developed novel methods for the analysis of reporter gene data obtained in microplate experiments, based on the use of regularized linear inversion. This allows a range of estimation problems in the analysis of reporter gene data, notably the inference of growth rate, promoter activity, and protein concentration profiles, to be solved in a mathematically sound and practical manner. This work was presented at the major bioinformatics conference ISMB/ECCB and published in the special issue of *Bioinformatics* associated with the conference last year. The linear inversion methods have been implemented in the Python package WELLFARE and integrated in the web application WELLINVERTER (Section 5.3). Funded by the Institut Français de Bioinformatique (IFB), Yannick Martin is currently extending WellInverter into a scalable and user-friendly web service providing a guaranteed quality of service, in terms of availability and response time. This web service will be deployed on the IFB platform and accompanied by extensive user documentation, online help, and a tutorial.

While the use of microplate readers results in population-level measurements of gene expression, for many applications it is mandatory to monitor gene expression over time on the level of individual cells. Several developments in the past decade have enormously extended the capabilities to achieve this, in particular the combination of fluorescence time-lapse microscopy for precisely quantifying gene expression in single cells and microfluidics technology for cultivating bacteria in confined spatial compartments and under well-controlled experimental conditions. One of the most wide-spread microfluidics devices is the so-called mother machine shown in Figure 5. A major problem is that software for image analysis (segmentation, tracking, lineage reconstruction, ...) adapted to the requirements of mother machine applications are still missing. IBIS therefore collaborates with the BEAGLE project-team for the adaptation of their tool FLUOBACTRACKER to the analysis of time-lapse movies of fluorescent reporter expression and bacterial growth in microfluidics devices. This collaboration is supported by the Technology Transfer and Innovation department of Inria, in the framework of the Inria Hub program, and has allowed the hiring of Cyril Dutrieux as a software engineer in IBIS.

6.3. Models of carbon metabolism in bacteria

Adaptation of bacterial growth to changes in environmental conditions, such as the availability of specific carbon sources, is triggered at the molecular level by the reorganization of metabolism and gene expression: the concentration of metabolites is adjusted, as well as the concentration and activities of enzymes, the rate of metabolic reactions, the transcription and translation rates, and the stability of proteins and RNAs. This reprogramming of the bacterial cell is carried out by i) specific interactions involving regulatory proteins or

RNAs that specifically respond to the change of environmental conditions and ii) global regulation involving changes in the concentration of RNA polymerase, ribosomes, and metabolite pools that globally affect the rates of transcription, translation, and degradation of all RNAs and proteins. While these phenomena have been well studied in steady-state growth conditions, much less is known about adaptation during growth transitions. In particular, only very few data are available on changes in the concentration and activity of the transcription and translation machineries and almost no data exost for the dynamic response of the degradation machinery.

In the framework of the PhD thesis of Manon Morin, supported by a Contrat Jeune Scientifique INRA-Inria (2012-2015), the collaboration of Delphine Ropers with Muriel Cocaign-Bousquet and Brice Enjalbert at INRA/INSA de Toulouse has allowed to disentangle the role of post-transcriptional regulation from other regulatory interactions in the dynamic adaptation of central carbon metabolism in *E. coli*. In a multi-scale analysis of a wild-type strain and its isogenic mutant attenuated for the protein CsrA, a variety of experimental data have been acquired in relevant conditions, including growth parameters, gene expression levels, metabolite pools, enzyme activities and metabolic fluxes. Data integration, metabolic flux analysis and regulation analysis revealed the pivotal role of post-transcriptional regulation for shaping carbon metabolism. In particular, the work has shed light on *csrA* essentiality and has provided an explanation for the glucose-phosphate stress observed in the mutant strain. A paper summarizing the work has been published in *Molecular Microbiology* this year [14]. A follow-up study conducted with various mutant strains of the carbon storage regulator system has elucidated the role of post-transcriptional regulation in the dynamics of glycogen storage and consumption, as well as the key role of the latter compound for bacterial fitness. A paper summarizing the work is being prepared for publication.

The collaboration with INRA/INSA de Toulouse is continued in the context of the PhD thesis of Thibault Etienne, funded by an INRA-Inria PhD grant, with the objective of developing models able to explain how cells coordinate their physiology and the functioning of the transcription, translation, and degradation machineries following changes in the availability of carbon sources in the environment.

6.4. Stochastic modeling and identification of gene regulatory networks in bacteria

At the single-cell level, the processes that govern single-cell dynamics in general and gene expression in particular are better described by stochastic models. Modern techniques for the real-time monitoring of gene expression in single cells enable one to apply stochastic modelling to study the origins and consequences of random noise in response to various environmental stresses, and the emergence of phenotypic variability. The potential impact of single-cell stochastic analysis and modelling ranges from a better comprehension of the biochemical regulatory mechanisms underlying cellular phenotypes to the development of new strategies for the (computer assisted or genetically engineered) control of cell populations and even of single cells.

Work in IBIS on gene expression and interaction dynamics at the level of individual cells is addressed in terms of identification of intrinsic noise models from population snapshot data, on the one hand, and the inference of models focusing on cellular variability within isogenic populations from fluorescence microscopy gene expression profiles, on the other hand. Along with modelling and inference comes analysis of the inferred models in various respects, notably in terms of identifiability, single-cell state estimation and control. Other problems related with single-cell modelling and extracellular variability are considered in eukaryotic cells through external collaborations.

In the context of the response of yeast cells to osmotic shocks, in collaboration with the LIFEWARE project team and colleagues from Université Paris Descartes and University of Pavia (Italy), Eugenio Cinquemani has investigated the use of mixed effects-modelling and identification techniques to characterize individual cell dynamics in isogenic cell populations. Mixed-effects models are hierarchical models where parametric response profiles of individuals is subject to inter-individual parameter variability following a common population distribution. Starting from identification approaches in pharmacokinetics, we have developed and applied inference methods to microfluidics data, with a focus on the response of budding yeast to osmotic shocks. Results were described in a publication in *PLoS Computational Biology* [13]. A study of statistical validation methods for mixed-effects and alternative stochastic modelling paradigms has been presented at the *IFAC Conference on Foundations of Systems Biology in Engineering (FOSBE)* in Magdeburg [19]. In collaboration with the project-team BIOCORE at Inria Sophia-Antipolis - Méditerranée, the approach is now being investigated for the joint modelling of growth and gene expression in *E. coli*, based on single-cell microfluidics data from growth arrest-and-restart experiments. Further challenges stemming from this activity toward modelling and identification of extrinsic noise in individual cells are part of the recently started ANR project MEMIP (Section 8.2).

Work on identification and state estimation for single-cell gene network dynamics has been focused on the reconstruction of promoter activity profiles from fluorescent reporter data. In a stochastic, intrinsic noise modelling context, Eugenio Cinquemani addressed the problem of inferring promoter activity statistics over a cell population, such as mean and variance, from analogous statistics of the reporter output, as obtained from so-called population snapshot data. This nontrivial extension of the deterministic promoter activity deconvolution problem from population-average data is the first, crucial step toward reconstruction of promoter activity regulation and inference of stochastic network models. Earlier results, concerning parameter identifiability of stochastic promoter activity models and reconstruction of promoter activity distributions in the special case of single-switch systems, were further developed in a contribution to the HSB conference this year [18]. The relationship between the spectrum of the promoter process (cross-correlation function) and the mean-variance profiles of fluorescent reporter readouts was derived and demonstrated on examples, laying down the bases for a full-blown observability analysis and the development of spectrum estimation methods.

The collaboration of Eugenio Cinquemani with Marianna Rapsomaniki (IBM Zurich Research Lab, Switzerland), Zoi Lygerou (University of Patras, Greece) and John Lygeros (ETH Zurich, Switzerland) is moving on to applications of joint work published in *Bioinformatics* last year. Deployment of the methods developed into an efficient cluster-based software for the inference of protein kinetics in single cells from Fluorescence Recovery After Photobleaching (FRAP) experiments is under study. Exploitation of the same methods for the simulation and analysis of more general biochemical processes in single cells is part of the ongoing research efforts.

6.5. Growth control in bacteria and biotechnological applications

The ability to experimentally control the growth rate is crucial for studying bacterial physiology. It is also of central importance for applications in biotechnology, where often the goal is to limit or even arrest growth. Growth-arrested cells with a functional metabolism open the possibility to channel resources into the production of a desired metabolite, instead of wasting nutrients on biomass production. The objective of the RESET project, supported in the framework of the Programme d'Investissements d'Avenir (Section 8.2), is to develop novel strategies to limit or completely stop microbial growth and to explore biotechnological applications of these approaches.

A foundation result for growth control in bacteria was published in the journal *Molecular Systems Biology* last year. In that publication, we described an engineered *E. coli* strain where the transcription of a key component of the gene expression machinery, RNA polymerase, is under the control of an inducible promoter. By changing the inducer concentration in the medium, we can adjust the RNA polymerase concentration and thereby switch bacterial growth between zero and the maximal growth rate supported by the medium. The publication also presented a biotechnological application of the synthetic growth switch in which both the wild-type *E. coli* strain and our modified strain were endowed with the capacity to produce glycerol when growing on glucose. Cells in which growth has been switched off continue to be metabolically active and harness the energy gain to produce glycerol at a twofold higher yield than in cells with natural control of RNA polymerase expression. Remarkably, without any further optimization, the improved yield is close to the theoretical maximum computed from a flux balance model of *E. coli* metabolism. This work is being continued in several directions in the context of the RESET project by Célia Boyat. In order to further explore the possibility of transferring this technology to biotechnology companies, we participated in the Challenge Out of Labs (http://www.linksium.fr/lancez-vous/resultat-challenge-out-of-labs/) organized by Linksium, the local incubator for technology transfer and start-up building. The presentation by Hans Geiselmann was selected for further development by Linksium.

In a review recently accepted for publication in *Trends in Microbiology* [11], we have put the scientific results mentioned above in a broader context. As illustrated by the synthetic growth switch, reengineering the gene expression machinery allows modifying naturally evolved regulatory networks and thereby profoundly reorganizing the manner in which bacteria allocate resources to different cellular functions. This opens new opportunities for our fundamental understanding of microbial physiology and for a variety of applications. We describe how recent breakthroughs in genome engineering and the miniaturization and automation of culturing methods have offered new perspectives for the reengineering of the transcription and translation machinery in bacteria as well as the development of novel *in vitro* and *in vivo* gene expression systems. In our paper, we review different examples from the unifying perspective of resource reallocation, and discuss the impact of these approaches for microbial systems biology and biotechnological applications.

Whereas the synthetic growth switch has been designed for biotechnological purposes, the question can be asked how resource allocation is organized in wild-type strains that have naturally evolved. Recent work has shown that coarse-grained models of resource allocation can account for a number of empirical regularities relating the the macromolecular composition of the cell to the growth rate. Some of these models hypothesize control strategies enabling microorganisms to optimize growth. While these studies focus on steady-state growth, such conditions are rarely found in natural habitats, where microorganisms are continually challenged by environmental fluctuations. The aim of the PhD thesis of Nils Giordano is to extend the study of microbial growth strategies to dynamical environments, using a self-replicator model. In collaboration with the BIOCORE project-team, we formulate dynamical growth maximization as an optimal control problem that can be solved using Pontryagin's Maximum Principle. We compare this theoretical gold standard with different possible implementations of growth control in bacterial cells. We find that simple control strategies enabling growth-rate maximization at steady state are suboptimal for transitions from one growth regime to another, for example when shifting bacterial cells to a medium supporting a higher growth rate. A near-optimal control strategy in dynamical conditions is shown to require information on several, rather than a single physiological variable. Interestingly, this strategy has structural analogies with the regulation of ribosomal protein synthesis by ppGpp in *E. coli*. It involves sensing a mismatch between precursor and ribosome concentrations, as well as the adjustment of ribosome synthesis in a switch-like manner. Our results show how the capability of regulatory systems to integrate information about several physiological variables is critical for optimizing growth in a changing environment. A paper describing the above results was published in *PLoS Computational Biology* this year [12].

7. Bilateral Contracts and Grants with Industry

7.1. BGene

Participants: Johannes Geiselmann, Hidde de Jong, Corinne Pinel.

BGene is a start-up company of Université Grenoble Alpes in the field of DNA engineering. BGene proposes efficient and custom-made modifications of bacterial genomes, leaving no scars or antibiotics resistance genes. The company has know-how and expertise at all stages of the development process, including the *in-silico* design of a desired construction, the choice of the appropriate genetic tools, and the delivery of the finished product. Former IBIS-member Caroline Ranquet and Johannes Geiselmann are co-founders of BGene, together with Marie-Gabrielle Jouan (Floralis, Université Grenoble Alpes). Johannes Geiselmann and Hidde de Jong are members of its scientific advisory board. For more information on BGene, see http://www.bgene-genetics.com/.

7.2. Genostar

Participants: Hidde de Jong, Michel Page, François Rechenmann.

Genostar, an Inria start-up created in 2004, provides bioinformatics solutions for the comparative analysis of bacterial genomes, proteomes and metabolomes. Genostar's software suite performs the annotation of sets of genomic sequences, *i.e.*, the identification of the coding sequences and other features, followed by the prediction of the functions of the gene products. The modules which make up the software suite were originally developed within the Genostar consortium and the HELIX project team at Inria Grenoble - Rhône-Alpes. The software suite also includes the modeling and simulation tool GNA developed by members of IBIS (Section 5.1). Genostar offers a comprehensive service line-up that spans genome sequencing, read assembly, annotation, and comparison. Genostar thus works with trusted subcontractors, each specialized in state-of-the-art sequencing technologies. François Rechenmann is CEO of the company. For more information, see http://www.genostar.com.

8. Partnerships and Cooperations

8.1. Regional Initiatives

Project name	RNAfluo: Quantification d'ARN régulateurs in vivo
Coordinators	S. Lacour
IBIS participants	S. Lacour
Type	AGIR program, Université Grenoble Alpes

8.2. National Initiatives

Project name	AlgeaInSilico: Prédire et optimiser la productivité des microalgues en fonction de leur milieu de croissance
Coordinator	O. Bernard
IBIS participants	H. de Jong, N. Giordano
Type	Inria Project Lab (2015-2019)
Web page	https://project.inria.fr/iplalgaeinsilico/

Project name	RESET – Arrest and restart of the gene expression machinery in bacteria: from mathematical models to biotechnological applications
Coordinator	H. de Jong
IBIS participants	C. Boyat, E. Cinquemani, J. Geiselmann, H. de Jong, S. Lacour, L. Lancelot, Y. Markowicz, C. Pinel, D. Ropers
Type	Bioinformatics call, Investissements d'Avenir program (2012-2017)
Web page	https://project.inria.fr/reset/

Project name	MEMIP – Modèles à effets mixtes de processus intracellulaires : méthodes, outils et applications
Coordinator	G. Batt
IBIS participants	E. Cinquemani, D. Ropers
Type	ANR project (2016-2020)

Project name	ENZINVIVO – Détermination in vivo des paramètres enzymatiques dans une voie métabolique synthétique
Coordinator IBIS participants Type	G. Truan J. Geiselmann, H. de Jong ANR project (2016-2020)

Project name	Analyse intégrative de la coordination entre stabilité des ARNm et physiologie cellulaire chez Escherichia coli
Coordinators IBIS participants Type	D. Ropers, M. Cocaign-Bousquet (Inra, LISBP) T. Etienne, D. Ropers Contrat Jeune Scientifique Inra-Inria (2016-2019)

Project name	A web application for the analysis of time-series fluorescent reporter gene data
Coordinator IBIS participants Type	H. de Jong E. Cinquemani, J. Geiselmann, Y. Martin, M. Page, D. Ropers, V. Zulkower (University of Edinburgh) IFB call for development of innovative bioinformatics services for life sciences (2016-2017)

Project name	FluoBacTracker – Adaptation et valorisation scientifique du logiciel FluoBacTracker
Coordinator IBIS participants Type	H. de Jong, H. Berry C. Dutrieux, H. de Jong, J. Geiselmann Inria Hub (2016-2017)

8.3. European Initiatives

8.3.1. Collaborations with Major European Organizations

Laboratoire d'Automatique at Ecole Polytechnique Fédérale de Lausanne (Switzerland), Giancarlo Ferrari-Trecate

Control theory and systems identification with applications to systems biology

Automatic Control Lab at ETH Zürich (Switzerland), John Lygeros

Control theory and systems identification with applications to systems biology

Computational Microbiology research group, Institute of Food Research, Norwich (United Kingdom), Aline Métris and József Baranyi

Mathematical modelling of survival and growth of bacteria

8.4. International Research Visitors

8.4.1. Visits of International Scientists

Invited researcher	Alberto Soria-Lopéz (Centro de Investigación y de Estudios Avanzados (Cinestav) of Instituto Politécnico Nacional (IPN), Mexico)
Subject	Development of an automatically-controlled system of multiplexed mini-bioreactors

Invited researcher Subject	Aline Métris (Institute of Food Research (IFR), Norwich, UK) Comparative analysis of metabolic networks of Escherichia coli and Salmonella

9. Dissemination

9.1. Research

9.1.1. Scientific events: organizing committees

9.1.1.1. Member of organizing committees

IBIS members	Conference, workshop, school	Date
Eugenio Cinquemani	Fifth International Workshop on Hybrid Systems Biology (HSB 2016), Grenoble	October 2017
Hidde de Jong	CompSysBio: Advanced Lecture Course on Computational Systems Biology, Aussois	March 2017
Delphine Ropers	Séminaire de Modélisation du Vivant (SeMoVi), Lyon and Grenoble	2016

9.1.2. Scientific events: selection committees

9.1.2.1. Chair of conference program committees

IBIS member	Conference, workshop, school	Role
Eugenio Cinquemani	European Control Conference (ECC 2016)	Associate editor
Eugenio Cinquemani	Fifth International Workshop on Hybrid Systems Biology (HSB 2016)	Program chair
Hidde de Jong	International Conference on Intelligent Systems in Molecular Biology (ISMB 2016)	Area chair

9.1.2.2. Member of conference program committees

IBIS member	Conference, workshop, program
Eugenio Cinquemani	HSB 2016, SASB 2016
Hidde de Jong	ISMB 2016, ECCB 2016, HSB 2016, FOSBE 2016
Delphine Ropers	JOBIM 2017

9.1.3. Journals

9.1.3.1. Member of editorial boards

IBIS member	Journal
Johannes Geiselmann	Frontiers in Microbiology (review editor)
Hidde de Jong	Journal of Mathematical Biology
Hidde de Jong	Biosystems
Hidde de Jong	ACM/IEEE Transactions on Computational Biology and Bioinformatics

9.1.4. Scientific evaluation and expertise

IBIS member	Organism	Role
Johannes Geiselmann	BGene	Member scientific advisory board
Johannes Geiselmann	ANR	Member of selection committee
Johannes Geiselmann	INRA	Member of scientific advisory committee Microbiologie, Adaptation, Pathogénie
Johannes Geiselmann	UMR5240 CNRS-UCBL-INSA-BayerCropScience	Member scientific council
Johannes Geiselmann	ARC1, Rhône-Alpes region	Member scientific committee
Hidde de Jong	International Human Frontier Science Program (HFSP)	Member selection and review committees
Hidde de Jong	Microbiology and Food Chain Department, Inra	Member scientific council
Hidde de Jong	BGene	Member scientific advisory board
Hidde de Jong	HCERES	Member of evaluation committee of TAGC laboratory (UMR U1090), Marseille

9.1.5. Recruitment committees

IBIS member	Organism	Recruitment
Hidde de Jong	Université Pierre et Marie Curie, Paris	Full professors in systems biology, applied to microbiology and to physiology
Delphine Ropers	Inria Lille	Chargés de recherche (jury d'admissibilité)
Delphine Ropers	Inria	Chargés de recherche (jury d'admission)
Delphine Ropers	INSA de Lyon	Assistant professor

9.1.6. Invited talks

Eugenio Cinquemani

Title	Event and location	Date
Reconstruction of promoter activity statistics from reporter protein population snapshot data	Seminar at Control theory and systems biology laboratory, D-BSSE, Basel, Switzerland	January 2016
Identifying variability of gene expression dynamics from time-course data	Seminar at IBM Research Center, Zurich, Switzerland	January 2016
Reconstruction of promoter activity statistics from reporter protein population snapshot data	Seminar at Automatic control laboratory, ETH Zurich, Switzerland	January 2016
Inference of regulatory networks from time-series reporter gene data: The case of promoter regulation in the E. coli motility network	Invited talk at workshop on Static Analysis in Systems Biology (SASB 2016), Edinburgh, UK	September 2016
On observability and reconstruction of promoter activity statistics from reporter protein mean and variance profiles	Presentation at 5th International Workshop on Hybrid Systems Biology (HSB 2016), Grenoble	October 2016

Hidde de Jong

Title	Event and location	Date
Natural and synthetic control of growth rate and gene expression in bacteria	Seminar Centre de Biologie Intégrative de Toulouse	February 2016
Natural and synthetic control of resource allocation in bacteria	Seminar MIRA institute, University of Twente, the Netherlands	July 2016
A synthetic growth switch based on controlled expression of RNA polymerase	Presentation at 17th International Conference on Systems Biology (ICSB 2016), Barcelona, Spain	October 2016
Natural and synthetic control of resource allocation in bacteria	Journée Biologie des systémes BiLille, Lille	November 2016

Johannes Geiselmann

Title	Event and location	Date
Growth control in bacteria	Seminar at CPBS Montpellier	June 2016

Nils Giordano

Title	Event and location	Date
Dynamical allocation of cellular resources as an optimal control problem: Novel insights into microbial growth strategies	Talk during annual meeting of working group GT-BIOSS, Lyon	July 2016

Stephan Lacour

Title	Event and location	Date
Direct versus indirect gene regulation by the stress response SigmaS factor	Seminar Institut de Biologie Structurale, Grenoble	February 2016
Identification of novel curli regulators in Escherichia coli	Poster at Biofilms7, Porto, Portugal	June 2016
Quantification of non-coding RNAs in bacterial cells using a Broccoli aptamer	Poster at 8th Bordeaux RNA Club Symposium & Aptamers in Bordeaux	June 2016

Aline Métris

Title	Event and location	Date
What does it take for a foodborne pathogen to survive a pinch of salt? Bioinformatics and systems biology approaches to model food safety	Invited researcher seminar Inria Grenoble - Rhône-Alpes	December 2016
Modèles et –omics pour mieux comprendre la réponse des pathogènes alimentaires au stress osmotique	INRA Avignon	December 2016

Delphine Ropers

Title	Event and location	Date
Adaptation of E. coli growth to environmental cues: global control of gene expression and post-transcriptional regulations	Institute for Food Research, Norwich, UK	March 2016
Adaptation of E. coli growth to environmental cues: global control of gene expression and post-transcriptional regulations	Journées INRA-Inria, Mallemort	October 2016

9.1.7. Research administration

IBIS member	Committee	Role
Eugenio Cinquemani	Inria Grenoble - Rhône-Alpes	Member Comité des Emplois Scientifiques (CES)
Eugenio Cinquemani	Inria Grenoble - Rhône-Alpes	Member Comité des Utilisateurs des Moyens Informatiques (CUMI)
Eugenio Cinquemani	Inria	Member Comité Administrative Paritaire (CAP)
Johannes Geiselmann	Department of Biology, Université Grenoble Alpes	Member scientific council
Hidde de Jong	Inria Grenoble - Rhône-Alpes	Member scientific council
Hidde de Jong	Inria	Member working group on International Relations of Conseil d'Orientation Scientifique et Technique (COST)
Delphine Ropers	Inria	Member of Commission d'évaluation d'Inria
Delphine Ropers	Inria Grenoble - Rhône-Alpes	Référente chercheurs
Delphine Ropers	Inria Grenoble - Rhône-Alpes	Member of Comité des études doctorales (CED)

9.2. Teaching - Supervision - Committees

9.2.1. Teaching

Four members of the IBIS team are either full professor, associate professor or assistant professor at the Université Grenoble Alpes. They therefore have a full teaching service (at least 192 hours per year) and administrative duties related to the organization and evaluation of the university course programs on all levels (from BSc to PhD). Besides the full-time academic staff in IBIS, the following people have contributed to courses last year.

Eugenio Cinquemani

Master: Stochastic modelling of gene regulatory networks, M2, BIM, INSA de Lyon (6 h)

Master: Statistics for systems biology, M1, Master Approches Interdisciplinaires du Vivant, CRI/Université Paris Descartes (24 h)

Master: Modelling and identification of metabolic networks, M1, Phelma, INP Grenoble (4 h)

Hidde de Jong

Master: Modeling and simulation of gene regulatory networks, M2, BIM, INSA de Lyon (20 h)

Master: Integrated models of the cell: metabolism, gene expression, signalling, M2, ENS Paris (6 h)

Master: Integrated models of the cell: metabolism, gene expression, signalling, M2, Institut de Technologie et d'Innovation, Paris Sciences Lettres (PSL) (6 h)

Nils Giordano

Bachelor: La bio-informatique : de l'analyse du génome à la modélisation, L2, Université Grenoble Alpes (9 h)

François Rechenmann

E-learning: MOOC Bioinformatique : algorithmes et génomes (https://www.fun-mooc.fr/courses/inria/41003S02/session02/about)

French language version of Bioinformatics MOOC published last year, including the possibility to run the algorithms by means of a dedicated Python notebook (in collaboration with Thierry Parmentelat from Inria Sophia-Antipolis - Méditerranée).

Delphine Ropers

Master: Modelling in systems biology, M1, Phelma, INP Grenoble (16 h)

Master: Modeling and simulation of genetic regulatory networks, M1, Université Grenoble Alpes (6 h)

Master: Modeling and simulation of genetic regulatory networks, M2, INSA de Toulouse (4 h)

9.2.2. Supervision

PhD in progress: **Stefano Casagranda**, Analysis and control of cell growth models. Supervisors: Jean-Luc Gouzé (BIOCORE) and Delphine Ropers

PhD in progress: **Nils Giordano**, Régulation de la croissance chez *Escherichia coli* : étude théorique et expérimentale à l'aide de modèles coûts-bénéfices. Supervisors: Hidde de Jong and Johannes Geiselmann

PhD in progress: **Bernard Chielli Ponce de Leon**, Stochasticity of gene expression in strains of *E. coli* with a controlled growth rate and number of chromosomes. Supervisors: Irina Mihalcescu (Université Grenoble Alpes) and Johannes Geiselmann

PhD in progress: **Thibault Etienne**, Analyse intégrative de la coordination entre stabilité des ARNm et physiologie cellulaire chez *Escherichia coli*. Supervisors: Delphine Ropers and Muriel Cocaign-Bousquet (INRA Toulouse)

PhD in progress: Joël Espel: RNA engineering: Design of the dynamical folding of RNA and of RNA switches. Supervisors: Alexandre Dawid (Université Grenoble Alpes) and Johannes Geiselmann

9.2.3. PhD thesis committees, PhD advisory committees, and habilitation committees

PhD thesis committees

IBIS member	Role	PhD student	University	Date
Hidde de Jong	Rapporteur	Jetse Scholma	University of Twente, the Netherlands	July 2016
Hidde de Jong	Rapporteur	Jean-Baptiste Lugagne	Université Paris Descartes	December 2016
Hidde de Jong	Président	José Morales Morales	Université de Grenoble	December 2016
Hidde de Jong	Rapporteur	Sébastien Raguideau	AgroParisTech	December 2016
Johannes Geiselmann	Président	Jessica Penin	Université de Grenoble	April 2016
Johannes Geiselmann	Rapporteur	Minyeong Yoo	Université Paul Sabatier Toulouse	May 2016
Johannes Geiselmann	Président	Ramachandran Boopathi	ENS de Lyon	May 2016
Johannes Geiselmann	Rapporteur	Ayyappasamy Sudalaiyadum Perumal	Université de Montpellier	June 2016
Stéphan Lacour	Examinateur	Simon Léonard	Université de Lyon	September 2016
Stéphan Lacour	Examinateur	Alice Berry	Université de Grenoble	November 2016

Habilitation (HDR) committees

IBIS member	Role	PhD student	University	Date
Hidde de Jong	Examinateur	Morgan Magnin	Université de Nantes	Avril 2016
Johannes Geiselmann	President	Jan Bednar	Université de Grenoble	December 2015

PhD advisory committees

IBIS member	PhD student	University
Johannes Geiselmann	Jean-Baptiste Lugagne	Université Paris Descartes

9.2.4. Teaching adminstration

Yves Markowicz is director of the BSc department at Université Grenoble Alpes.

Michel Page is coordinator of the master Systèmes d'information et d'organisation at the Institut d'Adminstration des Entreprises (IAE), Université Grenoble Alpes.

Eugenio Cinquemani organizes a module on statistics in systems biology at CRI/Université Paris Descartes.

Delphine Ropers organizes a module on the mathematical modeling of biological systems at PHELMA, INP Grenoble.

Hidde de Jong organizes with Daniel Kahn a module on the modeling of genetic and metabolic networks at INSA de Lyon.

9.3. Science education

Delphine Ropers gave a course on bacteria and antibiotic resistance at the primary school Ecole Bizanet in Grenoble (December 2016).

10. Bibliography

Major publications by the team in recent years

[1] G. BAPTIST, C. PINEL, C. RANQUET, J. IZARD, D. ROPERS, H. DE JONG, J. GEISELMANN.*A genome-wide screen for identifying all regulators of a target gene*, in "Nucleic Acids Research", 2013, vol. 41, n^{o} 17, 11, http://hal.inria.fr/hal-00857345.

[2] S. BERTHOUMIEUX, M. BRILLI, H. DE JONG, D. KAHN, E. CINQUEMANI.*Identification of metabolic network models from incomplete high-throughput datasets*, in "Bioinformatics", 2011, vol. 27, n^{o} 13, p. i186-i195.

[3] S. BERTHOUMIEUX, M. BRILLI, D. KAHN, H. DE JONG, E. CINQUEMANI.*On the identifiability of metabolic network models*, in "Journal of Mathematical Biology", 2013, vol. 67, n^{o} 6-7, p. 1795-1832, http://hal.inria.fr/hal-00762620.

[4] S. BERTHOUMIEUX, H. DE JONG, G. BAPTIST, C. PINEL, C. RANQUET, D. ROPERS, J. GEISELMANN.*Shared control of gene expression in bacteria by transcription factors and global physiology of the cell*, in "Molecular Systems Biology", January 2013, vol. 9, n^{o} 1, 11 [*DOI :* 10.1038/MSB.2012.70], http://hal.inria.fr/hal-00793352.

[5] J. IZARD, C. GOMEZ-BALDERAS, D. ROPERS, S. LACOUR, X. SONG, Y. YANG, A. B. LINDNER, J. GEISELMANN, H. DE JONG.*A synthetic growth switch based on controlled expression of RNA polymerase*, in "Molecular Systems Biology", November 2015, vol. 11, n^{o} 11, 16, https://hal.inria.fr/hal-01247993.

[6] A. KREMLING, J. GEISELMANN, D. ROPERS, H. DE JONG.*Understanding carbon catabolite repression in Escherichia coli using quantitative models*, in "Trends in Microbiology", 2015, vol. 23, n^{o} 2, p. 99-109, https://hal.inria.fr/hal-01103556.

[7] C. PEANO, J. WOLF, J. DEMOL, E. ROSSI, L. PETITI, G. DE BELLIS, J. GEISELMANN, T. EGLI, S. LACOUR, P. LANDINI.*Characterization of the Escherichia coli σ(S) core regulon by Chromatin Immunoprecipitation-sequencing (ChIP-seq) analysis*, in "Scientific Reports", 2015, vol. 5, 15 [*DOI :* 10.1038/SREP10469], https://hal.inria.fr/hal-01217828.

[8] M. A. RAPSOMANIKI, E. CINQUEMANI, N. N. GIAKOUMAKIS, P. KOTSANTIS, J. LYGEROS, Z. LYGEROU.*Inference of protein kinetics by stochastic modeling and simulation of fluorescence recovery after photobleaching experiments*, in "Bioinformatics", 2015, vol. 31, n^o 3, p. 355-362 [*DOI :* 10.1093/BIOINFORMATICS/BTU619], https://hal.inria.fr/hal-01096966.

[9] D. STEFAN, C. PINEL, S. PINHAL, E. CINQUEMANI, J. GEISELMANN, H. DE JONG.*Inference of quantitative models of bacterial promoters from time-series reporter gene data*, in "PLoS Computational Biology", 2015, vol. 11, n^o 1, e1004028, https://hal.inria.fr/hal-01097632.

[10] V. ZULKOWER, M. PAGE, D. ROPERS, J. GEISELMANN, H. DE JONG.*Robust reconstruction of gene expression profiles from reporter gene data using linear inversion*, in "Bioinformatics", 2015, vol. 31, n^o 12, p. i71-i79, https://hal.inria.fr/hal-01217800.

Publications of the year

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[11] H. DE JONG, J. GEISELMANN, D. ROPERS.*Resource reallocation in bacteria by reengineering the gene expression machinery*, in "Trends in Microbiology", 2017, https://hal.inria.fr/hal-01420729.

[12] N. GIORDANO, F. MAIRET, J.-L. GOUZÉ, J. GEISELMANN, H. DE JONG.*Dynamical allocation of cellular resources as an optimal control problem: Novel insights into microbial growth strategies*, in "PLoS Computational Biology", March 2016, vol. 12, n^o 3, e1004802 [*DOI :* 10.1371/JOURNAL.PCBI.1004802], https://hal.inria.fr/hal-01332394.

[13] A. LLAMOSI, A. GONZALEZ, C. VERSARI, E. CINQUEMANI, G. FERRARI-TRECATE, P. HERSEN, G. BATT.*What population reveals about individual cell identity: Single-cell parameter estimation of models of gene expression in yeast*, in "PLoS Computational Biology", February 2016, vol. 12, n^o 2, e1004706 [*DOI :* 10.1371/JOURNAL.PCBI.1004706], https://hal.inria.fr/hal-01248298.

[14] M. MORIN, D. ROPERS, F. LETISSE, S. LAGUERRE, J.-C. J.-C. PORTAIS, M. COCAIGN-BOUSQUET, B. ENJALBERT.*The post-transcriptional regulatory system CSR controls the balance of metabolic pools in upper glycolysis of Escherichia coli*, in "Molecular Microbiology", January 2016, vol. 100, n^o 4, p. 686-700 [*DOI :* 10.1111/MMI.13343], https://hal.inria.fr/hal-01418224.

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[16] D. ROPERS, A. MÉTRIS.*Data for the qualitative modeling of the osmotic stress response to NaCl in Escherichia coli*, in "Data in Brief", September 2016, vol. 9, p. 606-612 [*DOI :* 10.1016/J.DIB.2016.09.028], https://hal.inria.fr/hal-01417966.

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[17] S. CASAGRANDA, D. ROPERS, J.-L. GOUZÉ.*Model simplification and process analysis of biological models*, in "The 5th International Symposium on Positive Systems (POSTA)", Rome, Italy, September 2016, https://hal.inria.fr/hal-01412049.

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[18] E. CINQUEMANI.*On observability and reconstruction of promoter activity statistics from reporter protein mean and variance profiles*, in "Fifth International workshop on Hybrid Systems Biology - HSB 2016", Grenoble, France, E. CINQUEMANI, A. DONZÉ (editors), Hybrid Systems Biology, Springer, October 2016, vol. 9957, p. 147-163 [*DOI :* 10.1007/978-3-319-47151-8], https://hal.inria.fr/hal-01399934.

[19] A. M. GONZALEZ-VARGAS, E. CINQUEMANI, G. FERRARI-TRECATE.*Validation Methods for Population Models of Gene Expression Dynamics*, in "6th IFAC Conference on Foundations of Systems Biology in Engineering - FOSBE 2016", Magdeburg, Germany, October 2016, https://hal.inria.fr/hal-01399921.

Books or Proceedings Editing

[20] E. CINQUEMANI, A. DONZÉ (editors). *Hybrid Systems Biology: 5th International Workshop, HSB 2016, Grenoble, France, October 20-21, 2016, Proceedings*, Lecture Notes in Bioinformatics, Springer, Grenoble, France, 2016, n° 9957 [*DOI :* 10.1007/978-3-319-47151-8], https://hal.inria.fr/hal-01399942.

Research Reports

[21] A. M. GONZALEZ-VARGAS, E. CINQUEMANI, G. FERRARI-TRECATE.*Validation methods for population models of gene expression dynamics*, Inria Grenoble - Rhône-Alpes, July 2016, n° RR-8938, 17, https://hal.inria.fr/hal-01349030.

Project-Team IMAGINE

Intuitive Modeling and Animation for Interactive Graphics & Narrative Environments

IN COLLABORATION WITH: Laboratoire Jean Kuntzmann (LJK)

IN PARTNERSHIP WITH:
CNRS

Institut polytechnique de Grenoble

Université Grenoble Alpes

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Interaction and visualization

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Project-Team IMAGINE

Creation of the Team: 2012 January 01, updated into Project-Team: 2013 January 01

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5.5. - Computer graphics
5.5.1. - Geometrical modeling
5.5.3. - Computational photography
5.5.4. - Animation
5.7. - Audio modeling and processing
8.3. - Signal analysis

Other Research Topics and Application Domains:

2. - Health
2.2. - Physiology and diseases
3. - Environment and planet
3.3. - Geosciences
5. - Industry of the future
5.2. - Design and manufacturing
5.7. - 3D printing
9.1. - Education
9.2.2. - Cinema, Television
9.2.3. - Video games
9.2.4. - Theater
9.5.6. - Archeology, History

1. Members

Research Scientists

Frederic Devernay [Inria, Senior Researcher]
Remi Ronfard [Inria, Senior Researcher, Team leader, HDR]

Faculty Members

Marie Paule Cani [Grenoble INP, Professor, ENSIMAG, HDR]
Francois Faure [Anatoscope, INCUB-RAL, Professor, HDR]
Stefanie Hahmann [Grenoble INP, Professor, ENSIMAG, HDR]
Jean Claude Leon [Grenoble INP, Professor, ENSE3, HDR]
Olivier Palombi [UJF, Professor in Anatomy and Neurosurgery, Anatomy Laboratory, HDR]
Damien Rohmer [CPE Lyon, Associate Professor]

Technical Staff

Antoine Begault [INP, March 2013 - March 2017, ERC Expressive]
Estelle Charleroy [INP, Computer Artist, September 2013 - March 2017, ERC Expressive]
Alexandre Gauthier-Foichat [Inria, January 2016 - December 2017]
Gabriel Gonzalez [UGA, November 2015 - October 2016]
Thomas Lemaire [Inria, September 2013 – April 2017, Piper]

Matthieu Nesme [Inria, September 2012 - September 2016, Dynam'it]
Ole-Andre Rodlie [Inria, December 2015 - November 2016]
Romain Testylier [Inria, October 2013 – Sept 2016, Collodi]
Harold Vilmart [Grenoble INP, May 2016 – December 2018]
Youna Le Vaou [Grenoble INP Grenoble, from November 2016]
Boris Gallet [Floralys, February 2015 - July 2016]

PhD Students

Leo Allemand-Giorgis [Grenoble University, October 2012 - April 2016, alloc MENSR, 50% with MAVERICK]
Armelle Bauer [UJF, October 2013 - October 2016, Labex Persyval]
Romain Bregier [SILEANE, January 2016 - September 2017, granted by CIFRE]
Guillaume Cordonnier [Univ. Grenoble I, October 2015 - September 2018, alloc MENSR]
Pablo Coves [INP Grenoble, April 2015 - March 2018, ARC6 POTASSE]
Sébastien Crozet [CEA, December 2014 - December 2017]
Even Entem [INP Grenoble, November 2013 - November 2016, ERC Expressive]
Amelie Fondevilla [Grenoble University, October 2016 - September 2019]
Maxime Garcia [UGA, October 2016 - September 2019]
Geoffrey Guingo [INP, October 2015 - September 2018, ERC Expressive, 50% with U. Strasbourg]
Aarohi Singh Johal [EDF, October 2013 - September 2016, granted by CIFRE]
Pierre Luc Manteaux [Grenoble University, October 2012 - September 2016, ERC Expressive]
Sandra Nabil Mahrous Yacoub [Inria, October 2015 - September 2018]
Gregoire Nieto [Inria, January 2016 - September 2019]
Robin Roussel [Grenoble University, October 2015 - October 2018, ERC Expressive, 50% with UCL London]
Camille Schreck [Grenoble INP, October 2013 - October 2016, ERC Expressive]
Tibor Stanko [Grenoble University and CEA, October 2014 - October 2017, Bourse CEA, 50% with Maverick]
Ulysse Vimont [Grenoble INP, October 2013 - November 2016, ERC Expressive]

Post-Doctoral Fellows

Adela Barbulescu [INP Grenoble, December 2015 - November 2016]
Thomas Delame [Grenoble INP, September 2014 - September 2016, ERC Expressive]

Visiting Scientist

James Gain [University of Cape Town, June 2016 - September 2016]

Administrative Assistants

Catherine Bessiere [50% Inria, until October 2016]
Sanie Claraz [ERC Expressive, from March 2016]
Fatima Kassimi [ERC Expressive, until March 2016]
Marion Ponsot [Inria, from October 2016]

2. Overall Objectives

2.1. Context

With the fast increase of computational power and of memory space, increasingly complex and detailed 3D content is expected for virtual environments. Unfortunately, 3D modeling methodologies did not evolve as fast: most users still use standard CAD or 3D modeling software (such as Maya, 3DS or Blender) to design each 3D shape, to animate them and to manually control cameras for movie production. This is highly time consuming when large amounts of detailed content need to be produced. Moreover the quality of results is fully left in the user's hand, which restricts applicability to skilled professional artists. More intuitive software such as Z-Brush are restricted to shape design and still require a few months for being mastered by sculpture practitioners. Reducing user load can be done by capturing and re-using real objects or motions, at the price of restricting the range of possible content. Lastly, procedural generation methods can be used in specific cases to automatically get some detailed, plausible content. Although they save user's time, these procedural methods typically come at the price of control: indirect parameters need to be tuned during a series of trial and errors until the desired result is reached. Stressing that even skilled digital artists tend to prefer pen and paper than 3D computerized tools during the design stages of shapes, motion, and stories, Rob Cook, vice president of technology at Pixar animation studios recently stated (key-note talk, Siggraph Asia 2009): *new grand challenge in Computer Graphics is to make tools as transparent to the artists as special effects were made transparent to the general public*.

Could digital modeling be turned into a tool, even more expressive and simpler to use than a pen, to quickly convey and refine shapes, motions and stories? This is the long term vision towards which we would like to advance.

2.2. Scientific goals

The goal of the IMAGINE project is to develop **a new generation of models, algorithms and interactive environments for the interactive creation of animated 3D content and its communication through virtual cinematography**.

Our insight is to revisit models for shapes, motion, and narration from a user-centred perspective, i.e. to give models an intuitive, predictable behaviour from the user's view-point. This will ease both semi-automatic generation of animated 3D content and fine tuning of the results. The three main fields will be addressed:

1. **Shape design**: We aim to develop intuitive tools for designing and editing 3D shapes and their assemblies, from arbitrary ones to shapes that obey application-dependent constraints - such as, for instance, developable surfaces representing cloth or paper, or shape assemblies used for CAD of mechanical prototypes.
2. **Motion synthesis**: Our goal is to ease the interactive generation and control of 3D motion and deformations, in particular by enabling intuitive, coarse to fine design of animations. The applications range from the simulation of passive objects to the control of virtual creatures.
3. **Narrative design**: The aim is to help users to express, refine and convey temporal narrations, from stories to educational or industrial scenarios. We develop both virtual direction tools such as interactive storyboarding frameworks, and high-level models for virtual cinematography, such as rule-based cameras able to automatically follow the ongoing action and automatic film editing techniques.

In addition to addressing specific needs of digital artists, this research contributes to the development of new expressive media for 3D content. The long term goal would be to enable any professional or scientist to model and interact with their object of study, to provide educators with ways to quickly express and convey their ideas, and to give the general public the ability to directly create animated 3D content.

3. Research Program

3.1. Methodology

As already stressed, thinking of future digital modeling technologies as an Expressive Virtual Pen enabling to seamlessly design, refine and convey animated 3D content, leads to revisit models for shapes, motions and stories from a user-centered perspective. More specifically, inspiring from the user-centered interfaces developed in the Human Computer Interaction domain, we introduced the new concept of user-centered graphical models. Ideally, such models should be designed to behave, under any user action, the way a human user would have predicted. In our case, user's actions may include creation gestures such as sketching to draft a shape or direct a motion, deformation gestures such as stretching a shape in space or a motion in time, or copy-paste gestures to transfer some of the features from existing models to other ones. User-centered graphical models need to incorporate knowledge in order to seamlessly generate the appropriate content from such actions. We are using the following methodology to advance towards these goals:

- Develop high-level models for shapes, motion and stories that embed the necessary knowledge to respond as expected to user actions. These models should provide the appropriate handles for conveying the user's intent while embedding procedural methods that seamlessly take care of the appropriate details and constraints.
- Combine these models with expressive design and control tools such as gesture-based control through sketching, sculpting, or acting, towards interactive environments where users can create a new virtual scene, play with it, edit or refine it, and semi-automatically convey it through a video.

3.2. Validation

Validation is a major challenge when developing digital creation tools: there is no ideal result to compare with, in contrast with more standard problems such as reconstructing existing shapes or motions. Therefore, we had to think ahead about our validation strategy: new models for geometry or animation can be validated, as usually done in Computer Graphics, by showing that they solve a problem never tackled before or that they provide a more general or more efficient solution than previous methods. The interaction methods we are developing for content creation and editing rely as much as possible on existing interaction design principles already validated within the HCI community. We also occasionally develop new interaction tools, most often in collaboration with this community, and validate them through user studies. Lastly, we work with expert users from various application domains through our collaborations with professional artists, scientists from other domains, and industrial partners: these expert users validate the use of our new tools compared to their usual pipeline.

3.3. Application Domains

This research can be applied to any situation where users need to create new, imaginary, 3D content. Our work should be instrumental, in the long term, for the visual arts, from the creation of 3D films and games to the development of new digital planning tools for theater or cinema directors. Our models can also be used in interactive prototyping environments for engineering. They can help promoting interactive digital design to scientists, as a tool to quickly express, test and refine models, as well as an efficient way for conveying them to other people. Lastly, we expect our new methodology to put digital modeling within the reach of the general public, enabling educators, media and other practitioners to author their own 3D content.

Our current application domains are:

- Visual arts
  - Modeling and animation for 3D films and games.
  - Virtual cinematography and tools for theater directors.
- Engineering
  - Industrial design.
  - Mechanical & civil engineering.
- Natural Sciences
  - Virtual functional anatomy.
  - Virtual plants.
- Education and Creative tools
  - Sketch-based teaching.
  - Creative environments for novice users.

The diversity of users these domains bring, from digital experts to other professionals and novices, gives us excellent opportunities to validate our general methodology with different categories of users. Our ongoing projects in these various application domains are listed in Section 6.

4. Highlights of the Year

4.1. Highlights of the Year

- We had one paper accepted to EUROGRAPHICS [10].
- Our work on virtual paper crumpling, published in ACM TOG paper in Dec. 2015 [5], was presented at ACM SIGGRAPH 2016 in Anaheim (July 2016). Moreover, our paper on the sound of virtual paper [24] received the best paper award at the ACM-EG Symposium on Computer Animation (SCA) 2016.
- We participated to two state of the art papers published in Computer Graphics Forum, respectively on Adaptive physically based models in computer graphics [13], and on 3D Skeletons [15].
- The paper The 2D Shape Structure Dataset: A User Annotated Open Access Database. Axel Carlier, Kathryn Leonard, Stefanie Hahmann, Geraldine Morin, Misha Collins. SMI'16, Computer & Graphics 58, pp. 23-30 (2016).received the "Reproducability Award" (http://www.reproducibilitystamp.com).
- Four students defended their PhD within the team.
- Anatoscope, the start-up founded by François Faure and Olivier Palombi, was selected by *Sud De France Dévelopement* to have a booth at the CES, Las Vegas, in January. They featured a live demonstration of the Living Book of Anatomy.
- The first FUI project Collodi with TeamTo and Mercenaries engineering terminated this year. We have successfully delivered the physics simulation engine for cloth and hair to include it in the commercial distribution of the project. A a second FUI project Collodi 2 focusing on animation is starting in December 2016.

4.1.1. Awards

BEST PAPERS AWARDS :

[24] **Eurographics/ ACM SIGGRAPH Symposium on Computer Animation (2016)**. C. SCHRECK, D. ROHMER, D. L. JAMES, S. HAHMANN, M.-P. CANI.

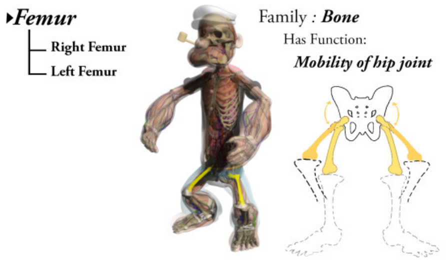
5. New Software and Platforms

5.1. Expressive

Expressive is a new C++ library created in 2013 for gathering and sharing the models and algorithms developed within the ERC Expressive project. It enables us to make our latest research results on new creative tools - such as high level models with intuitive, sketching or sculpting interfaces - soon available to the rest of the group and easily usable for our collaborators, such as Evelyne Hubert (Inria, Galaad) or Loic Barthe (IRIT, Toulouse). The most advanced part is a new version of Convol, a library dedicated to implicit modeling, with a main focus on integral surfaces along skeletons. Convol incorporates all the necessary material for constructive implicit modeling, a variety of blending operators and several methods for tessellating an implicit surface into a mesh, and for refining it in highly curved regions. The creation of new solid geometry can be performed by direct manipulation of skeletal primitives or through sketch-based modeling and multi-touch deformations.

- Participants: Marie Paule Cani, Antoine Begault, Even Entem, Thomas Delame, Ulysse Vimont
- Contact: Marie Paule Cani

5.2. MyCF



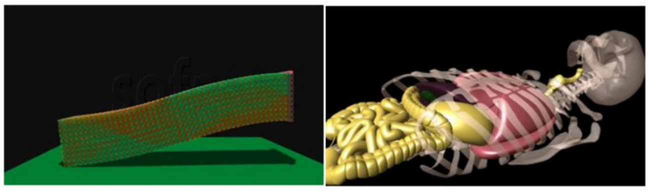


Figure 1. Left: My Corporis Fabrica is an anatomical knowledge database developed in our team. Right: SOFA is an open source simulator for physically based modeling.

My Corporis Fabrica (**MyCF**) is an anatomical knowledge ontology developed in our group. It relies on FMA (Foundational Model of Anatomy), developed under Creative Commons license (CC-by). MyCF browser is available on line, and is already in use for education and research in anatomy. Moreover, the MyCf's generic programming framework can be used for other domains, since the link it provides between semantic and 3D models matches several other research applications at IMAGINE.

- Participants: Olivier Palombi, Armelle Bauer, François Faure, Ali Hamadi Dicko
- Contact: Olivier Palombi
- URL: http://www.mycorporisfabrica.org

5.3. SOFA

Simulation Open Framework Architecture
SOFA is an Open Source framework primarily targeted at real-time simulation, with an emphasis on medical simulation. It is mostly intended for the research community to help develop new algorithms, but can also be used as an efficient prototyping tool. Based on an advanced software architecture, it allows : the creation of complex and evolving simulations by combining new algorithms with algorithms already included in SOFA, the modification of most parameters of the simulation (deformable behavior, surface representation, solver, constraints, collision algorithm, etc.) by simply editing an XML file, the building of complex models from simpler ones using a scene-graph description, the efficient simulation of the dynamics of interacting objects using abstract equation solvers, the reuse and easy comparison of a variety of available methods.
Sofa is extensively used by Anatoscope, who add proprietary plugins and helps maintaining the public plugins.

- Participants: François Faure, Armelle Bauer, Matthieu Nesme, Romain Testylier.
- Contact: François Faure
- URL: http://www.sofa-framework.org

5.4. Natron

Natron (http://natron.fr) is a professional-quality video post-production software specialized in compositing and visual effects. Compositing is the combining of visual elements from separate sources into single images, often to create the illusion that all those elements are parts of the same scene. The math behind compositing was formalized by Porter & Duff (1984) after the preliminary work by Wallace (1981).

Typical examples of compositing are, for example:

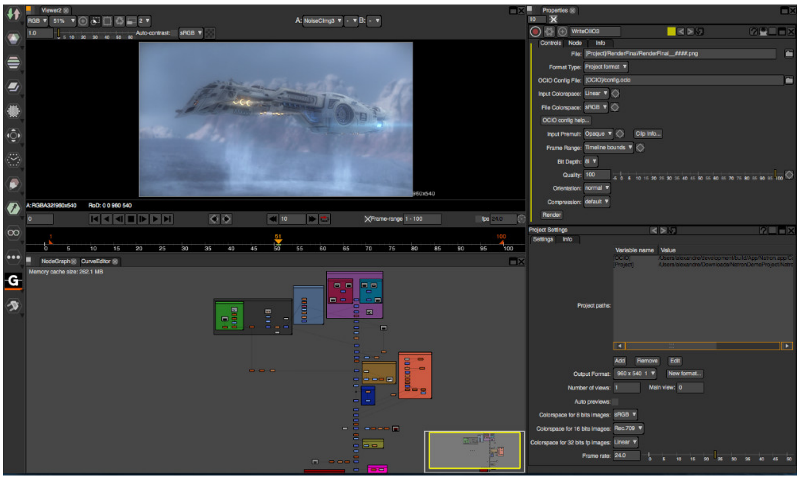


Figure 2. Video compositing using the Natron interface.

- The superimposition of a character filmed on a green background over a scene shot in another place, at another time, or a computer-generated scene; - The manual detouring (also called rotoscopy) of an element in a video to embed it in another video, possibly with a different motion; - Artistic modifications of a video, after shooting a live-action scene or rendering a CGI scene, in order to modify its lighting, colors, depth of field, camera motion, or to remove noise or add film grain.

A video compositing software is not a 3D computer graphics software, like Blender or Maya, but it is perfectly suited for combining computer-generated elements produced by other software with live-action video or 2D animation. Rather than rendering a full 3D scene with the 3D software, which may cost many hours of computation, the video compositing software can assemble the elements produced separately with a much more reactive interface and an almost instantaneous visual feedback.

- Participants: Frédéric Devernay, Alexandre Gauthier-Foichat.
- Contact: Frédéric Devernay
- URL: http://natron.fr

6. New Results

6.1. User-centered Models for Shapes and Shape Assemblies

- **Scientist in charge**: Stefanie Hahmann.
- **Other permanent researchers**: Marie-Paule Cani, Jean-Claude Léon, Damien Rohmer.

Our goal, is to develop responsive shape models, i.e. 3D models that respond in the expected way under any user action, by maintaining specific application-dependent constraints (such as a volumetric objects keeping their volume when bent, or cloth-like surfaces remaining developable during deformation, etc). We are extending this approach to composite objects made of distributions and/or combination of sub-shapes of various dimensions.

6.1.1. Shape analysis

Figure 3. Left: Illustration of comparative study of 3D medial axis quality in [21]. Right: Hierarchies for similar shapes (dancers) in different poses to show that the proposed hierarchy is stable under articulation [22]. Coarser levels of the hierarchy are consistent even if finer levels are added in the presence of finer details. Also, note that the hierarchy is retained even with occlusion: The pink level of the left arm of the first dancer is occluded, but the blue level begins as it should.

Within the post-doc of Thomas Delame a comparative study between 3D skeletonization methods has been achieved. This work has been summarized as a Eurographics State of the Art [15]. Moreover, a comparative study of the quality between 3D medial axis was assessed and published in Vision, Modeling and Visualization [21].

We developed a multilevel analysis method of 2D shapes and used it to find similarities between the different parts of a shape [22]. Such an analysis is important for many applications such as shape comparison, editing, and compression. Our robust and stable method decomposes a shape into parts, determines a parts hierarchy, and measures similarity between parts based on a salience measure on the medial axis, the Weighted Extended Distance Function, providing a multi-resolution partition of the shape that is stable across scale and articulation. Comparison with our extensive user study on the MPEG-7 database, see below, demonstrates that our geometric results are consistent with user perception. This work has been accomplished within a collaboration between S. Hahmann, Kathryn Leonard (CSUCI), and Geraldine Morin and Axel Carlier (IRIT, ENSEEIHT). K. Leonard was visiting the Imagine team during several month in 2016 as an invited professor funded by the ERC Expressive grant.

We also conducted a large user-study and made the results available throughout an open access data base: The 2D Shape Structure database [9] is a public, user-generated dataset of 2D shape decompositions into a hierarchy of shape parts with geometric relationships retained. It is the outcome of a large-scale user study obtained by crowdsourcing, involving over 1200 shapes in 70 shape classes, and 2861 participants. A total of 41953 annotations has been collected with at least 24 annotations per shape. For each shape, user decompositions into main shape, one or more levels of parts, and a level of details are available. This database reinforces a philosophy that understanding shape structure as a whole, rather than in the separated categories of parts decomposition, parts hierarchy, and analysis of relationships between parts, is crucial for full shape understanding. We provide initial statistical explorations of the data to determine representative ("mean") shape annotations and to determine the number of modes in the annotations. The primary goal of this work is to make this rich and complex database openly available (through the website http://2dshapesstructure.github.io), providing the shape community with a ground truth of human perception of holistic shape structure. This paper has received the « Reproducibility Award » (http://www.reproducibilitystamp.com).

6.1.2. Surface design

Recent surface acquisition technologies based on micro-sensors produce three-space tangential curve data which can be transformed into a network of space curves with surface normals. In the thesis of Tibor Stanko, which is funded by the CEA-LETI, we dispose such a mobile device equipped with several micro-sensors.

Figure 4. Left: Illustration of results of [14].

The goal of the thesis is to develop surface acquisitions methods using this equipped mobile device. As a first step, we address the theoretical and algorithmic problem of surfacing an arbitrary closed 3D curve network with given surface normals. Thanks to the normal vector input, the patch finding problem can be solved unambiguously and an initial piecewise smooth triangle mesh is computed. The input normals are propagated throughout the mesh. Together with the initial mesh, the propagated normals are used to compute mean curvature vectors. We then compute the final mesh as the solution of a new variational optimization method based on the mean curvature vectors. The intuition behind this original approach is to guide the standard Laplacian-based variational methods by the curvature information extracted from the input normals. The normal input increases shape fidelity and allows to achieve globally smooth and visually pleasing shapes. This work has been presented at Eurographics 2016 as a short paper [25] and GTMG 2016 [26] and has been published as a journal paper [14].

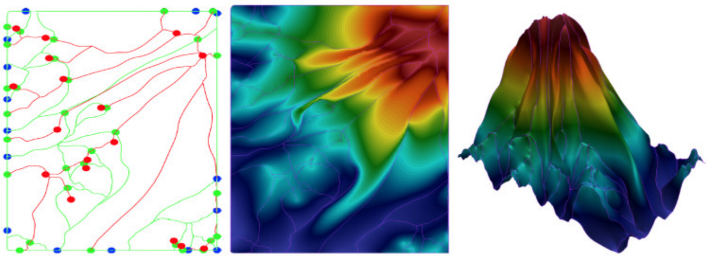


Figure 5. The terrain data set of Mt Rainier: Surface reconstruction (c) with contour lines (b) from the MS complex with 69 critical points(a) [31].

Morse-Smale complexes have been proposed to visualize topological features of scalar fields defined on manifold domains. Herein, three main problems have been addressed in the past: (a) efficient computation of the initial combinatorial structure connecting the critical points; (b) simplification of these combinatorial structures; (c) reconstruction of a scalar field in accordance to the simplified Morse-Smale complex. The PhD thesis of Leo Allemand-Giorgis faces the third problem by proposing a novel approach for computing a scalar field coherent with a given simplified MS complex that privileges the use of piecewise polynomial functions [31]. Based on techniques borrowed from shape preserving design in Computer Aided Geometric Design, our method constructs the surface cell by cell using piecewise polynomial curves and surfaces.

6.2. Motion & Sound Synthesis

- **Scientist in charge**: François Faure.
- **Other permanent researchers**: Marie-Paule Cani, Damien Rohmer, Rémi Ronfard.

Animating objects in real-time is mandatory to enable user interaction during motion design. Physically-based models, an excellent paradigm for generating motions that a human user would expect, tend to lack efficiency for complex shapes due to their use of low-level geometry (such as fine meshes). Our goal is therefore two-folds: first, develop efficient physically-based models and collisions processing methods for arbitrary passive objects, by decoupling deformations from the possibly complex, geometric representation; second, study the combination of animation models with geometric responsive shapes, enabling the animation of complex constrained shapes in real-time. The last goal is to start developing coarse to fine animation models for virtual creatures, towards easier authoring of character animation for our work on narrative design.

6.2.1. Physically-based models

We proposed a survey on the exhisting adaptative physically based models in Computer Graphics in collaboration with IST Austria, University of Minnesota, and NANO-D Inria team. Models where classified according to the strategy they use for adaptation, from time-stepping and freezing techniques to geometric adaptivity in the form of structured grids, meshes, and particles. Applications range from fluids, through deformable bodies, to articulated solids. The survey has been published as a Eurographics state of the art [13].

In collaboration with the *Reproduction et Développement des Plantes* Lab (ENS Lyon), we proposed a realistic three-dimensional mechanical model of the indentation of a flower bud using the SOFA library, in order to provide a framework for the analysis of force-displacement curves obtained experimentally [12].

6.2.2. Simulating paper material with sound

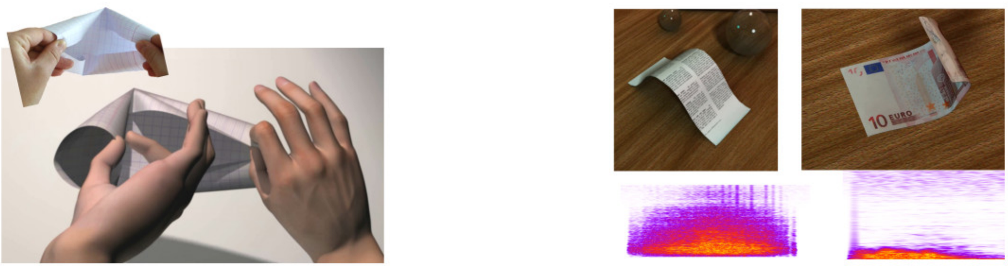


Figure 6. Left: Geometrical deformation using our geometrical model from [5]. Right: Various paper deformation and type leading to different synthesized sounds [24].

We developed within the PhD from Camille Schreck a dedicated approach to model a real time deforming virtual sheet of paper. First we developed a geometrical model interleaving physically based elastic deformation with a dedicated geometrical correction and remeshing. The key idea consists in modeling the surface using a set of generalized cones able to model developable ruled surfaces instead of the more traditional set of triangles. This surface can handle length preservation with respect to the 2D pattern, and permanent non smooth crumpling appearance. This geometrical model published in ACM Transactions on Graphics in Dec. 2015 [5] has been presented at ACM SIGGRAPH this summer and is currently under investigation to be part of Inria Showroom. This model has then been extended to real time sound synthesis of crumpled paper within the collaboration with Doug James (Stanford University). This method was the first to handle real-time shape dependent sound synthesis. During the interactive deformation, sudden curvature changes and friction are detected. These sound generating events are then associated to a geometrical region where the sound resonates and defined efficiently using previous geometrical model. Finally, the sound is synthesized using a pre-recorded sound data base of crumple and friction events sorted with respect to the resonator region size. This work has been published at Symposium on Computer Animation [24] and received the best paper award.

6.2.3. Human motion

Figure 7. Live tracking and visualization of a plausible anatomical skeleton following the pose the subject [17].

Armelle Bauer defended her PhD in November, co-advised with TIMC (Jocelyne Troccaz as principal advisor), on Augmented Reality for the interactive visualization of human anatomy. This is one of the main achievements of the Living Book of Anatomy project, funded by Labex Persyval. This work was partly published at the Motion in Games conference (MIG 2016) [17]. It served as a basis for the follow-up ANR project Anatomy2020 involving Anatoscope, TIMC and LIG laboratories, and Univ Lyon 2.

6.3. Knowledge-based Models for Narrative Design

- **Scientist in charge**: Rémi Ronfard.
- **Other permanent researchers**: Marie-Paule Cani, Frédéric Devernay, François Faure, Jean-Claude Léon, Olivier Palombi.

Our long term goal is to develop high-level models helping users to express and convey their own narrative content (from fiction stories to more practical educational or demonstrative scenarios). Before being able to specify the narration, a first step is to define models able to express some a priori knowledge on the background scene and on the object(s) or character(s) of interest. Our first goal is to develop 3D ontologies able to express such knowledge. The second goal is to define a representation for narration, to be used in future storyboarding frameworks and virtual direction tools. Our last goal is to develop high-level models for virtual cinematography such as rule-based cameras able to automatically follow the ongoing action and semi-automatic editing tools enabling to easily convey the narration via a movie.

6.3.1. Virtual cameras

Filming live action requires a coincidence of many factors: actors of course, but also lighting, sound capture, set design, and finally the camera (position, frame, and motion). Some of these, such as sound and lighting, can be more or less reworked in post-production, but the camera parameters are usually considered to be fixed at shooting time. We developed two kinds of image-based rendering technique, which allows to change in post-production either the camera frame (in terms of pan, tilt, and zoom), or the camera position.

To be able to change the camera frame after shooting, we developed techniques to construct a video panorama from a set of cameras placed roughly at the same position. Video panorama exhibits a specific problem, which is not present in photo panorama: because the projection centers of the cameras can not physically be at the same location, there is residual parallax between the video sequences, which produce artifacts when the videos are stitched together. Sandra Nabil has worked during her PhD on producing video panoramas without visible artifacts, which can be used to freely pick the camera frame in terms of pan, tilt and zoom during the post-production phase.

Modifying the camera position itself is an even greater challenge, since it either requires a perfect 3D reconstruction of the scene or a dense sampling of the 4D space of optical rays at each time (called the 4D lightfield). During the PhD of Gregoire Nieto, we developed image-based rendering (IBR) techniques which are designed to work in cases where the 3D reconstruction cannot be obtained with a high precision, and the number of cameras used to capture the scene is low, resulting in a sparse sampling of the 4D lightfield.

6.3.2. Virtual actors

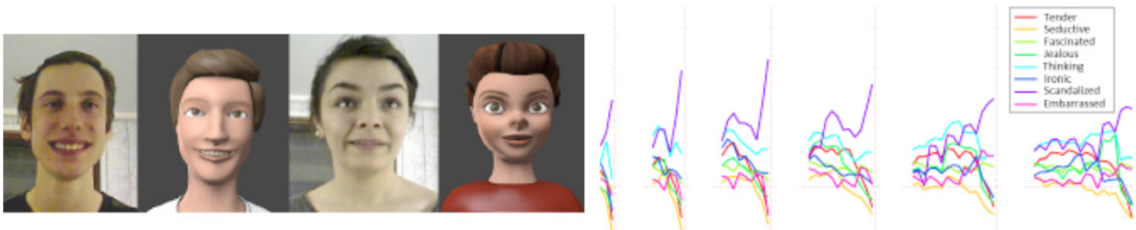


Figure 8. Left: Examples of video and animation frames for a dramatic attitude (seductive) played by two semi-professional actors. Right: Prosodic contours for 8 dramatic attitudes, showing evidence that "scandalized" and "thinking" strongly stand out from other attitudes.

Following up on Adela Barbelescu's PhD thesis, we tested the capability of audiovisual parameters (voice frequency, rhythm, head motion and facial expressions) to discriminate among different dramatic attitudes in both real actors (video) and virtual actors (3D animation). Using Linear Discriminant Analysis classifiers, we showed that sentence-level features present a higher discriminating rate among the attitudes and are less dependent on the speaker than frame and sylable features. We also performed perceptual evaluation tests, showing that voice frequency is correlated to the perceptual results for all attitudes, while other features, such as head motion, contribute differently, depending both on the attitude and the speaker. Those new results were presented at the Interspeech conference [16].

6.4. Creating and Interacting with Virtual Prototypes

- **Scientist in charge**: Jean-Claude Léon.
- **Other permanent researchers**: Marie-Paule Cani, Frédéric Devernay, Olivier Palombi, Damien Rohmer, Rémi Ronfard.

The challenge is to develop more effective ways to put the user in the loop during content authoring. We generally rely on sketching techniques for quickly drafting new content, and on sculpting methods (in the sense of gesture-driven, continuous distortion) for further 3D content refinement and editing. The objective is to extend these expressive modeling techniques to general content, from complex shapes and assemblies to animated content. As a complement, we are exploring the use of various 2D or 3D input devices to ease interactive 3D content creation.

6.4.1. Sculpting Virtual Worlds

Extending expressive modeling paradigms to full virtual worlds, with complex terrains, streams and oceans, and vegetation is a challenging goal. To achieve this, we need to combine procedural methods that accurately simulate physical, geological and biological phenomena shaping the world, which high level user control. This year, our work in the area was three-folds:

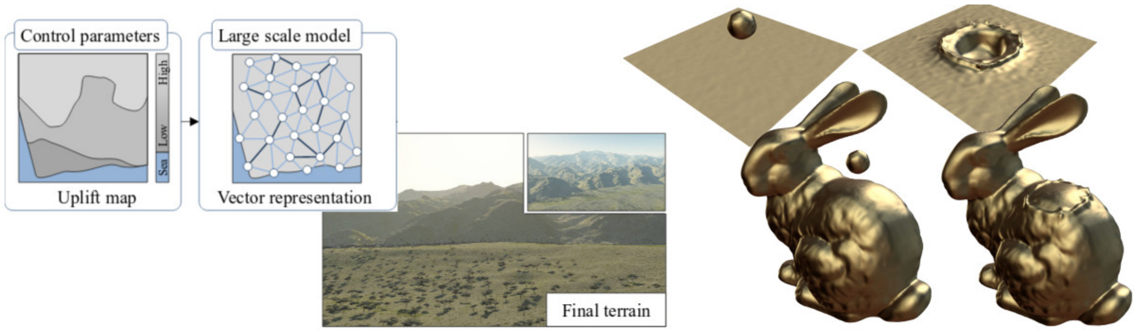


Figure 9. Left: Generating a large-scale terrain following fluvial erosion principle from a coarse set of control parameters [10]. Right: Copy of an animated drop of fluid and its effect on the underlying surface into another animation [23].

Firstly, in collaboration with Jean Braun, professor in geo-morphology and other colleagues, we designed the fist efficient simulation method able to take into account large-scale fluvial erosion to shape mountains. This method was published at Eurographics [10]. We also designed an interactive sculpting system with multi-touch finger interaction, able to shape mountain ranges based on tectonic forces. This method, combined in real-time with our erosion simulation process, was submitted for a journal publication.

Secondly, we extended the "Worldbrush" system proposed in 2015 (Emilien et al, Siggraph 2015) in order to consistently populate virtual worlds with learned statistical distributions of trees and plants. The main contributor to this project was James Gain, our visiting professor. After clustering the input terrain into a number of characteristic environmental conditions, we computed sand-box (small-scale) simulations of ecosystems (plant growth) for each of these conditions, and then used learned statistical models (an extension of worldbrush) to populate the full terrain with consistent sets of species. This work was submitted for publication.

Third, we extended interactive sculpting paradigms to the sculpting of liquid simulation results, such as editing waves on a virtual ocean [23]. Liquid simulations are both compute intensive and very hard to control, since they are typically edited by re-launching the simulations with slightly different initial conditions until the user is satisfied. In contrast, our method enables users to directly edit liquid animation results (coming in the form of animated meshes) in order to directly output new animations. More precisely, the method offer semi-automatic clustering methods enabling users to select features such as droplets and waves, edit them in space and time and them paste them back into the current liquid animation or to another one.

6.4.2. Sketch based design

Using 2D sketches is one of the easiest way for creating 3D contents. While prior knowledge on the object being sketch can be used to retrieve the missing information, and thus consistently inferring 3D, interpreting more general sketches and generating 3D shapes from them in indeed a challenging long-term goals. This year, our work in the area was two-folds:

Firstly, we participated to a course on Sketch-based Modeling, presented at both Eurographics 2016 and Siggraph Asia 2016 [18]. The parts we worked on was sketch-based modeling from prior knowledge, with the examples of our works on animals, garments (developable surfaces) and trees.

Secondly, we advanced towards the interpretation of general sketches representing smooth, organic shapes. The key features of our methods are a new approach for aesthetic contour completion, and an interactive algorithm for progressively interpreting internal silhouettes (suggestive contours) in order to progressively

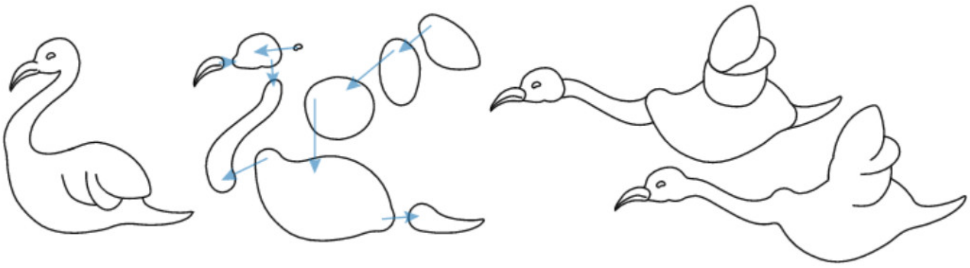


Figure 10. Progressive extraction of sub-parts of an input sketch in depth with automatic contour completion [37].

extract sub-parts of the shape from the drawing. These parts are ordered in depth. Our first results were presented as a poster at the Siggraph 2016 conference [37], and then extended an submitted for publication. We are now extending them towards the inference of 3D, organic shapes from a 2D sketch.

7. Partnerships and Cooperations

7.1. Regional Initiatives

7.1.1. ARC6 PoTAsse (2015 - 2018)

Participants: Pablo Coves, Jean-Claude Léon, Damien Rohmer.

We received a doctoral grant (AdR) from the ARC6 program to generate functional CAD assemblies from scanned data (*PoTAsse*: POint clouds To ASSEmblies) as a collaboration between Imagine team (LJK/Inria) and Geomod team (LIRIS). Our PhD student Pablo Coves is advised by Jean-Claude Léon and Damien Rohmer at Imagine, Raphaëlle Chaine and Julie Digne in Geomod team.

7.2. National Initiatives

7.2.1. FUI Collodi (October 2013 - October 2016)

Participants: Francois Faure, Romain Testylier.

This 3-year contract with two industrial partners: TeamTo and Mercenaries Engineering (software for production rendering), was a follow-up and a generalization of Dynam'it. The goal was to propose an integrated software for the animation and final rendering of high-quality movies, as an alternative to the ever-ageing Maya. It included dynamics similarly to Dynam'it This contract, started in October, funded 2 engineers for 3 years.

This project will be pursued within the new FUI Collodi 2 between 2017 - 2018.

7.3. European Initiatives

7.3.1. ERC Grant Expressive

Title: EXPloring REsponsive Shapes for Seamless desIgn of Virtual Environments.

Programm: ERC Advanced Grant

Duration: 04/2012 - 03/2017

Inria contact: Marie-Paule Cani

To make expressive and creative design possible in virtual environments, the goal is to totally move away from conventional 3D techniques, where sophisticated interfaces are used to edit the degrees of freedom of pre-existing geometric or physical models: this paradigm has failed, since even trained digital artists still create on traditional media and only use the computer to reproduce already designed content. To allow creative design in virtual environments, from early draft to progressive refinement and finalization of an idea, both interaction tools and models for shape and motion need to be revisited from a user-centred perspective. The challenge is to develop reactive 3D shapes – a new paradigm for high-level, animated 3D content – that will take form, refine, move and deform based on user intent, expressed through intuitive interaction gestures inserted in a user-knowledge context. Anchored in Computer Graphics, this work reaches the frontier of other domains, from Geometry, Conceptual Design and Simulation to Human Computer Interaction.

7.3.2. PIPER

Title: Position and Personalize Advanced Human Body Models for Injury Prediction

Programm: FP7

Duration: November 2013 - April 2017

Inria contact: F. Faure

In passive safety, human variability is currently difficult to account for using crash test dummies and regulatory procedures. However, vulnerable populations such as children and elderly need to be considered in the design of safety systems in order to further reduce the fatalities by protecting all users and not only so called averages. Based on the finite element method, advanced Human Body Models for injury prediction have the potential to represent the population variability and to provide more accurate injury predictions than alternatives using global injury criteria. However, these advanced HBM are underutilized in industrial R&D. Reasons include difficulties to position the models – which are typically only available in one posture – in actual vehicle environments, and the lack of model families to represent the population variability (which reduces their interest when compared to dummies). The main objective of the project will be to develop new tools to position and personalize these advanced HBM. Specifications will be agreed upon with future industrial users, and an extensive evaluation in actual applications will take place during the project. The tools will be made available by using an Open Source exploitation strategy and extensive dissemination driven by the industrial partners.Proven approaches will be combined with innovative solutions transferred from computer graphics, statistical shape and ergonomics modeling. The consortium will be balanced between industrial users (with seven European car manufacturers represented), academic users involved in injury bio-mechanics, and partners with different expertise with strong potential for transfer of knowledge. By facilitating the generation of population and subject-specific HBM and their usage in production environments, the tools will enable new applications in industrial R&D for the design of restraint systems as well as new research applications.

7.4. International Research Visitors

7.4.1. Visits of International Scientists

- Jean-Charles Bazin (ETH Zurich): The convergence space of visual computing.
- Ariel Shamir (Interdisciplinary Center, Israel): Creating visual stories.
- Eugene Fiume (Univ. Toronto, Canada): Procedural Speech Synchronization for Facial Animation.
- Rahul Narain (Univ. Minnesota, USA): Adaptivity and Optimization for Physics-Based Animation.
- Christian Jacquemin (Univ. Paris Sud): Arts and science: examples in computer graphics and image processing, and critical analysis.
- James Gain (Univ. Cape Town, South Africa): Parallel, Realistic and Controllable Terrain Synthesis.
- Nils Thuerey (Technical Univ. of Munich, Germany): Data-driven Fluid Simulation.

- Bernhard Thomaszewski (Disney Research Zurich, ETH Zurich, Switzerland): Computational Design Tools for the Age of Digital Fabrication.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. Member of the Organizing Committees

Remi Ronfard was

- co-organizer of the Eurographics workshop on intelligent cinematography and editing (WICED) in Lisbon, Portugal in May 2016.
- co-organizer of the Computational Modeling of Narrative (CMN) conference in Cracow, Poland in July 2016.

8.1.2. Scientific Events Selection

8.1.2.1. Chair of Conference Program Committees

- Marie-Paule Cani was chosen as Technical Paper Chair of Siggraph 2017 and started working on this since January 2016, with several meetings in the US throughout the year.
- Stefanie Hahmann was Paper Chair of Symposium on Solid and Physical Modeling (SPM) 2016.

8.1.2.2. Member of the Conference Program Committees

- Marie-Paule Cani served in the Papers Committees of Eurographics 2016 and Siggraph 2016.
- Frédéric Devernay served as a member of the program committee for IEEE CVPR 2016, ECCV 2016, 3DV 2016, CVMP 2016, RFIA 2016.
- Damien Rohmer was member of the International Program Committee for Symposium on Solid and Physical Modeling (SPM) and Shape Modeling International-Sculpting Event (SMI-FASE). He was also member of the jury of the best paper for AFIG-EGFR.
- Remi Ronfard was a member of the Program Committees for Motion in Games (MIG 2016), International Conference on Interactive Storytelling (ICIDS 2016) and Intelligent Narrative Technology (INT 2016).
- Stefanie Hahmann serves in the International Program Committee for Eurographics 2016 and Shape Modeling International (SMI) 2016.
- Jean-Claude Léon was member of the International Program Committee for Symposium on Solid and Physical Modeling (SPM) and Shape Modeling International-Sculpting Event (SMI-FASE)

8.1.2.3. Reviewer

- Damien Rohmer was reviewer for ACM SIGGRAPH Asia.
- Remi Ronfard was a reviewer for Computer Vision and Pattern Recognition (CVPR) and Computer Human Interface (CHI) conferences in 2016.

8.1.3. Journal

8.1.3.1. Member of the Editorial Boards

- Marie-Paule Cani is an Associate Editor of ACM Transactions on Graphics (TOG).
- Stefanie Hahmann was a guest Editor of the journal CAD Vol. 78 (Elsevier): Special Issue on Solid and Physical Modeling SPM'16, (eds.) Mario Botsch (Allemagne), Stefanie Hahmann, Scott Schaefer (USA).
- Jean-Claude Léon is an Associate Editor of CAD (Elsevier)

8.1.3.2. Reviewer - Reviewing Activities

- Remi Ronfard was a reviewer for the « Computers and Graphics » and « Graphical Models » journals in 2016.
- Stefanie Hahmann was a reviewer for the journals CAGD and CAD
- Jean-Claude Léon was a reviewer for the journal ASME JCISE

8.1.4. Invited Talks

Marie-Paule Cani gave the following invited talks

- Towards the Expressive Design of Virtual Worlds: Combining Knowledge and Control. Key-note talk, Eurographics'2016, Lisbon, Portugal, May 2016.
- Expressive 3D Modeling: User-centered models for seamless creation through gestures. Key-note talk, Graphics Interface'2016, Victoria, Canada June 2016
- Modélisation 3D expressive: du design numérique à la création de mondes virtuels animés. 3h talks for the Computer Science students of ENS Paris-Saclay (previously called ENS Cachan)
- Towards the Expressive Design of Virtual Worlds: Combining Knowledge and Control. Inria Sophia Antipolis colloquium series, September 2016.
- Modélisation 3D Expressive : du design numérique à la création de mondes virtuels animés. Invited lecture. l'Université de Corse, Corte, Octobre 2016.
- Expressive 3D modeling: from digital design to the creation of animated virtual worlds. Computer Science colloquium, University Paris VI, November 2016.

Rémi Ronfard gave the following invited talks

- Directing virtual worlds, Xerox Research Center Europe, Meylan.
- The prose storyboard language, a tool for annotating and directing movies, Research seminar on digital images, ENS Ulm, February 11, 2016.
- Directing virtual worlds, Disney Research, Zurich.
- Génération et montage de rushes cinématographiques par analyse vidéo et application aux captations de théâtre. Séminaire en humanités numériques: Valoriser la recherche en arts performatifs par le numérique, Maison des Sciences de l'Homme, Lille, April 18, 2016.
- Can computers pay attention ? Journée d'étude sur Attention humaine / Exo-attention computationnelle (Human Attention / Computational Exo-Attention) at University Grenoble Alpes, October 13, 2016.

8.1.5. Scientific Expertise

- Marie-Paule Cani
  - was a reviewer for a consolidator and a starting ERC project.
  - did some consulting for Disney Research, Zurich.
- Remi Ronfard
  - was a reviewer for the AXIOM GAMMA project at the European Commission (review meetings in March and July 2016).
  - was a member of the scientific committee at IMAGINOVE in 2016.
- Stefanie Hahmann
  - was an expert for the Netherlands Organisation for Scientific Research.
  - serves as a member of the Advisory Board (2014-2018) for the Européen Marie-Curie Training Network ARCADES.

8.1.6. Research Administration

- Marie-Paule Cani served as first Vice-Chair and chair of the Steering Committee of the Eurographics association.
- Marie-Paule Cani and Rémi Ronfard are elected members of the executive board (CA) of EG-France, the french chapter of Eurographics.
- Marie-Paule Cani became joint director of Laboratoire Jean Kuntzmann from July 2016.
- Damien Rohmer is member of the Conseil d'Administration of Association Française d'Informatique Graphique (AFIG).
- Rémi Ronfard
  - was the Head of the Image and Geometry Department at Laboratoire Jean Kuntzmann until July 2016.
  - is the co-organizer of the action « Visage, geste, action et comportement » at GDR ISIS.
  - has been the head (by interim) of the Imagine team from April 2016.
- Stefanie Hahmann
  - is an elected member of the Executive Committee of SMA (Solid Modeling Association) since 2013.
  - is the head of the French working group "GTMG" (Groupe de travail en Modélisation Géométrique) part of the CNRS GDR IM and GDR IGRV.
  - was member of the Conseil de laboratoire of the LJK lab.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

- Marie-Paule Cani is responsible for two courses at Ensimag/Grenoble-INP: 3D Graphics (a course that attracts about 80 master 1 students per year) and IRL (Introduction à la recherche en laboratoire), a course enabling engineering students to work on a personal project in a research lab during one semester, to get an idea of what academic research is.
- Stefanie Hahmann is co-responsible of the department MMIS (Images and Applied Maths) at Grenoble INP with 120 students. (http://ensimag.grenoble-inp.fr/cursus-ingenieur/modelisation-mathematique-images-simulation-124674.kjsp)

  Stefanie Hahmann had teaching load of 192h per year. She is responsible of 3 courses at Ensimag/Grenoble INP: Numerical Methods (240 students, 3rd year Bachelor level), Geometric Modeling (60 students, Master 1st year) and Surface Modeling (30 students, Master 2nd year).
- Olivier Palombi is responsible of the French Campus numérique of anatomy. He is responsible and national leader of the project SIDES (http://side-sante.org/). All the French medical schools (43) have planed to use the same e-learning framework (SIDES) to manage evaluations (examen) and to create a large shared database of questions.
- François Faure was responsible of the GVR-(Graphics, Vision and Robotic) program in the MOSIG Master.
- Damien Rohmer is coordinator of the Math, Signal, Image program at the engineering school CPE Lyon in supervising the scientific and technical content of the program. He is also co-responsible of the *Image, Modeling & Computing* specialization program attracting 35 students per year. He gives, and is responsible, for of one Computer Science class (130 student, 3rd year Bachelor level), an introductory Computer Graphics class (110 students, Master 1st year), and 5 specialization classes on C++ programming, OpenGL programming, 3D modeling, animation and rendering (35 students, Master 1st and 2nd year). He coordinates the association between CPE and the new computer graphics master program ID3D (Image, Développement et Technologie 3D) from University Lyon1. He also coordinates the association between CPE and the Gamagora computer game project.

- Rémi Ronfard taught courses in Computational modeling of narrative texts, movies and games, MSTII Doctoral School, University Grenoble Alpes (18 hours in March-April 2016); Game Engine Programming, M2R IMAGINA, University of Montpellier (36 hours in October-December 2016) and Advanced 3D animation, M2R MOSIG, University of Grenoble Alpes (12 hours in December 2016).
- Jean-Claude Léon is in charge of the module Mechanical Systems at Grenoble-INP ENSE3 (300 students, 64h, coordination of three courses)
- Frédéric Devernay teaches Computer Science and Algorithmics to L1 and L2 students (Cycle Préparatoire Polytechnique : CPP) at INP Grenoble (50h).

Note that MOSIG is joint master program between University Joseph Fourier (UJF) and Institut Polytechnique de Grenoble (INPG) taught in English since it hosts a number of internal students. It belongs to the doctoral school MSTII.

Most of the members of our team are Professor or Assistant Professor in University where the common teaching load is about 200h per year. Rémi Ronfard who is only researcher usually perform some teaching in vacations.

8.2.2. Supervision

- PhD: Léo Allemand-Giorgis. *Reconstruction de surfaces à partir de complexes de Morse-Smale*. Thèse MENRT. October 2012-Juin 2016. Stefanie Hahmann and GP Bonneau (Maverick team).
- PhD: Pierre-Luc Manteaux. *Simulation et contrôle de phénomènes physiques*. Grenoble University. October 2012-September 2016. Marie-Paule Cani and François Faure.
- PhD: Camille Schreck. *Interactive deformation of virtual paper*. Grenoble Université, October 2013 - October 2016. Stefanie Hahmann, Damien Rohmer.
- PhD: Ulysse Vimont. *Novel Methods for the Interactive Design of Complex Objects and Animations* October 2013 - November 2016. Marie-Paule Cani, Damien Rohmer.
- PhD in progress: Romain Brégier (Université de Grenoble Alpes), *Dévracage d'objets à l'aide de bras robotisés*, encadrée par Frédéric Devernay et dirigée par James Crowley (LIG, Grenoble), soutenance prévue en octobre 2017.
- PhD in progress: Guillaume Cordonnier. *Graphical simulation of mountains based on geology*. Grenoble university. October 2015-September 2018. Marie-Paule Cani and Eric Galin.
- PhD in progress: Pablo Coves, *From Point Cloud Data to Functional CAD Model*. Grenoble Universit. Jean-Claude Léon, Damien Rohmer, Raphaëlle Chaine (LIRIS), Julie Digne (LIRIS).
- PhD in progress: Sébastien Crozet, *Calcul de distance minimale entre solides B-Rep CAO pour des applications de simulations mécaniques temps réelles*, Janvier 2015- Décembre 2017. Frédéric Devernay.
- PhD in progress: Even Entem. *3D modelling from a sketch*. Grenoble University. November 2013-March 2017. Marie-Paule Cani and Loic Barthe (IRIT Toulouse).
- PhD in progress: Amélie Fondevilla. *Sculpting and animating developable surfaces with video embedding*, Thèse MENRT. October 2016 - September 2021. Stefanie Hahmann.
- PhD in progress: Geoffrey Guingo. *Synthesis of animated textures*. Grenoble university. October 2015-September 2018. Marie-Paule Cani, Jean-Michel Dischler and Basile Sauvage.
- PhD in progress: Sandra Nabil (Université de Grenoble Alpes), *Vidéo panoramique 360 dégrés à très haute résolution*, encadrée par Frédéric Devernay et dirigée par James Crowley (LIG, Grenoble), soutenance prévue en octobre 2018.
- PhD in progress: Grégoire Niéto (Université de Grenoble Alpes), *Dispositifs de capture de type «caméra plénoptique» pour la vision à grande distance, et algorithmes de traitement et de visualisation*, encadrée par Frédéric Devernay et dirigée par James Crowley (LIG, Grenoble), soutenance prévue en octobre 2017.

- PhD in progress: Robin Roussel. *Function-aware design for objects to be fabricated*. UCL London. Octber 2015-September 2018.Niloy Mitra, Marie-Paule Cani and Jean-Claude Léon.
- PhD in progress: Tibor Stanko. *Modélisation de surfaces lisses maillées à partir de capteurs inertiels*. Thèse CEA. October 2014- September 2017. Stefanie Hahmann and GP Bonneau.
- M2R: Thibault Blanc-Beyne, Ensimag, Géraldine Morin (ENSEEIHT), Stefanie Hahmann
- M2R: Amélie Fondevilla, Ensimag, Stefanie Hahmann, Damien Rohmer
- M2R Maxime Garcia, ENSIMAG/MOSIG, Rémi Ronfard
- M2R: Thibault Lejemble, Ensimag, Stefanie Hahmann, Damien Rohmer
- M2R: Kevin Le Run, L3, ENS Cachan, Rémi Ronfard
- M2R: Estelle Noé, ParisTech et KTH, Damien Rohmer, Stefanie Hahmann, Marie-Paule Cani
- M2R: Aymeric Séguret, M2GICAO, Jean-Claude Léon,

8.2.3. Juries

- Marie-Paule Cani was member of the PhD committees of Elisabeth Rousset (Equipe IIHM, UGA), Yoann Weber (Université de Limoges), and Hamza Chouh (CEA Saclay - Université de Lyon).
- Remi Ronfard was a reader (rapporteur) for the PhD thesis of Fabio Zund, Augmented reality storytelling, ETH Zurich, October 2016.
- Stefanie Hahmann was a reviewer (rapporteur) for the PhD thesis of Florian Canezin (Univ. Toulouse), Hoang Ha Nguyen (Université Aix-Marseille) and Ngels Cervero (UPC Universitat Politènica de Catalunya, Barcelona).
- Jean-Claude Léon was reviewer (apporteur) for the PhD thesis of Lei Zhang (Ecole Centrale Marseille)

8.3. Popularization

Marie-Paule Cani

- “Façonner l’Imaginaire…”: Towards the Expressive Design of Animated Virtual Worlds “Imagination Week de l’ESSEC, Paris, Janvier 2016.
- Formes, mouvements, et mondes virtuels… Quel média pour façonner l’imaginaire ? Forum des savoirs, Rouen, 2016. Exposé également donné à l’Institut de Biologie de Paris VI, octobre 2016.
- participation to a Round Table within the conference:“Mathématiques Oxygène du Numérique”, Paris, November 2016.

Damien Rohmer gave a presentation on

- Researches and applications in Computer Graphics to ENS Lyon students.
- Scientific image production to mathematiciens scientists at the MMI (Maison des Mathématiques et de l’Informatique) in Lyon.
- Garment and developable surface modeling at the R3iLab (Réseau innovation immatérielle pour l’industrie).

Rémi Ronfard

- Eye tracking and the arts. Invited talk at Experimenta, Grenoble, October 2016.
- Artificial Intelligence and the arts. Invited talk at Atelier Arts et Science, CEA/Hexagone, Grenoble, October 2016.

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[5] C. SCHRECK, D. ROHMER, S. HAHMANN, M.-P. CANI, S. JIN, C. WANG, J.-F. BLOCH.*Non-smooth developable geometry for interactively animating paper crumpling*, in "ACM Transactions on Graphics", December 2015, vol. 35, n^o^ 1 [*DOI :* 10.1145/2829947.2829948], https://hal.inria.fr/hal-01202571.

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[8] C. SCHRECK.*Interactive Deformation of Virtual Paper*, Universite Grenoble Alpes, October 2016, https://hal.inria.fr/tel-01427555.

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[9] A. CARLIER, K. LEONARD, S. HAHMANN, G. MORIN, M. COLLINS.*The 2D shape structure dataset: A user annotated open access database*, in "Computers and Graphics", 2016, vol. 58, p. 23-30 [*DOI :* 10.1016/J.CAG.2016.05.009], https://hal.inria.fr/hal-01322964.

[10] G. CORDONNIER, J. BRAUN, M.-P. CANI, B. BENES, E. GALIN, A. PEYTAVIE, E. GUÉRIN.*Large Scale Terrain Generation from Tectonic Uplift and Fluvial Erosion*, in "Computer Graphics Forum (Proc. EUROGRAPHICS 2016)", 2016, https://hal.inria.fr/hal-01262376.

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International Conferences with Proceedings

[16] A. BARBULESCU, R. RONFARD, G. BAILLY.*Characterization of Audiovisual Dramatic Attitudes*, in "17th Annual Conference of the International Speech Communication Association (Interspeech 2016)", San Francisco, United States, September 2016, p. 585-589, https://hal.inria.fr/hal-01337077.

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C. SCHRECK, D. ROHMER, D. L. JAMES, S. HAHMANN, M.-P. CANI.*Real-time sound synthesis for paper material based on geometric analysis*, in "Eurographics/ ACM SIGGRAPH Symposium on Computer Animation (2016)", Zürich, Switzerland, July 2016, https://hal.inria.fr/hal-01333238.

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[30] *Eurographics Workshop on Intelligent Cinematography and Editing*, Eurographics Workshop on Intelligent Cinematography and Editing, The Eurographics Association, Lisbonne, Portugal, May 2016, https://hal.inria.fr/hal-01427243.

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Project-Team MAVERICK

Models and Algorithms for Visualization and Rendering

IN COLLABORATION WITH: Laboratoire Jean Kuntzmann (LJK)

IN PARTNERSHIP WITH:
CNRS
Institut polytechnique de Grenoble
Université Grenoble Alpes

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Interaction and visualization

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Project-Team MAVERICK

Creation of the Team: 2012 January 01, updated into Project-Team: 2014 January 01

Keywords:

Computer Science and Digital Science:

5.2. - Data visualization
5.5. - Computer graphics
5.5.1. - Geometrical modeling
5.5.2. - Rendering
5.5.3. - Computational photography
5.5.4. - Animation

Other Research Topics and Application Domains:

5.5. - Materials
5.7. - 3D printing
9.2.2. - Cinema, Television
9.2.3. - Video games
9.2.4. - Theater
9.5.6. - Archeology, History

1. Members

Research Scientists

Nicolas Holzschuch [Team leader, Inria, Senior Researcher, HDR]
Fabrice Neyret [CNRS, Senior Researcher, HDR]
Cyril Soler [Inria, Researcher, HDR]

Faculty Members

Georges-Pierre Bonneau [Univ. Grenoble I, Professor]
Joëlle Thollot [INP Grenoble, Professor, HDR]
Romain Vergne [Univ. Grenoble I, Assistant Professor]

PhD Students

Benoit Arbelot [Inria]
Alexandre Bleron [Univ. Grenoble I]
Alban Fichet [Inria]
Guillaume Loubet [Univ. Grenoble I]
Jeremy Wambecke [Univ. Grenoble I,]
Benoit Zupancic [Inria, until Mar 2016, granted by ANR ALTA project]
Léo Allemand-Giorgis [Univ. Grenoble I, until June 16]

Post-Doctoral Fellow

Beibei Wang [Inria]

Visiting Scientist

Girijanandan Nucha [Granted by Inria]

Administrative Assistant

Diane Courtiol [Inria]

Others

Jean-Dominique Gascuel [Digisens SA. External collaborator]
Santiago Montesdeoca [Inria Internship, from Oct 2016]
Christopher Dubois [Inria, Internship, from Apr 2016 until Sep 2016]
Hugo Frezat [Inria, Internship, from May 2016 until Jul 2016]
Yannick Lanier [Inria, Internship, Feb 2016]
Thomas Lerchundi [Inria, Internship, from Feb 2016 until Jun 2016]

2. Overall Objectives

2.1. Overall Objectives

Computer-generated pictures and videos are now ubiquitous: both for leisure activities, such as special effects in motion pictures, feature movies and video games, or for more serious activities, such as visualization and simulation.

Maverick was created as a research team in January 2012 and upgraded as a research project in January 2014. We deal with image synthesis methods. We place ourselves at the end of the image production pipeline, when the pictures are generated and displayed (see figure 1). We take many possible inputs: datasets, video flows, pictures and photographs, (animated) geometry from a virtual world... We produce as output pictures and videos.

These pictures will be viewed by humans, and we consider this fact as an important point of our research strategy, as it provides the benchmarks for evaluating our results: the pictures and animations produced must be able to convey the message to the viewer. The actual message depends on the specific application: data visualization, exploring virtual worlds, designing paintings and drawings... Our vision is that all these applications share common research problems: ensuring that the important features are perceived, avoiding cluttering or aliasing, efficient internal data representation, etc.

Computer Graphics, and especially Maverick is at the crossroad between fundamental research and industrial applications. We are both looking at the constraints and needs of applicative users and targeting long term research issues such as sampling and filtering.

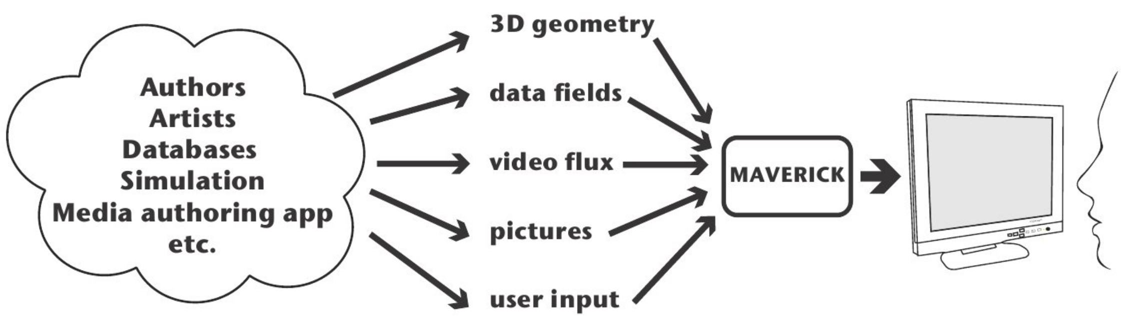

Figure 1. Position of the Maverick research team inside the graphics pipeline.

The Maverick project-team aims at producing representations and algorithms for efficient, high-quality computer generation of pictures and animations through the study of four *Research problems*:

- *Computer Visualization*, where we take as input a large localized dataset and represent it in a way that will let an observer understand its key properties,
- *Expressive Rendering*, where we create an artistic representation of a virtual world,
- *Illumination Simulation*, where our focus is modelling the interaction of light with the objects in the scene.
- *Complex Scenes*, where our focus is rendering and modelling highly complex scenes.

The heart of Maverick is *understanding* what makes a picture useful, powerful and interesting for the user, and designing algorithms to create these pictures.

We will address these research problems through three interconnected approaches:

- working on the *impact* of pictures, by conducting perceptual studies, measuring and removing artefacts and discontinuities, evaluating the user response to pictures and algorithms,
- developing *representations* for data, through abstraction, stylization and simplification,
- developing new methods for *predicting* the properties of a picture (*e.g.* frequency content, variations) and adapting our image-generation algorithm to these properties.

A fundamental element of the Maverick project-team is that the research problems and the scientific approaches are all cross-connected. Research on the *impact* of pictures is of interest in three different research problems: *Computer Visualization*, *Expressive rendering* and *Illumination Simulation*. Similarly, our research on *Illumination simulation* will gather contributions from all three scientific approaches: impact, representations and prediction.

3. Research Program

3.1. Introduction

The Maverick project-team aims at producing representations and algorithms for efficient, high-quality computer generation of pictures and animations through the study of four **research problems**:

- *Computer Visualization* where we take as input a large localized dataset and represent it in a way that will let an observer understand its key properties. Visualization can be used for data analysis, for the results of a simulation, for medical imaging data...
- *Expressive Rendering*, where we create an artistic representation of a virtual world. Expressive rendering corresponds to the generation of drawings or paintings of a virtual scene, but also to some areas of computational photography, where the picture is simplified in specific areas to focus the attention.
- *Illumination Simulation*, where we model the interaction of light with the objects in the scene, resulting in a photorealistic picture of the scene. Research include improving the quality and photorealism of pictures, including more complex effects such as depth-of-field or motion-blur. We are also working on accelerating the computations, both for real-time photorealistic rendering and offline, high-quality rendering.
- *Complex Scenes*, where we generate, manage, animate and render highly complex scenes, such as natural scenes with forests, rivers and oceans, but also large datasets for visualization. We are especially interested in interactive visualization of complex scenes, with all the associated challenges in terms of processing and memory bandwidth.

The fundamental research interest of Maverick is first, *understanding* what makes a picture useful, powerful and interesting for the user, and second *designing* algorithms to create and improve these pictures.

3.2. Research approaches

We will address these research problems through three interconnected research approaches:

3.2.1. Picture Impact

Our first research axis deals with the *impact* pictures have on the viewer, and how we can improve this impact. Our research here will target:

- *evaluating user response:* we need to evaluate how the viewers respond to the pictures and animations generated by our algorithms, through user studies, either asking the viewer about what he perceives in a picture or measuring how his body reacts (eye tracking, position tracking).
- *removing artefacts and discontinuities:* temporal and spatial discontinuities perturb viewer attention, distracting the viewer from the main message. These discontinuities occur during the picture creation process; finding and removing them is a difficult process.

3.2.2. Data Representation

The data we receive as input for picture generation is often unsuitable for interactive high-quality rendering: too many details, no spatial organisation... Similarly the pictures we produce or get as input for other algorithms can contain superfluous details.

One of our goals is to develop new data representations, adapted to our requirements for rendering. This includes fast access to the relevant information, but also access to the specific hierarchical level of information needed: we want to organize the data in hierarchical levels, pre-filter it so that sampling at a given level also gives information about the underlying levels. Our research for this axis include filtering, data abstraction, simplification and stylization.

The input data can be of any kind: geometric data, such as the model of an object, scientific data before visualization, pictures and photographs. It can be time-dependent or not; time-dependent data bring an additional level of challenge on the algorithm for fast updates.

3.2.3. Prediction and simulation

Our algorithms for generating pictures require computations: sampling, integration, simulation... These computations can be optimized if we already know the characteristics of the final picture. Our recent research has shown that it is possible to predict the local characteristics of a picture by studying the phenomena involved: the local complexity, the spatial variations, their direction...

Our goal is to develop new techniques for predicting the properties of a picture, and to adapt our image-generation algorithms to these properties, for example by sampling less in areas of low variation.

Our research problems and approaches are all cross-connected. Research on the *impact* of pictures is of interest in three different research problems: *Computer Visualization*, *Expressive rendering* and *Illumination Simulation*. Similarly, our research on *Illumination simulation* will use all three research approaches: impact, representations and prediction.

3.3. Cross-cutting research issues

Beyond the connections between our problems and research approaches, we are interested in several issues, which are present throughout all our research:

sampling is an ubiquitous process occurring in all our application domains, whether photorealistic rendering (*e.g.* photon mapping), expressive rendering (*e.g.* brush strokes), texturing, fluid simulation (Lagrangian methods), etc. When sampling and reconstructing a signal for picture generation, we have to ensure both coherence and homogeneity. By *coherence*, we mean not introducing spatial or temporal discontinuities in the reconstructed signal. By *homogeneity*, we mean that samples should be placed regularly in space and time. For a time-dependent signal, these requirements are conflicting with each other, opening new areas of research.

filtering is another ubiquitous process, occuring in all our application domains, whether in realistic rendering (*e.g.* for integrating height fields, normals, material properties), expressive rendering (*e.g.* for simplifying strokes), textures (through non-linearity and discontinuities). It is especially relevant when we are replacing a signal or data with a lower resolution (for hierarchical representation); this involves filtering the data with a reconstruction kernel, representing the transition between levels.

performance and scalability are also a common requirement for all our applications. We want our algorithms to be usable, which implies that they can be used on large and complex scenes, placing a great importance on scalability. For some applications, we target interactive and real-time applications, with an update frequency between 10 Hz and 120 Hz.

coherence and continuity in space and time is also a common requirement of realistic as well as expressive models which must be ensured despite contradictory requirements. We want to avoid flickering and aliasing.

animation: our input data is likely to be time-varying (*e.g.* animated geometry, physical simulation, time-dependent dataset). A common requirement for all our algorithms and data representation is that they must be compatible with animated data (fast updates for data structures, low latency algorithms...).

3.4. Methodology

Our research is guided by several methodological principles:

Experimentation: to find solutions and phenomenological models, we use experimentation, performing statistical measurements of how a system behaves. We then extract a model from the experimental data.

Validation: for each algorithm we develop, we look for experimental validation: measuring the behavior of the algorithm, how it scales, how it improves over the state-of-the-art... We also compare our algorithms to the exact solution. Validation is harder for some of our research domains, but it remains a key principle for us.

Reducing the complexity of the problem: the equations describing certain behaviors in image synthesis can have a large degree of complexity, precluding computations, especially in real time. This is true for physical simulation of fluids, tree growth, illumination simulation... We are looking for *emerging phenomena* and *phenomenological models* to describe them (see framed box “Emerging phenomena”). Using these, we simplify the theoretical models in a controlled way, to improve user interaction and accelerate the computations.

Transferring ideas from other domains: Computer Graphics is, by nature, at the interface of many research domains: physics for the behavior of light, applied mathematics for numerical simulation, biology, algorithmics... We import tools from all these domains, and keep looking for new tools and ideas.

Develop new fondamental tools: In situations where specific tools are required for a problem, we will proceed from a theoretical framework to develop them. These tools may in return have applications in other domains, and we are ready to disseminate them.

Collaborate with industrial partners: we have a long experiment of collaboration with industrial partners. These collaborations bring us new problems to solve, with short-term or medium-term transfert opportunities. When we cooperate with these partners, we have to find *what they need*, which can be very different from *what they want*, their expressed need.

4. Application Domains

4.1. Application Domains

The natural application domain for our research is the production of digital images, for example for movies and special effects, virtual prototyping, video games...

Our research have also been applied to tools for generating and editing images and textures, for example generating textures for maps.

Our current application domains are:

- Offline and real-time rendering in movie special effects and video games;
- Virtual prototyping;
- Scientific visualization;
- Content modeling and generation (e.g. generating texture for video games, capturing reflectance properties, etc);
- Image creation and manipulation.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Presentations at Siggraph

The paper "Flow-Guided Warping for Image-Based Shape Manipulation" co-authored by Romain Vergnes and Georges-Pierre Bonneau was presented at Siggraph 2016 [3]. The paper is completed by an open-source software running on mobile phones that allow interactive manipulation of images (http://bonneau.meylan.free.fr/ShwarpIt/ShwarpIt.html). See sections 6.7 and 7.1.3.

6. New Software and Platforms

6.1. Diffusion curves

KEYWORDS: Vector-based drawing - Shading
FUNCTIONAL DESCRIPTION Diffusion Curves is a vector-based design tool for creating complex shaded images. This prototype is composed of the Windows binary, along with the required shader programs (ie. in source code).

- Participants: Joelle Thollot, Pascal Barla, Adrien Bousseau and Alexandrina Orzan
- Partners: CNRS - INP Grenoble - LJK - Université Joseph-Fourier
- Contact: Joelle Thollot
- URL: http://maverick.inria.fr/Publications/2008/OBWBTS08/index.php

6.2. GRATIN

FUNCTIONAL DESCRIPTION Gratin is a node-based compositing software for creating, manipulating and animating 2D and 3D data. It uses an internal direct acyclic multi-graph and provides an intuitive user interface that allows to quickly design complex prototypes. Gratin has several properties that make it useful for researchers and students. (1) it works in real-time: everything is executed on the GPU, using OpenGL, GLSL and/or Cuda. (2) it is easily programmable: users can directly write GLSL scripts inside the interface, or create new C++ plugins that will be loaded as new nodes in the software. (3) all the parameters can be animated using keyframe curves to generate videos and demos. (4) the system allows to easily exchange nodes, group of nodes or full pipelines between people.

- Participants: Pascal Barla and Romain Vergne
- Partner: UJF
- Contact: Romain Vergne
- URL: http://gratin.gforge.inria.fr/

6.3. GigaVoxels

FUNCTIONAL DESCRIPTION Gigavoxel is a software platform which goal is the real-time quality rendering of very large and very detailed scenes which couldn't fit memory. Performances permit showing details over deep zooms and walk through very crowdy scenes (which are rigid, for the moment). The principle is to represent data on the GPU as a Sparse Voxel Octree which multiscale voxels bricks are produced on demand only when necessary and only at the required resolution, and kept in a LRU cache. User defined producer lays accross CPU and GPU and can load, transform, or procedurally create the data. Another user defined function is called to shade each voxel according to the user-defined voxel content, so that it is user choice to distribute the appearance-making at creation (for faster rendering) or on the fly (for storageless thin procedural details). The efficient rendering is done using a GPU differential cone-tracing using the scale corresponding to the 3D-MIPmapping LOD, allowing quality rendering with one single ray per pixel. Data is produced in case of cache miss, and thus only whenever visible (accounting for view frustum and occlusion). Soft-shadows and depth-of-field is easily obtained using larger cones, and are indeed cheaper than unblurred rendering. Beside the representation, data management and base rendering algorithm themself, we also worked on realtime light transport, and on quality prefiltering of complex data. Ongoing researches are addressing animation. GigaVoxels is currently used for the quality real-time exploration of the detailed galaxy in ANR RTIGE. Most of the work published by Cyril Crassin (and al.) during his PhD (see http://maverick.inria.fr/Members/Cyril.Crassin/) is related to GigaVoxels. GigaVoxels is available for Windows and Linux under the BSD-3 licence.

- Participants: Cyril Crassin, Fabrice Neyret, Prashant Goswami, Jérémy Sinoir, Pascal Guehl and Eric Heitz
- Contact: Fabrice Neyret
- URL: http://gigavoxels.inrialpes.fr

6.4. HQR

High Quality Renderer
KEYWORDS: Lighting simulation
FUNCTIONAL DESCRIPTION

HQR is a global lighting simulation platform. HQR software is based on the photon mapping method which is capable of solving the light balance equation and of giving a high quality solution. Through a graphical user interface, it reads X3D scenes using the X3DToolKit package developed at Maverick, it allows the user to tune several parameters, computes photon maps, and reconstructs information to obtain a high quality solution. HQR also accepts plugins which considerably eases the developpement of new algorithms for global illumination, those benefiting from the existing algorithms for handling materials, geometry and light sources.

- Participant: Cyril Soler
- Contact: Cyril Soler
- URL: http://artis.imag.fr/~Cyril.Soler/HQR

6.5. MobiNet

KEYWORDS: Co-simulation - Education - Programmation
FUNCTIONAL DESCRIPTION The MobiNet software allows for the creation of simple applications such as video games, virtual physics experiments or pedagogical math illustrations. It relies on an intuitive graphical interface and language which allows the user to program a set of mobile objects (possibly through a network). It is available in public domain for Linux,Windows and MacOS.

- Participants: Fabrice Neyret, Sylvain Lefebvre, Samuel Hornus, Joelle Thollot and Franck Hetroy-Wheeler
- Partners: Cies - CNRS - GRAVIR - INP Grenoble - Inria - IREM - LJK
- Contact: Fabrice Neyret
- URL: http://mobinet.imag.fr/index.en.html

6.6. PROLAND

PROcedural LANDscape

KEYWORDS: Real time - 3D - Realistic rendering - Masses of data - Atmosphere - Ocean

FUNCTIONAL DESCRIPTION The goal of this platform is the real-time quality rendering and editing of large landscapes. All features can work with planet-sized terrains, for all viewpoints from ground to space. Most of the work published by Eric Bruneton and Fabrice Neyret (see http://evasion.inrialpes.fr/Membres/Eric.Bruneton/) has been done within Proland and integrated in the main branch. Proland is available under the BSD-3 licence.

- Participants: Antoine Begault, Eric Bruneton, Guillaume Piolet and Fabrice Neyret
- Contact: Fabrice Neyret
- URL: https://proland.inrialpes.fr/

6.7. ShwarpIt

KEYWORD: Warping

FUNCTIONAL DESCRIPTION ShwarpIt is a simple mobile app that allows you to manipulate the perception of shapes in images. Slide the ShwarpIt slider to the right to make shapes appear rounder. Slide it to the left to make shapes appear more flat. The Scale slider gives you control on the scale of the warping deformation.

- Contact: Georges-Pierre Bonneau
- URL: http://bonneau.meylan.free.fr/ShwarpIt/ShwarpIt.html

6.8. VRender

FUNCTIONAL DESCRIPTION The VRender library is a simple tool to render the content of an OpenGL window to a vectorial device such as Postscript, XFig, and soon SVG. The main usage of such a library is to make clean vectorial drawings for publications, books, etc. In practice, VRender replaces the z-buffer based hidden surface removal of OpenGL by sorting the geometric primitives so that they can be rendered in a back-to-front order, possibly cutting them into pieces to solve cycles. VRender is also responsible for the vectorial snapshot feature of the QGLViewer library.

- Participant: Cyril Soler
- Contact: Cyril Soler
- URL: http://artis.imag.fr/Software/VRender/

6.9. X3D TOOLKIT

X3D Development platform

FUNCTIONAL DESCRIPTION X3DToolkit is a library to parse and write X3D files, that supports plugins and extensions.

- Participants: Gilles Debunne and Yannick Le Goc
- Contact: Cyril Soler
- URL: http://artis.imag.fr/Software/X3D/

6.10. libylm

LibYLM

KEYWORD: Spherical harmonics

FUNCTIONAL DESCRIPTION This library implements spherical and zonal harmonics. It provides the means to perform decompositions, manipulate spherical harmonic distributions and provides its own viewer to visualize spherical harmonic distributions. It is available for linux on the Launchpad PPA of the author.

- Author: Cyril Soler
- Contact: Cyril Soler
- URL: https://launchpad.net/~csoler-users/+archive/ubuntu/ylm

7. New Results

7.1. Computer-aided image manipulation

7.1.1. Automatic lighting design from photographic rules

Participants: Jérémy Wambecke, Romain Vergne, Georges-Pierre Bonneau, Joëlle Thollot.

Figure 2. Our lighting setup produces realistic images for any kind of opaque surfaces, where shapes of objects are always properly conveyed.

Lighting design is crucial in 3D scenes modeling for its ability to provide cues to understand the objects shape. However a lot of time, skills, trials and errors are required to obtain a desired result. Existing automatic lighting methods for conveying the shape of 3D objects are based either on costly optimizations or on non-realistic shading effects. Also they do not take the material information into account. In this work, we propose a new method that automatically suggests a lighting setup to reveal the shape of a 3D model, taking into account its material and its geometric properties (see Figure 2). Our method is independent from the rendering algorithm. It is based on lighting rules extracted from photography books, applied through a fast and simple geometric analysis. We illustrate our algorithm on objects having different shapes and materials, and we show by both visual and metric evaluation that it is comparable to optimization methods in terms of lighting setups quality. Thanks to its genericity our algorithm could be integrated in any rendering pipeline to suggest appropriate lighting. It has been published in WICED'2016 [8].

7.1.2. Automatic Texture Guided Color Transfer and Colorization

Participants: Benoit Arbelot, Romain Vergne, Thomas Hurtut, Joëlle Thollot.

This work targets two related color manipulation problems: *Color transfer* for modifying an image colors and *colorization* for adding colors to a greyscale image. Automatic methods for these two applications propose to modify the input image using a reference that contains the desired colors. Previous approaches usually do not target both applications and suffer from two main limitations: possible misleading associations between input and reference regions and poor spatial coherence around image structures. In this work, we propose a unified framework that uses the textural content of the images to guide the color transfer and colorization (see Figure 3). Our method introduces an edge-aware texture descriptor based on region covariance, allowing for local color transformations. We show that our approach is able to produce results comparable or better than state-of-the-art methods in both applications. It has been published in Expressive'2016 [4] and an extended version has been submitted to C&G.

Color transfer Colorization

Figure 3. Our framework allows for automatic local color transfer (left) and colorization (right) based on textural properties.

7.1.3. Flow-Guided Warping for Image-Based Shape Manipulation

Participants: Romain Vergne, Pascal Barla, Georges-Pierre Bonneau, Roland W. Fleming.

(a) Input image - ©Expertissim (b) Shape sharpening (c) Shape rounding

Figure 4. Our warping technique takes as input (a) a single image (Jules Bennes, after Barye: "walking lion") and modifies its perceived surface shape, either making it sharper in (b) or rounder in (c).

We present an interactive method that manipulates perceived object shape from a single input color image thanks to a warping technique implemented on the GPU. The key idea is to give the illusion of shape sharpening or rounding by exaggerating orientation patterns in the image that are strongly correlated to surface curvature. We build on a growing literature in both human and computer vision showing the importance of orientation patterns in the communication of shape, which we complement with mathematical relationships and a statistical image analysis revealing that structure tensors are indeed strongly correlated to surface shape features. We then rely on these correlations to introduce a flow-guided image warping algorithm, which in effect exaggerates orientation patterns involved in shape perception. We evaluate our technique by 1) comparing it to ground truth shape deformations, and 2) performing two perceptual experiments to assess its effects. Our algorithm produces convincing shape manipulation results on synthetic images and photographs, for various materials and lighting environments (see Figure 4). This work has been published in ACM TOG 2016 [3].

7.1.4. Local Shape Editing at the Compositing Stage

Participants: Carlos Jorge Zubiaga Peña, Gael Guennebaud, Romain Vergne, Pascal Barla.

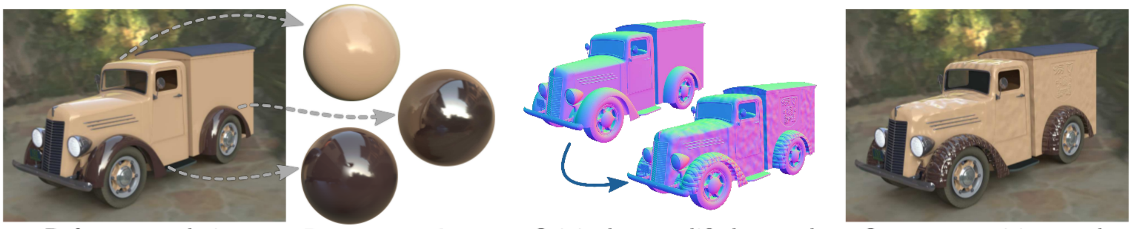

Figure 5. Our method permits to modify surface shape by making use of the shading and auxiliary buffers output by modern renderers. We first reconstruct shading environments for each object/material combination of the Truck scene, relying on normal and shading buffers. When normals are then modified by the compositing artist, the color image is recomposited in real-time, enabling interactive exploration. Our method reproduces inter-reflections between objects, as seen when comparing the reconstructed environments for rear and front mudguards.

Modern compositing software permit to linearly recombine different 3D rendered outputs (e.g., diffuse and reflection shading) in post-process, providing for simple but interactive appearance manipulations. Renderers also routinely provide auxiliary buffers (e.g., normals, positions) that may be used to add local light sources or depth-of-field effects at the compositing stage. These methods are attractive both in product design and movie production, as they allow designers and technical directors to test different ideas without having to re-render an entire 3D scene. We extend this approach to the editing of local shape: users modify the rendered normal buffer, and our system automatically modifies diffuse and reflection buffers to provide a plausible result (see Figure 5). Our method is based on the reconstruction of a pair of diffuse and reflection prefiltered environment maps for each distinct object/material appearing in the image. We seamlessly combine the reconstructed buffers in a recompositing pipeline that works in real-time on the GPU using arbitrarily modified normals. This work has been published in EGSR (EI & I) 2016 [13].

7.1.5. Map Style Formalization: Rendering Techniques Extension for Cartography

Participants: Hugo Loi, Benoit Arbelot, Romain Vergne, Joëlle Thollot.

Cartographic design requires controllable methods and tools to produce maps that are adapted to users' needs and preferences. The formalized rules and constraints for cartographic representation come mainly from the conceptual framework of graphic semiology. Most current Geographical Information Systems (GIS) rely on the Styled Layer Descriptor and Semiology Encoding (SLD/SE) specifications which provide an XML schema describing the styling rules to be applied on geographic data to draw a map. Although this formalism is relevant for most usages in cartography, it fails to describe complex cartographic and artistic styles. In order to overcome these limitations, we propose an extension of the existing SLD/SE specifications to manage extended map stylizations, by the means of controllable expressive methods. Inspired by artistic and cartographic sources (Cassini maps, mountain maps, artistic movements, etc.), we propose to integrate into our system three main expressive methods: linear stylization, patch-based region filling and vector texture generation. We demonstrate how our pipeline allows to personalize map rendering with expressive methods in several examples. This work is the result of the MAPSTYLE ANR and has been published at Expressive 20016 [5].

7.2. Illumination Simulation and Materials

7.2.1. A Physically-Based Reflectance Model Combining Reflection and Diffraction

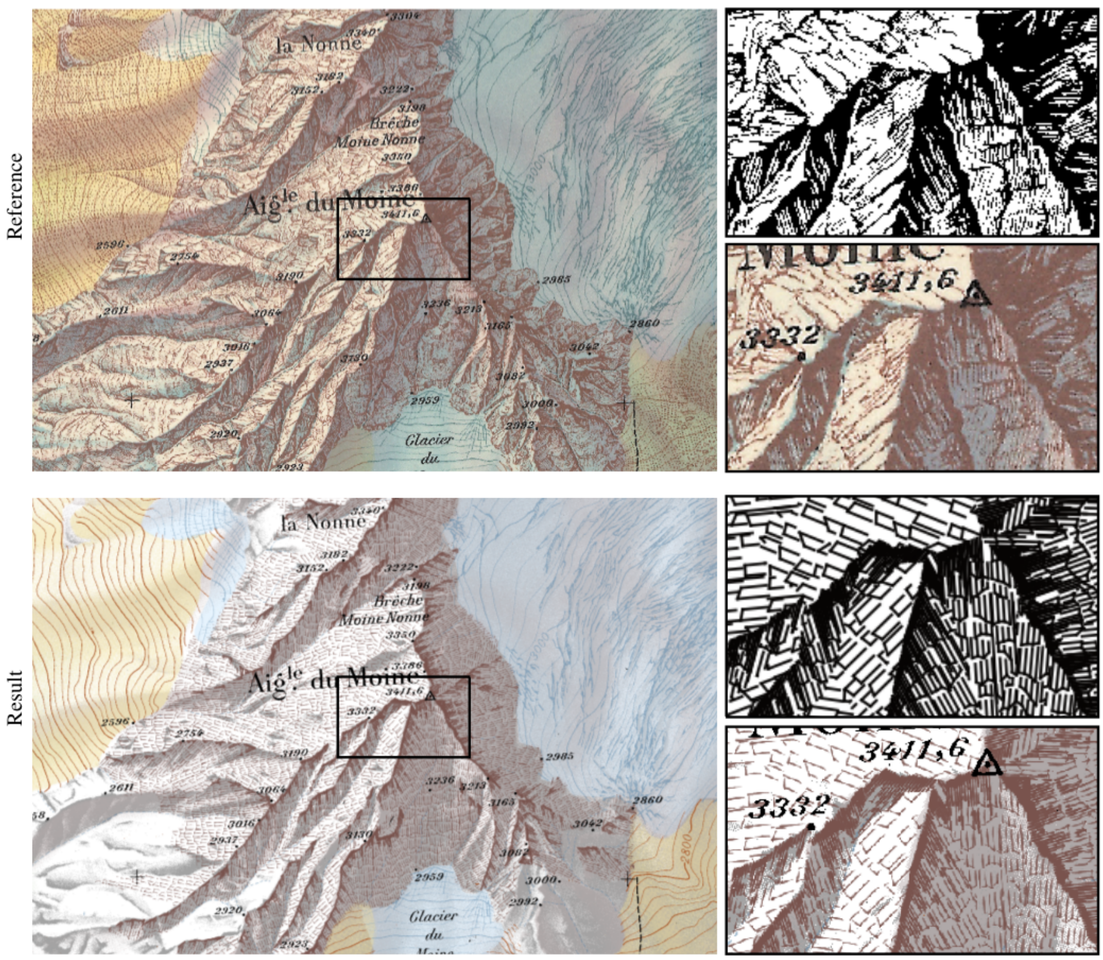

Figure 6. Reference and Resulting Mountain map "Aiguille du Moine", 1:10k scale: extracts of reference (first line) and resulting rocky areas (second line): on the right, zooms on, first the hatching primitives, second the stylized same ones. For a fair comparison, we provide resulting map at a resolution similar to the reference map.

Participant: Nicolas Holzschuch.

Reflectance properties express how objects in a virtual scene interact with light; they control the appearance of the object: whether it looks shiny or not, whether it has a metallic or plastic appearance. Having a good reflectance model is essential for the production of photo-realistic pictures. Measured reflectance functions provide high realism at the expense of memory cost. Parametric models are compact, but finding the right parameters to approximate measured reflectance can be difficult. Most parametric models use a model of the surface micro-geometry to predict the reflectance at the macroscopic level. We have shown that this micro-geometry causes two different physical phenomena: reflection and diffraction. Their relative importance is connected to the surface roughness. Taking both phenomena into account, we developped a new reflectance model that is compact, based on physical properties and provides a good approximation of measured reflectance (See Figure 7).

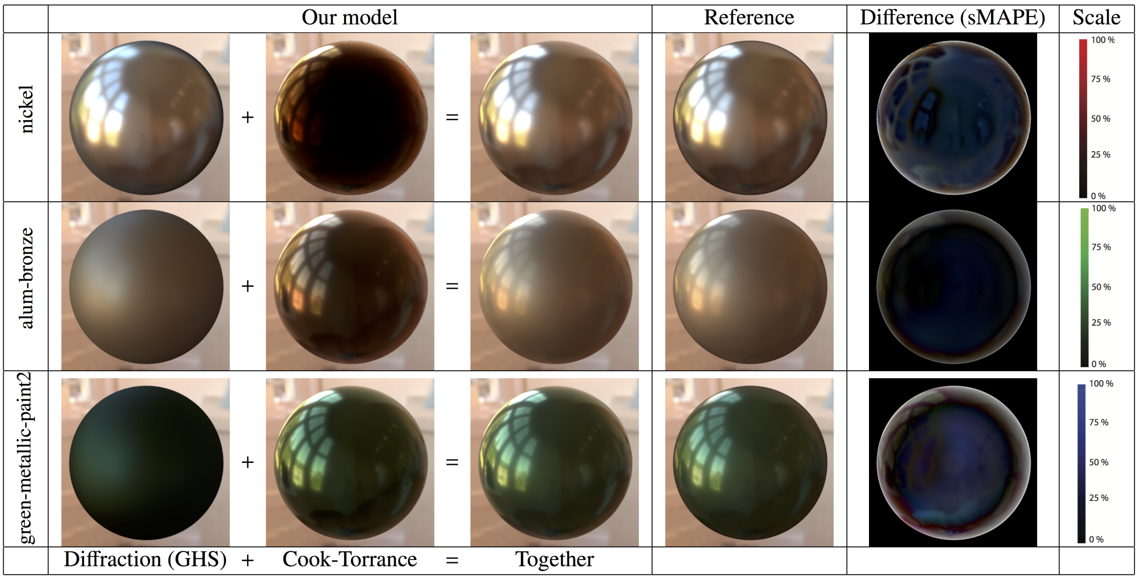

Figure 7. Surface micro-geometry contributes to its visible aspect (material reflectance). Two physical phenomena are acting together: reflection on micro-facets and diffraction. Our reflectance model combines them, with the proper energy repartition between them. The importance of diffraction depends on the roughness of the material. Even when it it relatively small, as for `green-metallic-paint2`, it has a significant impact of the aspect of the material. Our model explains even a very difficult material like `alum-bronze` (middle row) as a single material.

7.2.2. A Robust and Flexible Real-Time Sparkle Effect

Participant: Beibei Wang.

We present a fast and practical procedural sparkle effect for snow and other sparkly surfaces which we integrated into a recent video game. Following from previous work, we generate the sparkle glints by intersecting a jittered 3D grid of sparkle seed points with the rendered surface. By their very nature, the sparkle effect consists of high frequencies which must be dealt with carefully to ensure an anti-aliased and noise free result (See Figure 8). We identify a number of sources of aliasing and provide effective techniques to construct a signal that has an appropriate frequency content ready for sampling at pixels at both foreground and background ranges of the scene. This enables artists to push down the sparkle size to the order of 1 pixel and achieve a solid result free from noisy flickering or other aliasing problems, with only a few intuitive tweakable inputs to manage [9].

Figure 8. Two scenes rendered with our sparkle effect

7.2.3. Capturing Spatially Varying Anisotropic Reflectance Parameters using Fourier Analysis

Participants: Nicolas Holzschuch, Alban Fichet.

Reflectance parameters condition the appearance of objects in photorealistic rendering. Practical acquisition of reflectance parameters is still a difficult problem. Even more so for spatially varying or anisotropic materials, which increase the number of samples required. We present an algorithm for acquisition of spatially varying anisotropic materials, sampling only a small number of directions. Our algorithm uses Fourier analysis to extract the material parameters from a sub-sampled signal. We are able to extract diffuse and specular reflectance, direction of anisotropy, surface normal and reflectance parameters from as little as 20 sample directions (See Figure 9). Our system makes no assumption about the stationarity or regularity of the materials, and can recover anisotropic effects at the pixel level. This work has been published at Graphics Interface 2016 [6].

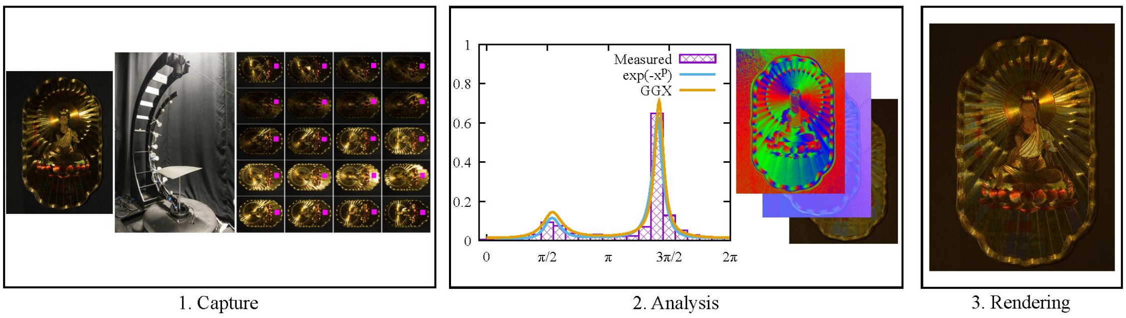

Figure 9. Our acquisition pipeline: first, we place a material sample on our acquisition platform, and acquire photographs with varying incoming light direction. In a second step, we extract anisotropic direction, shading normal, albedo and reflectance parameters from these photographs and store them in texture maps. We later use these texture maps to render new views of the material.

7.2.4. Estimating Local Beckmann Roughness for Complex BSDFs

Participant: Nicolas Holzschuch.

Many light transport related techniques require an analysis of the blur width of light scattering at a path vertex, for instance a Beckmann roughness. Such use cases are for instance analysis of expected variance (and potential biased countermeasures in production rendering), radiance caching or directionally dependent virtual point light sources, or determination of step sizes in the path space Metropolis light transport framework: recent advanced mutation strategies for Metropolis Light Transport, such as Manifold Exploration and Half Vector Space Light Transport employ local curvature of the BSDFs (such as an average Beckmann roughness) at all interactions along the path in order to determine an optimal mutation step size. A single average Beckmann roughness, however, can be a bad fit for complex measured materials and, moreover, such curvature is completely undefined for layered materials as it depends on the active scattering layer. We propose a robust estimation of local curvature for BSDFs of any complexity by using local Beckmann approximations, taking into account additional factors such as both incident and outgoing direction (See Figure 10). This work has been published as a Siggraph 2016 Talk [18].

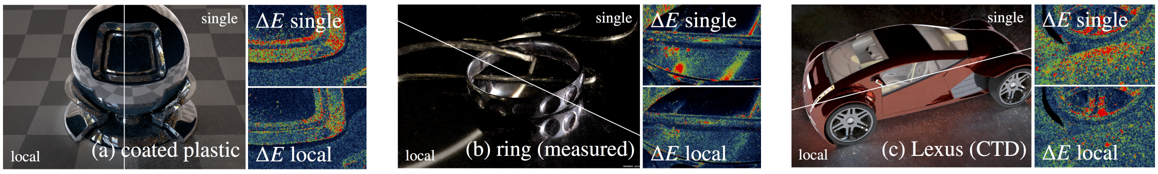

Figure 10. Indirect lighting (exposure in b and c increased for printouts) on three test scenes rendered with different materials: (a) multilayer coated plastic material, (b) measured materials on a ring, (c) CTD material on a car. The insets show difference to reference in CIE'76 ΔE. Top: single Gaussian, bottom: our local Gaussian approximation. We can render both analytic (a, c) and measured materials (b) more robustly because the local Gaussian approximation facilitates more even exploration of path space.

7.2.5. MIC based PBGI

Participant: Beibei Wang.

Point-Based Global Illumination (PBGI) is a popular rendering method in special effects and motion picture productions. The tree-cut computation is in gen eral the most time consuming part of this algorithm, but it can be formulated for efficient parallel execution, in particular regarding wide-SIMD hardware. In this context, we propose several vectorization schemes, namely single, packet and hybrid, to maximize the utilization of modern CPU architectures. Whil e for the single scheme, 16 nodes from the hierarchy are processed for a single receiver in parallel, the packet scheme handles one node for 16 receivers. These two schemes work well for scenes having smooth geometry and diffuse material. When the scene contains high frequency bumps maps and glossy reflection s, we use a hybrid vectorization method. We conduct experiments on an Intel Many Integrated Core architecture and report preliminary results on several sce nes, showing that up to a 3x speedup can be achieved when compared with non-vectorized execution [19].

7.2.6. Point-Based Light Transport for Participating Media with Refractive Boundaries

Participants: Beibei Wang, Jean-Dominique Gascuel, Nicolas Holzschuch.

Illumination effects in translucent materials are a combination of several physical phenomena: absorption and scattering inside the material, refraction at its surface. Because refraction can focus light deep inside the material, where it will be scattered, practical illumination simulation inside translucent materials is difficult. In this paper, we present an a Point-Based Global Illumination method for light transport on translucent materials with refractive boundaries. We start by placing volume light samples inside the translucent material and organising them into a spatial hierarchy. At rendering, we gather light from these samples for each camera ray. We compute separately the samples contributions to single, double and multiple scattering, and add them

(See Figure 11). Our approach provides high-quality results, comparable to the state of the art, with significant speed-ups (from 9× to 60× depending on scene c omplexity) and a much smaller memory footprint [10], [12].

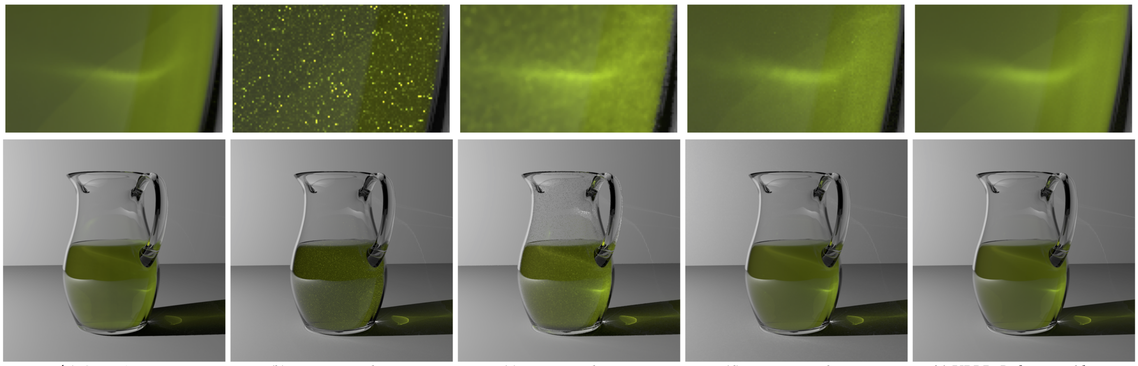

Figure 11. Our algorithm (a), compared with Bi-Directional Path Tracing (BDPT) (b), Photon Mapping with Beam-Radiance Estimate (BRE) (c) and Unified Points, Beams and Paths (UPBP) (d) (e). Our algorithm is up to 60 times faster than UPBP, with similar quality. Material: olive oil, $\alpha = 0.0042, 0.4535, 0.0995$; $\ell = 9.7087, 11.6279, 2.7397$. For this material with low albedo α and large mean-free-path ℓ, low-order scattering effects dominate.

7.3. Complex Scenes

In order to render both efficiently and accurately ultra-detailed large scenes, this approach consists in developing representations and algorithms able to account compactly for the quantitative visual appearance of a regions of space projecting on screen at the size of a pixel.

7.3.1. Appearance pre-filtering

Participants: Guillaume Loubet, Fabrice Neyret.

We address the problem of constructing appearance-preserving level of details (LoDs) of complex 3D models such as trees and propose a hybrid method that combines the strength of mesh and volume representations. Our main idea is to separate macroscopic (i.e. larger than the target spatial resolution) and microscopic (sub-resolution) surfaces at each scale and to treat them differently, because meshes are very efficient at representing macroscopic surfaces while sub-resolution geometry benefit from volumetric approximations. We introduce a new algorithm based on mesh analysis that detects the macroscopic surfaces of a 3D model at a given resolution. We simplify these surfaces with edge collapses and provide a method for pre-filtering their BRDFs parameters. To approximate microscopic details, we use a heterogeneous microflake participating medium and provide a new artifact-free voxelization algorithm that preserves local occlusion. Thanks to our macroscopic surface analysis, our algorithm is fully automatic and can generate seamless LoDs at arbitrarily coarse resolutions for a wide range of 3D models. We validated our method on highly complex geometry and show that appearance is consistent across scales while memory usage and loading times are drasticall y reduced (see Figure 12). This work has been submitted to EG2017.

7.4. Texture Synthesis

7.4.1. Understanding and controlling contrast oscillations in stochastic texture algorithms using Spectrum of Variance

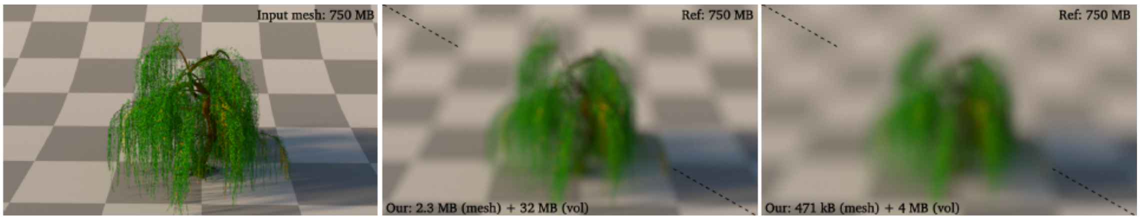

Figure 12. A weeping willow 3D model pre-filtered with our method. Our LoDs use meshes for representing macroscopic surfaces and a volumetric representation to approximate sub-resolution geometry. This approach allows for accurate preservation of the appearance of complex geometry acro ss scales while memory usage is drastic reduced. These images have been rendered with 256spp and a thin lense camera model in Mitsuba

Participants: Fabrice Neyret, Eric Heitz.

We identify and analyze a major issue pertaining to all power-spectrum based texture synthesis algorithms from Fourier synthesis to procedural noise algori thms like Perlin or Gabor noise, namely, the oscillation of contrast (see Figure 13). One of our key contributions is to introduce a simple yet powerf ul descriptor of signals, the Spectrum of Variance (not to be confused with the PSD), which, to our surprise, has never been leveraged before. In this new framework, several issues get easy to understand measure and control, with new handles, as we illustrate. We finally show that fixing oscillation of contra st opens many doors to a more controllable authoring of stochastic texturing. We explore some of the new reachable possibilities such as constrained noise content and bridges towards very different families of look such as cellular patterns, points-like distributions or reaction-diffusion [17].

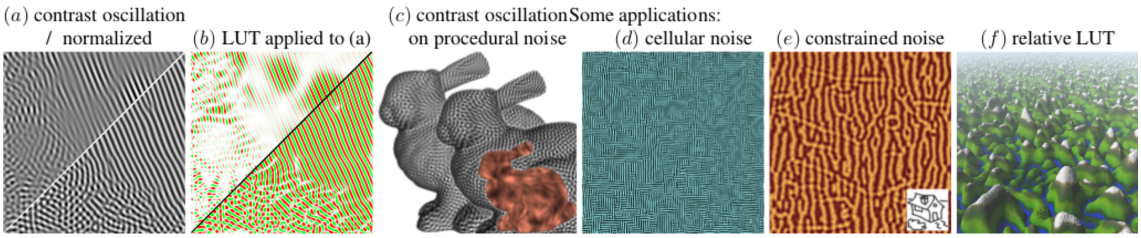

Figure 13. Power-spectrum based texturing algorithms (e.g., Gabor, Fourier synthesis) suffer from unexpected low frequency contrast variations (a,b,c top) even when the spectrum has no low frequency (the contrast field is display in red in (c)). This prevents precise authoring with non- linear transform, like color LUT (b top). Our renormalization method allows to control the stationarity (a,b,c bottom). It also opens many doors for noise authoring such as the generation of reaction-diffusion-like strips and spots (b bottom), cellular-like patterns (d), content constraints (e), or the parame trization of height maps relative to local extrema (f).

7.5. Visualization and Geometric Design

7.5.1. Surfacing Curve Networks with Normal Control

Participant: Georges-Pierre Bonneau.

Members of Maverick involved: Georges-Pierre Bonneau

This is a joint work with team-project IMAGINE (Tibor Stanko and Stefanie Hahmann) at Inria-Grenoble and CEA-Leti (Nathalie Saguin). Recent surface acquisition technologies based on microsensors produce three-space tangential curve data which can be transformed into a network of space curves with surface normals. This work addresses the problem of surfacing an arbitrary closed 3D curve network with given surface normals. Thanks to the normal vector input, the patch finding problem can be solved unambiguously and an initial piecewise smooth triangle mesh is computed. The input normals are propagated throughout the mesh. Together with the initial mesh, the propagated normals are used to compute mean curvature vectors. We compute the final mesh as the solution of a new variational optimization method based on the mean curvature vectors. The intuition behind this original approach is to guide the standard Laplacian-based variational methods by the curvature information extracted from the input normals. The normal input increases shape fidelity and allows to achieve globally smooth and visually pleasing shapes [2], [7]. This is a joint work with team-project IMAGINE (Tibor Stanko and Stefanie Hahmann) at Inria-Grenoble and CEA-Leti (Nathalie Saguin).

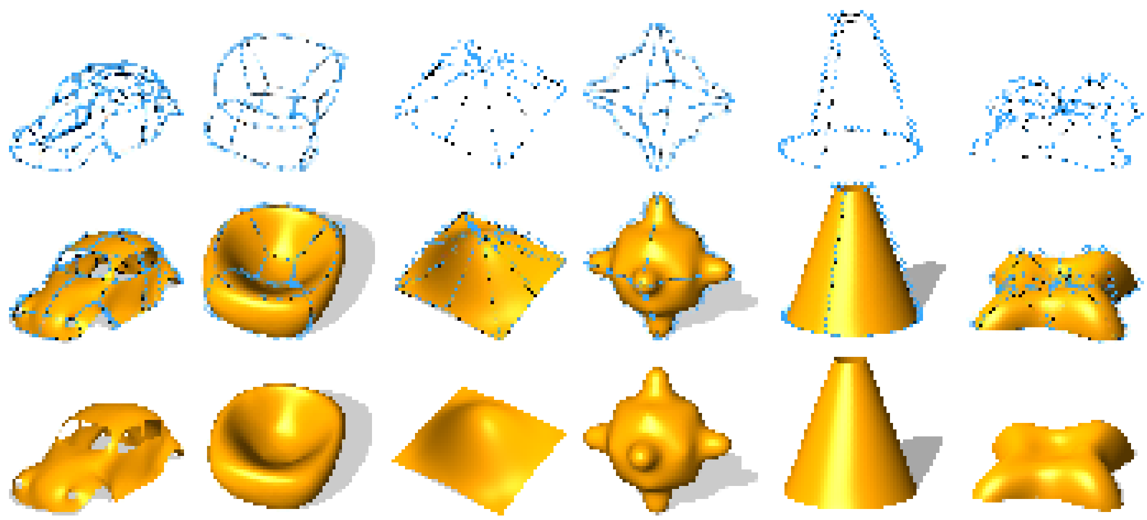

Figure 14. In [2] and [7] we address the problem of surfacing an arbitrary closed 3D curve network with given surface normals (top row). Our interpolating surfaces are visualized with (middle row) and without (bottom row) input curves.

7.5.2. Piecewise polynomial Reconstruction of Scalar Fields from Simplified Morse-Smale Complexes

Participants: Léo Allemand-Giorgis, Georges-Pierre Bonneau.

Morse-Smale (MS) complexes have been proposed to visualize topological features of scalar fields defined on manifold domains. Herein, three main problems have been addressed in the past: (a) efficient computation of the initial combinatorial structure connecting the critical points; (b) simplification of these combinatorial structures; (c) reconstruction of a scalar field in accordance to the simplified Morse-Smale complex. The present work faces the third problem by proposing a novel approach for computing a scalar field coherent with a given simplified MS complex that privileges the use of piecewise polynomial functions. Based on techniques borrowed from shape preserving design in Computer Aided Geometric Design, our method constructs the surface cell by cell using piecewise polynomial curves and surfaces. The benefit and limitations of using polynomials for reconstruction surfaces from topological data are studied in this work [14].

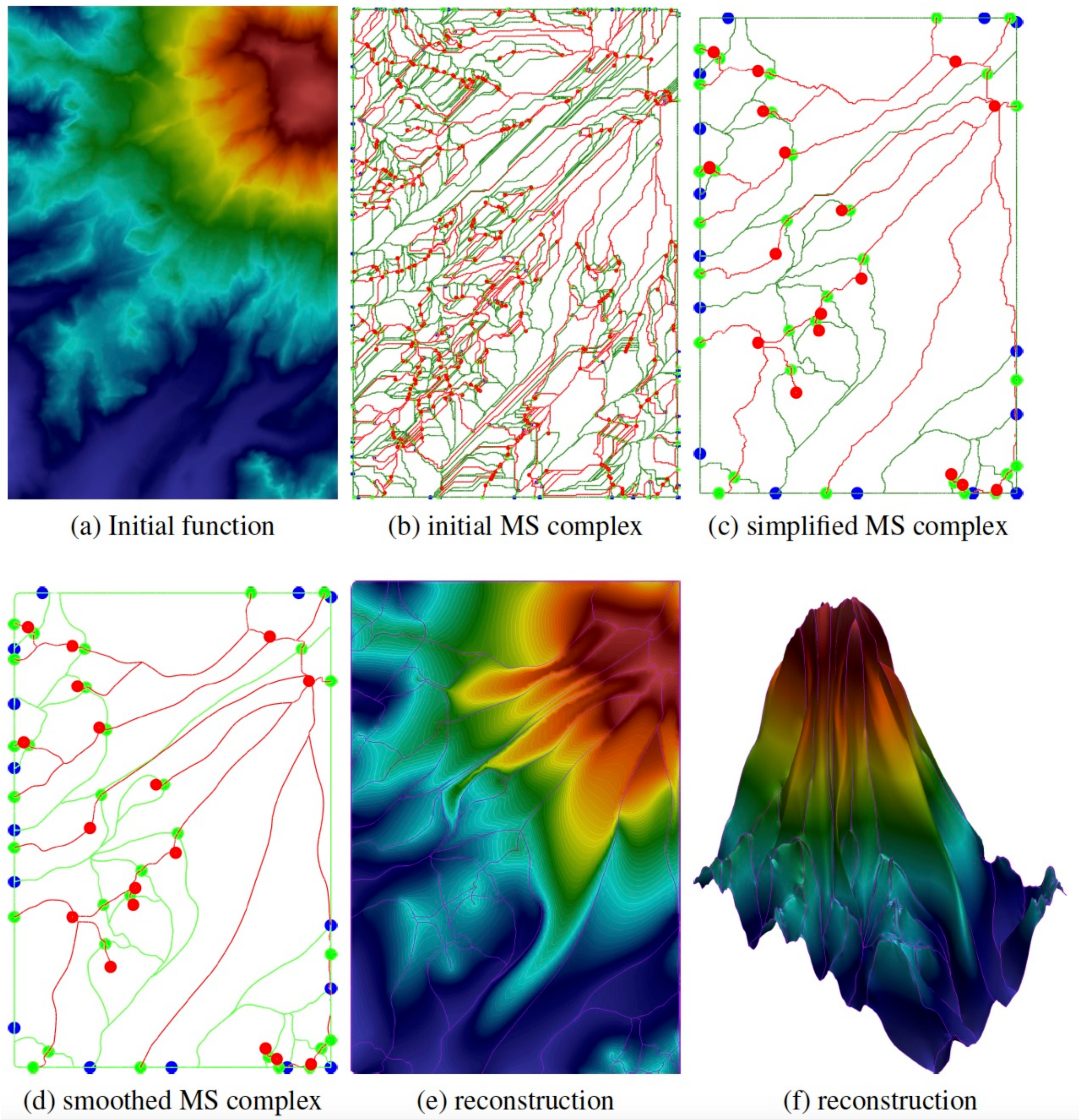

Figure 15. The terrain data set of Mt Rainier (a) has 1931 critical points (b). The simplified Morse-Smale complex with 69 critical points is reconstructed using our methods. The final function approximates the original one, with a topology that is simplified in a controlled-manner.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR BLANC: ALTA

Participants: Nicolas Holzschuch [contact], Cyril Soler.

We are funded by the ANR research program "Blanc" for a joint research project with two other Inria research teams, REVES in Sophia-Antipolis and Manao in Bordeaux. The goal of this project is studying light transport operators for global illumination, both in terms of frequency analysis and dimensional analysis. The grant started in October 2011, for 54 months.

8.1.2. ANR CONTINT: Galaxy/veRTIGE

Participants: Jean-Dominique Gascuel, Nicolas Holzschuch, Fabrice Neyret [contact].

RTIGE stands for Real-Time and Interactive Galaxy for Edutainment. This is an ANR CONTINT (Contents and Interactions) research program, for a joint research project with the EVASION Inria project-team, the GEPI and LERMA research teams at Paris Observatory, and the RSA Cosmos company. The goal of this project is to simulate the quality multi-spectral real-time exploration of the Galaxy with Hubble-like images, based on simulation data, statistical data coming from observation, star catalogs, and procedural amplification for stars and dust clouds distributions. RSA-Cosmos aims at integrating the results in digital planetariums (See Figures 16 and 17). The grant started in December 2010, for 60 months.

8.1.3. ANR CONTINT: MAPSTYLE

Participants: Joëlle Thollot [contact], Hugo Loi.

The MAPSTYLE project aims at exploring the possibilities offered by cartography and expressive rendering to propose original and new cartographic representations. Through this project, we target two types of needs. On the one hand, mapping agencies produce series paper maps with some renderings that are still derived from drawings made by hand 50 years ago: for example, rocky areas in the series TOP25 (to 1/25000) of the French Institut Géographique National (IGN). The rendering of these rocky areas must be automated and its effectiveness retained to meet the requirements of hikers safety. On the other hand, Internet mapping tools allow any user to become a cartographer. However, they provide default styles that cannot be changed (GeoPortal, Google Maps) or they are editable but without any assistance or expertise (CloudMade). In such cases, as in the case of mobile applications, we identify the need to offer users means to design map styles more personalised and more attractive to meet their expectations (decision-making, recreation, etc.) and their tastes. The grant started on October 2012, for 48 months.

8.1.4. ANR: Materials

Participants: Nicolas Holzschuch [contact], Romain Vergne.

Participants: Nicolas Holzschuch [contact], Romain Vergne. We are funded by the ANR for a joint research project on acquisition and restitution of micro-facet based materials. This project is in cooperation with Océ Print Logic technologies, the Museum of Ethnography at the University of Bordeaux and the Manao team at Inria Bordeaux. The grant started in October 2015, for 48 months.

8.2. International Initiatives

8.2.1. Inria International Partners

8.2.1.1. Declared Inria International Partners

Title: “MAIS”: Mathematical Analysis of Image Synthesis

International Partner (Institution - Laboratory - Researcher):

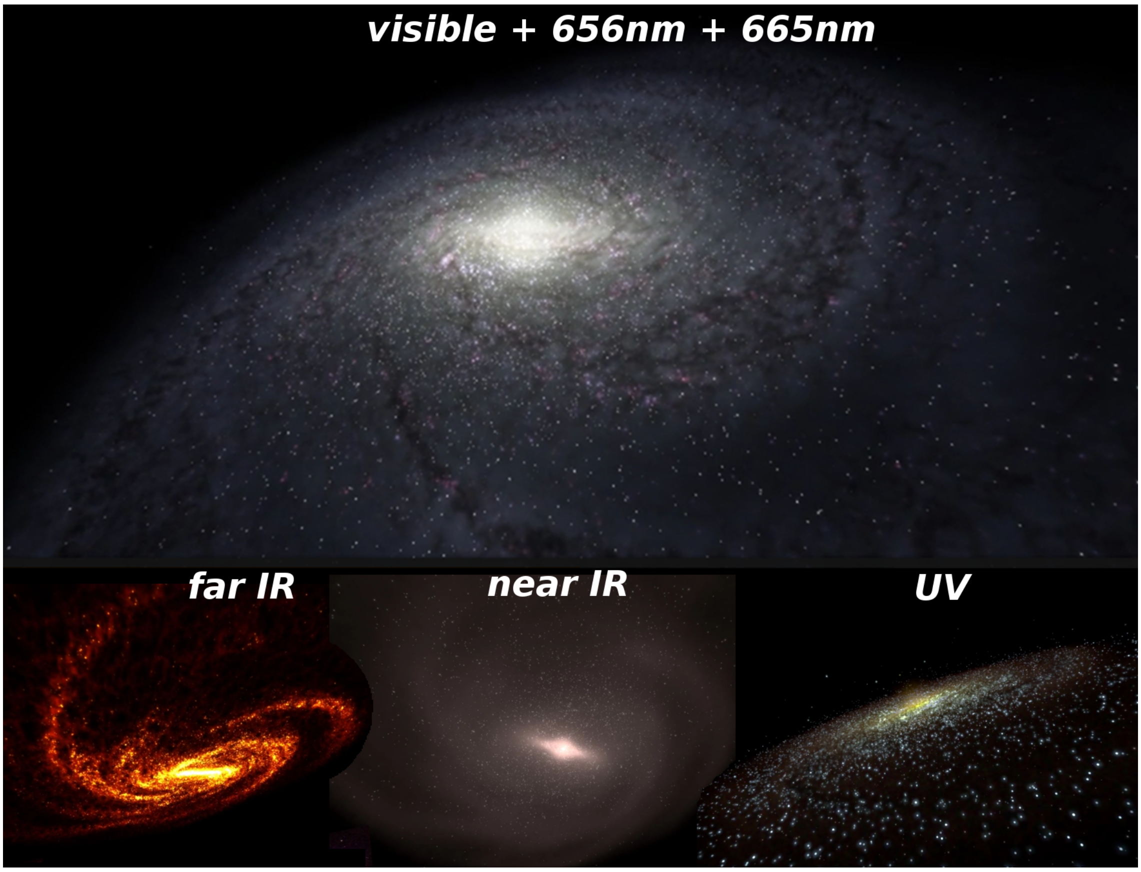

Figure 16. The interactive virtual galaxy integrated in the RSA Cosmos virtual planetarium Sky Explorer, rendered in real-time simulating various Hubble filters in the visible and invisible ranges.

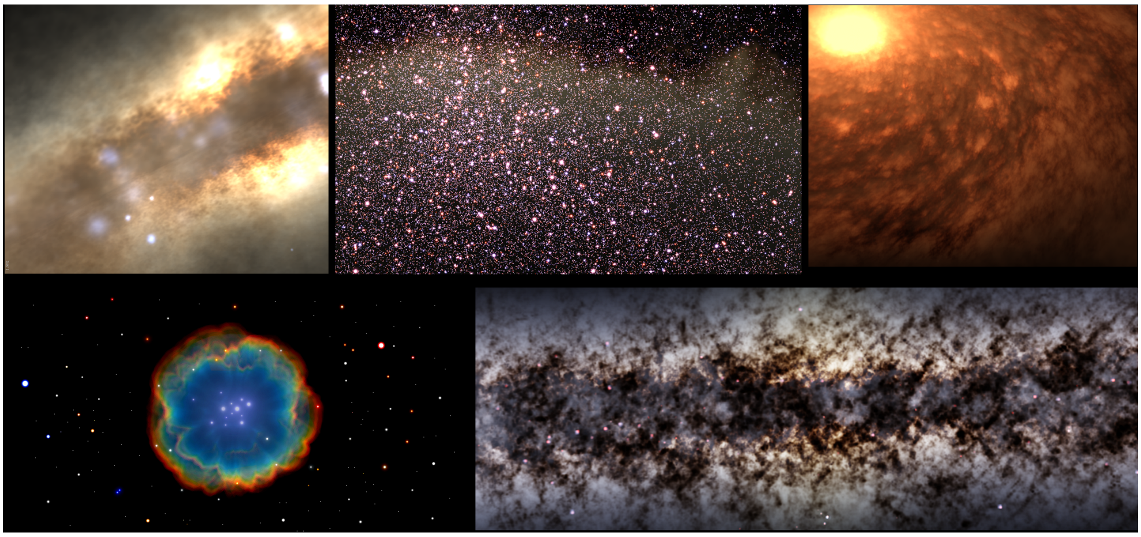

Figure 17. Some detailed views inside the galaxy using the experimental model GigaVoxels-veRTIGE.

University of Montreal (Canada) - Département d'Informatique et Recherche Opérationnelle - Derek Nowrouzezahrai

Duration: 2015 - 2019

Start year: 2015

See also: http://diro.umontreal.ca/accueil/

8.2.1.2. Informal International Partners

We have frequent exchanges and on-going collaborations with Cyril Crassin from nVIDIA-Research, and Eric Heitz, Laurent Belcour and Jonathan Dupuy from Unity-Research.

Maverick is part of the GPU Research Center labeled by nVIDIA at Inria Grenoble. Team contact: Fabrice NEYRET.

8.2.2. Participation in Other International Programs

8.2.2.1. Indo-French Center of Applied Mathematics

Topology-driven Visualization of Scientific Data

Title: Topology-driven Visualization of Scientific Data

International Partner (Institution - Laboratory - Researcher):

IISc Bangalore (India) - Deptartment of Science and Automation - Vijay Natarajan

Duration: Sept 2016 - Sept 2017

One of the greatest scientific challenges of the 21st century is how to master, organize, and extract useful knowledge from the overwhelming flow of information made available by today's data acquisition systems and computing resources. Visualization is the premium means of taking up this challenge. Topological analysis has recently emerged as a powerful class of methods for visualizing data. From the input data, these methods derive combinatorial structures capturing the essential features of the data. The goal of this project is to design new topological structures, study their properties, and develop efficient algorithms to compute them. In order to solve this challenge, we will combine our expertise in Topology for the Indian partner and in Geometric Modeling for the French partner. We plan to develop new geometric models that accurately and intuitively depict the topological combinatorial structures.

8.3. International Research Visitors

8.3.1. Visits of International Scientists

8.3.1.1. Internships

Nucha Girijanandan

Date: June 2016 - Jul 2016

Institution: IIS (India) - Deptartment of Science and Automation

Nucha worked on the project "Topology Driven Visualisation of Scientific Data", along with G-P. Bonneau.

Santiago Montesdeoca

Date: Oct 1st - Dec 31 2016

MAGIC - Nanyang Technological University, Singapore.

Santiago is doing research in watercolor rendering of 3D animation and environments, developing new stylization approaches and enforcing direct stylization frameworks in expressive rendering. His research interests include expressive/non-photorealistic rendering, computer animation, real-time rendering and image processing.

8.3.2. Visits to International Teams

8.3.2.1. Sabbatical programme

Soler Cyril

Date: Aug 2015 - Jul 2016

Institution: Université de Montréal (Canada)

During his stay in Montreal, C.Soler has worked in Collaboration with D.Nowrouzezahrai and P.Poulin (U.of Montreal) and Guillaume Lavoué (Université Lyon-I), on two projects associated to material appearance capture and characterisation. At the time of writing these two projects are actively followed by all partners and publications will be submitted to ACM Transaction on Graphics within a few months. C.Soler has also presented his work in the seminar of the DIRO in October 2015.

8.3.2.2. Research Stays Abroad

Fabrice Neyret

Date: Nov 2015 - Mar 2016

Institution: WETA Digital (New-Zeland)

The content of this collaboration is covered by a NDA.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Selection

9.1.1.1. Member of the Conference Program Committees

- Nicolas Holzschuch was a member of the International Program Committee of the Eurographics Symposium on Rendering (EGSR) 2016, the ACM Symposium on Interactive 3D Graphics (I3D) 2016 and 2017, and SIBGRAPI 2016.
- Cyril Soler was a member of the International Program Committee of the Eurographics Symposium on Rendering (EGSR) 2016
- Joëlle Thollot was a member of the International Program Committee of Expressive'2016

9.1.1.2. Reviewer

All members of the Maverick team work as reviewers for the most prestigious conferences, including Siggrah, Eurographics, the EG symposium on rendering.

9.1.2. Journal

9.1.2.1. Reviewer - Reviewing Activities

All members of the Maverick team work as reviewers for the most prestigious journals, including ACM TOG, IEEE TVCG, etc.

9.1.3. Invited Talks

- Fabrice Neyret, Feb 2, 2016. Victoria University, New-Zeland
- Cyril Soler, Nov, 2015. University of Montreal.

9.1.4. Research Administration

Nicolas Holzschuch is an elected member of Inria Evaluation Committee (CE), an elected member of Inria Comité Technique (CTI) and a reserve member of Inria Scientific Council (CS).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Joëlle Thollot and Georges-Pierre Bonneau are both full Professor of Computer Science. Romain Vergne is an associate professor in Computer Science. They teach general computer science topics at basic and intermediate levels, and advanced courses in computer graphics and visualization at the master levels. Nicolas Holzschuch teaches advanced courses in computer graphics at the Master level. In addition, Romain Vergne teached an advanced course on "perception & graphics" at the spring school of Ôkhra (Roussillon).

- Licence: Joëlle Thollot, Automates finis, 27h, L3 cursus alternance, ENSIMAG, France
- Licence: Joëlle Thollot, Théorie des langages, 18h, L3, ENSIMAG, France
- Master: Joëlle Thollot, Responsable du cursus en alternance, 48h, L3-M1-M2, ENSIMAG, France
- Master: Joëlle Thollot, Tutorat d'apprentis, 48h, L3-M1-M2, ENSIMAG, France

9.2.2. Supervision

- PhD in progress: Guillaume Loubet, *Représentations efficaces de l'apparence sous-pixel*, Université de Grenoble, October 2010, Fabrice Neyret
- PhD defended: Léo Allemand-Giorgis, *Visualisation de champs scalaires guidée par la topologie*, October 2012, Georges-Pierre Bonneau, Stefanie Hahmann. Defense
- PhD in progress : Aarohi Johal, *Algorithmes de génération automatique d'arbres de construction à partir de modèles géométriques CAO B-Rep*, September 2013, Jean-Claude Léon, Georges-Pierre Bonneau, thèse CIFRE EdR R&D.
- PhD in progress : Benoit Arbelot, Etudes statistiques de forme, de matériaux et d'environnement pour la manipulation de l'apparence, October 2013, Joëlle Thollot, Romain Vergne.
- PhD in progress: Alexandre Bleron, Stylization of animated 3D scenes in a painterly style, October 1, 2015, Joëlle Thollot, Romain Vergne, Thomas Hurtut.

9.2.3. Juries

- Nicolas Holzschuch was in the jury for the PhD defenses of Boris Raymond (Bordeaux), Thomas Subileau (Toulouse), and the "HDR" of Lionel Simonot (Physique, Poitiers).
- Joëlle Thollot has been a member of the jury for the PhD of Pierre-Luc Manteaux (Oct 2016 - UGA), Ulysse Vimont (dec 2016 - UGA), Jordane Suarez (dec 2016 - Paris 8).

9.3. Popularization

Every year, “MobiNet” (see section 4.5) classes are conducted with high school pupils of the large Grenoble area to practice initiation and intuition on Computer Science, Maths and Physics. Depending on the year, we have 2 to 4 groups in the scope of INP-Grenoble “Enginneering weeks”, and 0 to 2 groups in the scope of Math-C2+ operations.

10. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] L. ALLEMAND-GIORGIS.*Topology driven visualization of complex data*, Université Grenoble Alpes, June 2016, https://tel.archives-ouvertes.fr/tel-01431658.

Articles in International Peer-Reviewed Journal

[2] T. STANKO, S. HAHMANN, G.-P. BONNEAU, N. SAGUIN-SPRYNSKI.*Surfacing Curve Networks with Normal Control*, in "Computers and Graphics", 2016, https://hal.inria.fr/hal-01342465.

[3] R. VERGNE, P. BARLA, G.-P. BONNEAU, R. FLEMING.*Flow-Guided Warping for Image-Based Shape Manipulation*, in "ACM Transactions on Graphics (TOG)", July 2016 [*DOI :* 10.1145/2897824.2925937], https://hal.inria.fr/hal-01307571.

International Conferences with Proceedings

[4] B. ARBELOT, R. VERGNE, T. HURTUT, J. THOLLOT.*Automatic Texture Guided Color Transfer and Colorization*, in "Expressive 2016", Lisbonne, Portugal, Proceedings of Expressive 2016, May 2016, https://hal.archives-ouvertes.fr/hal-01305596.

[5] S. CHRISTOPHE, B. DUMÉNIEU, J. TURBET, C. HOARAU, N. MELLADO, J. ORY, H. LOI, A. MASSE, B. ARBELOT, R. VERGNE, M. BRÉDIF, T. HURTUT, J. THOLLOT, D. VANDERHAEGHE.*Map Style Formalization: Rendering Techniques Extension for Cartography*, in "Expressive 2016 The Joint Symposium on Computational Aesthetics and Sketch-Based Interfaces and Modeling and Non-Photorealistic Animation and Rendering", Lisbonne, Portugal, P. BÉNARD, H. WINNEMÖLLER (editors), Non-Photorealistic Animation and Rendering, The Eurographics Association, May 2016 [*DOI :* 10.2312/EXP.20161064], https://hal.archives-ouvertes.fr/hal-01317403.

[6] A. FICHET, I. SATO, N. HOLZSCHUCH.*Capturing Spatially Varying Anisotropic Reflectance Parameters using Fourier Analysis*, in "Graphics Interface 2016", Victoria, BC, Canada, June 2016, https://hal.inria.fr/hal-01302120.

[7] T. STANKO, S. HAHMANN, G.-P. BONNEAU, N. SAGUIN-SPRYNSKI.*Smooth Interpolation of Curve Networks with Surface Normals*, in "Eurographics 2016 Short Papers", Lisbonne, Portugal, May 2016 [*DOI :* 10.2312/EGSH.20161005], https://hal.inria.fr/hal-01342487.

[8] J. WAMBECKE, R. VERGNE, G.-P. BONNEAU, J. THOLLOT.*Automatic lighting design from photographic rules*, in "WICED: Eurographics Workshop on Intelligent Cinematography and Editing", Lisbon, Portugal, Eurographics, May 2016 [*DOI :* 10.2312/WICED.20161094], https://hal.inria.fr/hal-01316577.

[9] B. WANG, H. BOWLES.*A Robust and Flexible Real-Time Sparkle Effect*, in "EGSR 2016 E&I", Dublin, Ireland, June 2016, https://hal.inria.fr/hal-01327604.

[10] B. WANG, J.-D. GASCUEL, N. HOLZSCHUCH.*Point-Based Light Transport for Participating Media with Refractive Boundaries*, in "EGSR2016 EI&I", Dublin, Ireland, June 2016, https://hal.inria.fr/hal-01327239.

National Conferences with Proceeding

[11] T. STANKO, S. HAHMANN, G.-P. BONNEAU, N. SAGUIN-SPRYNSKI.*Smooth interpolation of curve networks with surface normals*, in "GTMG 2016 — Actes des Journées du Groupe de Travail en Modélisation Géométrique", Dijon, France, France, March 2016, https://hal.inria.fr/hal-01372958.

Conferences without Proceedings

[12] B. WANG, N. HOLZSCHUCH.*PBVLT: a point based method for volumetric light transport computation in participating media with refractive boundaries*, in "Groupe de Travail Rendu du GDR IG RV", Paris, France, February 2016, https://hal.inria.fr/hal-01273887.

[13] C. J. ZUBIAGA, G. GUENNEBAUD, R. VERGNE, P. BARLA.*Local Shape Editing at the Compositing Stage*, in "EGSR", Dublin, Ireland, June 2016, https://hal.inria.fr/hal-01338414.

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[14] L. ALLEMAND-GIORGIS, G.-P. BONNEAU, S. HAHMANN.*Piecewise polynomial Reconstruction of Scalar Fields from Simplified Morse-Smale Complexes*, in "Topological Data Analysis", H. CARR, C. GARTH, T. WEINKAUF (editors), Springer, 2016, https://hal.inria.fr/hal-01252477.

Research Reports

[15] P. GOSWAMI, F. NEYRET.*Real-time landscape-size convective clouds simulation and rendering*, Inria, February 2016, n^{o} RR-8919, 17, https://hal.inria.fr/hal-01325905.

[16] N. HOLZSCHUCH, R. PACANOWSKI.*A Physically-Based Reflectance Model Combining Reflection and Diffraction*, Inria, October 2016, n^{o} RR-8964, https://hal.inria.fr/hal-01386157.

[17] F. NEYRET, E. HEITZ.*Understanding and controlling contrast oscillations in stochastic texture algorithms using Spectrum of Variance*, LJK / Grenoble University - Inria, May 2016, 8, https://hal.inria.fr/hal-01349134.

Other Publications

[18] N. HOLZSCHUCH, A. KAPLANYAN, J. HANIKA, C. DACHSBACHER.*Estimating Local Beckmann Roughness for Complex BSDFs*, July 2016, ACM Siggraph talks [*DOI :* 10.1145/2897839.2927416], https://hal.inria.fr/hal-01312227.

[19] X. XU, P. WANG, B. WANG, L. WANG, C. TU, X. MENG, T. BOUBEKEUR.*Efficient Point based Global Illumination on Intel MIC Architecture*, May 2016, Eurographics 2016 poster, Poster, https://hal.inria.fr/hal-01316873.

Project-Team MISTIS

Modelling and Inference of Complex and Structured Stochastic Systems

IN COLLABORATION WITH: Laboratoire Jean Kuntzmann (LJK)

IN PARTNERSHIP WITH:
Institut polytechnique de Grenoble

Université Grenoble Alpes

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Optimization, machine learning and statistical methods

Table of contents

Project-Team MISTIS

Creation of the Project-Team: 2008 January 01

Keywords:

Computer Science and Digital Science:

3.1.1. - Modeling, representation
3.1.4. - Uncertain data
3.3.3. - Big data analysis
3.4.1. - Supervised learning
3.4.2. - Unsupervised learning
3.4.5. - Bayesian methods
3.4.7. - Kernel methods
6.1. - Mathematical Modeling
8.2. - Machine learning
8.3. - Signal analysis

Other Research Topics and Application Domains:

1.3.1. - Understanding and simulation of the brain and the nervous system
2.6.1. - Brain imaging
3.4.1. - Natural risks
3.4.2. - Industrial risks and waste
9.9.1. - Environmental risks

1. Members

Research Scientists

Florence Forbes [Team leader, Inria, Senior researcher, HDR]
Julyan Arbel [Inria, Researcher, from Sep 2016]
Stephane Girard [Inria, Senior researcher, HDR]
Gildas Mazo [Inria, Starting Research Position, from Oct 2016]

Faculty Member

Jean-Baptiste Durand [INP Grenoble, Associate professor]

Technical Staff

Jaime Eduardo Arias Almeida [Inria, since Oct 2016]
Thomas Perret [Inria, until Aug 2016]
Pascal Rubini [Inria]

PhD Students

Clement Albert [Inria]
Alexis Arnaud [Univ. Grenoble I]
Alessandro Chiancone [Univ. Grenoble I, until Oct 2016]
Aina Frau Pascual [Inria]
Brice Olivier [Univ. Grenoble I]
Thibaud Rahier [Schneider Electric]
Pierre-Antoine Rodesch [CEA]
Karina Ashurbekova [Gipsa-Lab, from Oct 2016]

Seydou Nourou Sylla [Inria, Univ. Gaston Berger, St Louis, Senegal, until Jul 2016]

Post-Doctoral Fellows

Pablo Mesejo Santiago [Inria, until Aug 2016]
Jean-Michel Becu [Inria, from Apr 2016]
Emeline Perthame [Inria]

Visiting Scientist

Maïlys Lopes [INRA, Nov 2016]

Administrative Assistants

Myriam Etienne [Inria, until Sep 2016]
Marion Ponsot [Inria, from Sep 2016]

Others

Karina Ashurbekova [Gipsa-Lab, Interns, from Feb 2016 until Jul 2016]
Jules Corset [Inria, Interns, Jan 2016]
Benjamin Lemasson [Inserm, GIN, Researcher, external collaborator from Jun 2016]

2. Overall Objectives

2.1. Overall Objectives

The Context of our work is the analysis of structured stochastic models with statistical tools. The idea underlying the concept of structure is that stochastic systems that exhibit great complexity can be accounted for by combining simple local assumptions in a coherent way. This provides a key to modelling, computation, inference and interpretation. This approach appears to be useful in a number of high impact applications including signal and image processing, neuroscience, genomics, sensors networks, etc. while the needs from these domains can in turn generate interesting theoretical developments. However, this powerful and flexible approach can still be restricted by necessary simplifying assumptions and several generic sources of complexity in data.

Often data exhibit complex dependence structures, having to do for example with repeated measurements on individual items, or natural grouping of individual observations due to the method of sampling, spatial or temporal association, family relationship, and so on. Other sources of complexity are related to the measurement process, such as having multiple measuring instruments or simulations generating high dimensional and heterogeneous data or such that data are dropped out or missing. Such complications in data-generating processes raise a number of challenges. Our goal is to contribute to statistical modelling by offering theoretical concepts and computational tools to handle properly some of these issues that are frequent in modern data. So doing, we aim at developing innovative techniques for high scientific, societal, economic impact applications and in particular via image processing and spatial data analysis in environment, biology and medicine.

The methods we focus on involve mixture models, Markov models, and more generally hidden structure models identified by stochastic algorithms on one hand, and semi and non-parametric methods on the other hand.

Hidden structure models are useful for taking into account heterogeneity in data. They concern many areas of statistics (finite mixture analysis, hidden Markov models, graphical models, random effect models, ...). Due to their missing data structure, they induce specific difficulties for both estimating the model parameters and assessing performance. The team focuses on research regarding both aspects. We design specific algorithms for estimating the parameters of missing structure models and we propose and study specific criteria for choosing the most relevant missing structure models in several contexts.

Semi and non-parametric methods are relevant and useful when no appropriate parametric model exists for the data under study either because of data complexity, or because information is missing. When observations are curves, they enable us to model the data without a discretization step. These techniques are also of great use for *dimension reduction* purposes. They enable dimension reduction of the functional or multivariate data with no assumptions on the observations distribution. Semi-parametric methods refer to methods that include both parametric and non-parametric aspects. Examples include the Sliced Inverse Regression (SIR) method which combines non-parametric regression techniques with parametric dimension reduction aspects. This is also the case in *extreme value analysis*, which is based on the modelling of distribution tails by both a functional part and a real parameter.

3. Research Program

3.1. Mixture models

Participants: Alexis Arnaud, Jean-Baptiste Durand, Florence Forbes, Aina Frau Pascual, Alessandro Chiancone, Stephane Girard, Julyan Arbel, Gildas Mazo, Jean-Michel Becu.

Key-words: mixture of distributions, EM algorithm, missing data, conditional independence, statistical pattern recognition, clustering, unsupervised and partially supervised learning.

In a first approach, we consider statistical parametric models, θ being the parameter, possibly multi-dimensional, usually unknown and to be estimated. We consider cases where the data naturally divides into observed data $y = \{y_1, ..., y_n\}$ and unobserved or missing data $z = \{z_1, ..., z_n\}$. The missing data z_i represents for instance the memberships of one of a set of K alternative categories. The distribution of an observed y_i can be written as a finite mixture of distributions,

$$f(y_i; \theta) = \sum_{k=1}^{K} P(z_i = k; \theta) f(y_i \mid z_i; \theta) \ . \tag{2}$$

These models are interesting in that they may point out hidden variables responsible for most of the observed variability and so that the observed variables are *conditionally* independent. Their estimation is often difficult due to the missing data. The Expectation-Maximization (EM) algorithm is a general and now standard approach to maximization of the likelihood in missing data problems. It provides parameter estimation but also values for missing data.

Mixture models correspond to independent z_i's. They have been increasingly used in statistical pattern recognition. They enable a formal (model-based) approach to (unsupervised) clustering.

3.2. Markov models

Participants: Brice Olivier, Thibaud Rahier, Jean-Baptiste Durand, Florence Forbes, Karina Ashurbekova.

Key-words: graphical models, Markov properties, hidden Markov models, clustering, missing data, mixture of distributions, EM algorithm, image analysis, Bayesian inference.

Graphical modelling provides a diagrammatic representation of the dependency structure of a joint probability distribution, in the form of a network or graph depicting the local relations among variables. The graph can have directed or undirected links or edges between the nodes, which represent the individual variables. Associated with the graph are various Markov properties that specify how the graph encodes conditional independence assumptions.

It is the conditional independence assumptions that give graphical models their fundamental modular structure, enabling computation of globally interesting quantities from local specifications. In this way graphical models form an essential basis for our methodologies based on structures.

The graphs can be either directed, e.g. Bayesian Networks, or undirected, e.g. Markov Random Fields. The specificity of Markovian models is that the dependencies between the nodes are limited to the nearest neighbor nodes. The neighborhood definition can vary and be adapted to the problem of interest. When parts of the variables (nodes) are not observed or missing, we refer to these models as Hidden Markov Models (HMM). Hidden Markov chains or hidden Markov fields correspond to cases where the z_i's in (1) are distributed according to a Markov chain or a Markov field. They are a natural extension of mixture models. They are widely used in signal processing (speech recognition, genome sequence analysis) and in image processing (remote sensing, MRI, etc.). Such models are very flexible in practice and can naturally account for the phenomena to be studied.

Hidden Markov models are very useful in modelling spatial dependencies but these dependencies and the possible existence of hidden variables are also responsible for a typically large amount of computation. It follows that the statistical analysis may not be straightforward. Typical issues are related to the neighborhood structure to be chosen when not dictated by the context and the possible high dimensionality of the observations. This also requires a good understanding of the role of each parameter and methods to tune them depending on the goal in mind. Regarding estimation algorithms, they correspond to an energy minimization problem which is NP-hard and usually performed through approximation. We focus on a certain type of methods based on variational approximations and propose effective algorithms which show good performance in practice and for which we also study theoretical properties. We also propose some tools for model selection. Eventually we investigate ways to extend the standard Hidden Markov Field model to increase its modelling power.

3.3. Functional Inference, semi- and non-parametric methods

Participants: Clement Albert, Alessandro Chiancone, Stephane Girard, Seydou Nourou Sylla, Pablo Mesejo Santiago, Florence Forbes, Emeline Perthame, Jean-Michel Becu.

Key-words: dimension reduction, extreme value analysis, functional estimation.

We also consider methods which do not assume a parametric model. The approaches are non-parametric in the sense that they do not require the assumption of a prior model on the unknown quantities. This property is important since, for image applications for instance, it is very difficult to introduce sufficiently general parametric models because of the wide variety of image contents. Projection methods are then a way to decompose the unknown quantity on a set of functions (*e.g.* wavelets). Kernel methods which rely on smoothing the data using a set of kernels (usually probability distributions) are other examples. Relationships exist between these methods and learning techniques using Support Vector Machine (SVM) as this appears in the context of *level-sets estimation* (see section 3.3.2). Such non-parametric methods have become the cornerstone when dealing with functional data [77]. This is the case, for instance, when observations are curves. They enable us to model the data without a discretization step. More generally, these techniques are of great use for *dimension reduction* purposes (section 3.3.3). They enable reduction of the dimension of the functional or multivariate data without assumptions on the observations distribution. Semi-parametric methods refer to methods that include both parametric and non-parametric aspects. Examples include the Sliced Inverse Regression (SIR) method [80] which combines non-parametric regression techniques with parametric dimension reduction aspects. This is also the case in *extreme value analysis* [76], which is based on the modelling of distribution tails (see section 3.3.1). It differs from traditional statistics which focuses on the central part of distributions, *i.e.* on the most probable events. Extreme value theory shows that distribution tails can be modelled by both a functional part and a real parameter, the extreme value index.

3.3.1. Modelling extremal events

Extreme value theory is a branch of statistics dealing with the extreme deviations from the bulk of probability distributions. More specifically, it focuses on the limiting distributions for the minimum or the maximum of a large collection of random observations from the same arbitrary distribution. Let $X_{1,n} \leq ... \leq X_{n,n}$ denote n ordered observations from a random variable X representing some quantity of interest. A p_n-quantile of X is the value x_{p_n} such that the probability that X is greater than x_{p_n} is p_n, *i.e.* $P(X > x_{p_n}) = p_n$. When $p_n < 1/n$, such a quantile is said to be extreme since it is usually greater than the maximum observation $X_{n,n}$ (see Figure 1).

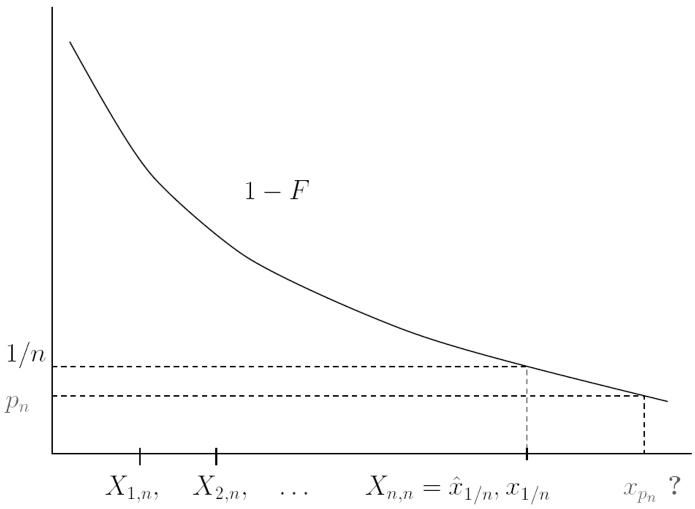

Figure 1. The curve represents the survival function $x \to P(X > x)$. The $1/n$-quantile is estimated by the maximum observation so that $\widehat{x}_{1/n} = X_{n,n}$. As illustrated in the figure, to estimate p_n-quantiles with $p_n < 1/n$, it is necessary to extrapolate beyond the maximum observation.

To estimate such quantiles therefore requires dedicated methods to extrapolate information beyond the observed values of X. Those methods are based on Extreme value theory. This kind of issue appeared in hydrology. One objective was to assess risk for highly unusual events, such as 100-year floods, starting from flows measured over 50 years. To this end, semi-parametric models of the tail are considered:

$$P(X > x) = x^{-1/\theta}\ell(x),\ x > x_0 > 0, \tag{3}$$

where both the extreme-value index $\theta > 0$ and the function $\ell(x)$ are unknown. The function ℓ is a slowly varying function *i.e.* such that

$$\frac{\ell(tx)}{\ell(x)} \to 1 \text{ as } x \to \infty \tag{4}$$

for all $t > 0$. The function $\ell(x)$ acts as a nuisance parameter which yields a bias in the classical extreme-value estimators developed so far. Such models are often referred to as heavy-tail models since the probability of extreme events decreases at a polynomial rate to zero. It may be necessary to refine the model (2,3) by specifying a precise rate of convergence in (3). To this end, a second order condition is introduced involving an additional parameter $\rho \leq 0$. The larger ρ is, the slower the convergence in (3) and the more difficult the estimation of extreme quantiles.

More generally, the problems that we address are part of the risk management theory. For instance, in reliability, the distributions of interest are included in a semi-parametric family whose tails are decreasing exponentially fast. These so-called Weibull-tail distributions [9] are defined by their survival distribution function:

$$P(X > x) = \exp\{-x^{\theta}\ell(x)\},\ x > x_0 > 0. \tag{5}$$

Gaussian, gamma, exponential and Weibull distributions, among others, are included in this family. An important part of our work consists in establishing links between models (2) and (4) in order to propose new estimation methods. We also consider the case where the observations were recorded with a covariate information. In this case, the extreme-value index and the p_n-quantile are functions of the covariate. We propose estimators of these functions by using moving window approaches, nearest neighbor methods, or kernel estimators.

3.3.2. Level sets estimation

Level sets estimation is a recurrent problem in statistics which is linked to outlier detection. In biology, one is interested in estimating reference curves, that is to say curves which bound 90% (for example) of the population. Points outside this bound are considered as outliers compared to the reference population. Level sets estimation can be looked at as a conditional quantile estimation problem which benefits from a non-parametric statistical framework. In particular, boundary estimation, arising in image segmentation as well as in supervised learning, is interpreted as an extreme level set estimation problem. Level sets estimation can also be formulated as a linear programming problem. In this context, estimates are sparse since they involve only a small fraction of the dataset, called the set of support vectors.

3.3.3. Dimension reduction

Our work on high dimensional data requires that we face the curse of dimensionality phenomenon. Indeed, the modelling of high dimensional data requires complex models and thus the estimation of high number of parameters compared to the sample size. In this framework, dimension reduction methods aim at replacing the original variables by a small number of linear combinations with as small as a possible loss of information. Principal Component Analysis (PCA) is the most widely used method to reduce dimension in data. However, standard linear PCA can be quite inefficient on image data where even simple image distorsions can lead to highly non-linear data. Two directions are investigated. First, non-linear PCAs can be proposed, leading to semi-parametric dimension reduction methods [78]. Another field of investigation is to take into account the application goal in the dimension reduction step. One of our approaches is therefore to develop new Gaussian models of high dimensional data for parametric inference [74]. Such models can then be used in a Mixtures or Markov framework for classification purposes. Another approach consists in combining dimension reduction, regularization techniques, and regression techniques to improve the Sliced Inverse Regression method [80].

4. Application Domains

4.1. Image Analysis

Participants: Alexis Arnaud, Aina Frau Pascual, Florence Forbes, Stephane Girard, Pascal Rubini, Alessandro Chiancone, Thomas Perret, Pablo Mesejo Santiago, Jaime Eduardo Arias Almeida, Pierre-Antoine Rodesch.

As regards applications, several areas of image analysis can be covered using the tools developed in the team. More specifically, in collaboration with team PERCEPTION , we address various issues in computer vision involving Bayesian modelling and probabilistic clustering techniques. Other applications in medical imaging are natural. We work more specifically on MRI and functional MRI data, in collaboration with the Grenoble Institute of Neuroscience (GIN) and the NeuroSpin center of CEA Saclay. We also consider other statistical 2D fields coming from other domains such as remote sensing, in collaboration with Laboratoire de Planétologie de Grenoble. We worked on hyperspectral images. In the context of the "pole de competivité" project I-VP, we worked of images of PC Boards. We also address reconstruction problems in tomography with CEA Grenoble.

4.2. Multi sensor Data Analysis

Participants: Jean-Michel Becu, Florence Forbes.

A number of our methods are at the the intersection of data fusion, statistics, machine learning and acoustic signal processing. The context can be the surveillance and monitoring of a zone acoustic state from data acquired at a continuous rate by a set of sensors that are potentially mobile and of different nature (eg WIFUZ project with the ACOEM company in the context of a DGA-rapid initiative). Typical objectives include the development of prototypes for surveillance and monitoring that are able to combine multi sensor data coming from acoustic sensors (microphones and antennas) and optical sensors (infrared cameras) and to distribute the processing to multiple algorithmic blocs. Our interest in acoustic data analysis mainly started from past European projects, POP and Humavips, in collaboration with the PERCEPTION team (PhD theses of Vassil Khalidov, Ramya Narasimha, Antoine Deleforge, Xavier alameda, and Israel Gebru).

4.3. Biology, Environment and Medicine

Participants: Pablo Mesejo Santiago, Aina Frau Pascual, Florence Forbes, Stephane Girard, Seydou Nourou Sylla, Emeline Perthame, Jean-Baptiste Durand, Clement Albert, Julyan Arbel, Jean-Michel Becu, Thibaud Rahier, Brice Olivier, Karina Ashurbekova.

A third domain of applications concerns biology and medicine. We considered the use of missing data models in epidemiology. We also investigated statistical tools for the analysis of bacterial genomes beyond gene detection. Applications in neurosciences are also considered. In the environmental domain, we considered the modelling of high-impact weather events.

5. Highlights of the Year

5.1. Highlights of the Year

- The Pixyl startup (http://pixyl.io) created in March 2015 by F. Forbes (Mistis) with M. Dojat (INSERM), a former Mistis post-doctoral fellow S. Doyle (CEO) and IT Translation is one of the two Inria start-ups winners of the NETVA 2016 competition. S. Doyle travelled to Washington to take part in a personalized support program to learn about the North American markets. The NETVA competition is open to French hi-tech start-ups. It is organized by the science and technology departments of the French embassies in Canada and the USA. Pixyl develops neuro-imaging software which automatically analyses brain lesion load using MRI scans, for improved decision-making during clinical trials and routine clinical use.
- Vision 4.0 FUI Minalogic project: Mistis is one of the 4 partners in the Vision 4.0 project that started in October 2016. This is one of the 8 projects funded by the Minalogic Pôle de competitivité in 2016. The support is of 3.4 Meuros.

5.1.1. Awards

- 2016 Award for Outstanding Contributions in Neural Systems. Antoine Deleforge (now with the PANAMA team, Inria Bretagne-Atlantique), Florence Forbes (MISTIS team) and Radu Horaud (PERCEPTION team) received the 2016 Hojjat Adeli Award for Outstanding Contributions in Neural Systems for their paper: A. Deleforge, F. Forbes, and R. Horaud (2015), Acoustic Space Learning for Sound-source Separation and Localization on Binaural Manifolds, International Journal of Neural Systems, 25:1,(21 pages) [75]. The Award for Outstanding Contributions in Neural Systems established by World Scientific Publishing Co. in 2010, is awarded annually to the most innovative paper published in the previous volume/year of the International Journal of Neural Systems.
- MITACS Globalink Research Award - Inria - for research in Canada. Alexis Arnaud received the MITACS award and a 5 kdollars grant to spend 5 months in the Mathematics and statistics department of McGill University in Montreal, Canada, working with Prof. Russel Steele.

6. New Software and Platforms

6.1. BOLD model FIT

KEYWORDS: Functional imaging - FMRI - Health
FUNCTIONAL DESCRIPTION

This Matlab toolbox performs the automatic estimation of biophysical parameters using the extended Balloon model and BOLD fMRI data. It takes as input a MAT file and provides as output the parameter estimates achieved by using stochastic optimization

- Authors: Pablo Mesejo Santiago, Jan M Warnking and Florence Forbes
- Contact: Pablo Mesejo Santiago
- URL: https://hal.archives-ouvertes.fr/hal-01221115v2/

6.2. MMST

Mixtures of Multiple Scaled Student T distributions
KEYWORDS: Health - Statistics - Brain MRI - Medical imaging - Robust clustering
FUNCTIONAL DESCRIPTION

The package implements mixtures of so-called multiple scaled Student distributions, which are generalization of multivariate Student T distribution allowing different tails in each dimension. Typical applications include Robust clustering to analyse data with possible outliers. In this context, the model and package have been used on large data sets of brain MRI to segment and identify brain tumors.

- Participants: Alexis Arnaud, Florence Forbes and Darren Wraith
- Contact: Florence Forbes
- URL: http://mistis.inrialpes.fr/realisations.html

6.3. PyHRF

KEYWORDS: FMRI - Statistic analysis - Neurosciences - IRM - Brain - Health - Medical imaging
FUNCTIONAL DESCRIPTION

As part of fMRI data analysis, PyHRF provides a set of tools for addressing the two main issues involved in intra-subject fMRI data analysis : (i) the localization of cerebral regions that elicit evoked activity and (ii) the estimation of the activation dynamics also referenced to as the recovery of the Hemodynamic Response Function (HRF). To tackle these two problems, PyHRF implements the Joint Detection-Estimation framework (JDE) which recovers parcel-level HRFs and embeds an adaptive spatio-temporal regularization scheme of activation maps.

- Participants: Thomas Vincent, Solveig Badillo, Lotfi Chaari, Christine Bakhous, Florence Forbes, Philippe Ciuciu, Laurent Risser, Thomas Perret, Aina Frau Pascual and Jaime Eduardo Arias Almeida
- Partners: CEA - NeuroSpin
- Contact: Florence Forbes
- URL: http://pyhrf.org

6.4. xLLiM

High dimensional locally linear mapping
KEYWORDS: Clustering - Regression
FUNCTIONAL DESCRIPTION

This is an R package available on the CRAN.

XLLiM provides a tool for non linear mapping (non linear regression) using a mixture of regression model and an inverse regression strategy. The methods include the GLLiM model (Deleforge et al (2015)) based on Gaussian mixtures and a robust version of GLLiM, named SLLiM (see [71]) based on a mixture of Generalized Student distributions.

- Participants: Emeline Perthame, Florence Forbes and Antoine Deleforge
- Contact: Florence Forbes
- URL: https://cran.r-project.org/web/packages/xLLiM/index.html

7. New Results

7.1. Mixture models

7.1.1. *High dimensional Kullback-Leilbler divergence for supervised clustering*

Participant: Stephane Girard.

Joint work with: C. Bouveyron (Univ. Paris 5), M. Fauvel and M. Lopes (ENSAT Toulouse))

In the PhD work of Charles Bouveyron [74], we proposed new Gaussian models of high dimensional data for classification purposes. We assume that the data live in several groups located in subspaces of lower dimensions. Two different strategies arise:

- the introduction in the model of a dimension reduction constraint for each group
- the use of parsimonious models obtained by imposing to different groups to share the same values of some parameters

This modelling yielded a supervised classification method called High Dimensional Discriminant Analysis (HDDA) [4]. Some versions of this method have been tested on the supervised classification of objects in images. This approach has been adapted to the unsupervised classification framework, and the related method is named High Dimensional Data Clustering (HDDC) [3]. In the framework of Mailys Lopes PhD, our recent work [50], consists in adapting this work to the classification of grassland management practices using satellite image time series with high spatial resolution. The study area is located in southern France where 52 parcels with three management types were selected. The spectral variability inside the grasslands was taken into account considering that the pixels signal can be modeled by a Gaussian distribution. A parsimonious model is discussed to deal with the high dimension of the data and the small sample size. A high dimensional symmetrized Kullback-Leibler divergence (KLD) is introduced to compute the similarity between each pair of grasslands. The model is positively compared to the conventional KLD to construct a positive definite kernel used in SVM for supervised classification.

7.1.2. *Single-run model selection in mixtures*

Participants: Florence Forbes, Alexis Arnaud.

Joint work with: Russel Steele, McGill University, Montreal, Canada.

A number of criteria exist to select the number of components in a mixture automatically based on penalized likelihood criteria (eg. AIC, BIC, ICL etc.) but they usually require to run several models for different number of components to choose the best one. In this work, the goal was to investigate existing alternatives that can select the component number from a single run and to develop such a procedure for our MRI analysis. These objectives were achieved for the main part as 1) different single run methods have been implemented and tested for Gaussian and Standard mixture models, 2) a Bayesian version of Generalized Student mixtures have been designed that allows the use of the methods in 1), and 3) we also proposed a new heuristic based on this Bayesian model that shows good performance and lower computational times. A more complete validation on simulated data and tests on real MRI data need still to be performed. The single run methods studied are based on a fully Bayesian approach involving therefore specification of appropriate priors and choice of hyperparameters. To estimate our Bayesian mixture model, we use a Variational Expectation-Maximization algorithm (VEM). For the heuristic, we add an additional step inside VEM in order to compute in parallel the corresponding VEM step with one less component. If the lower-bound of the model likelihood is higher with one less component, then we delete this component and go to the next VEM step, until convergence of the algorithm. As regards software development, the Rcpp package has been used to bridge pure R code with more efficient C++ code. This project has been initiated with Alexis Arnaud's visit to McGill University in Montreal in the context of his Mitacs award.

7.1.3. Sequential Quasi Monte Carlo for Dirichlet Process Mixture Models

Participant: Julyan Arbel.

Joint work with: Jean-Bernard Salomond (Université Paris-Est).

In mixture models, latent variables known as allocation variables play an essential role by indicating, at each iteration, to which component of the mixture observations are linked. In sequential algorithms, these latent variables take on the interpretation of particles. We investigate the use of quasi Monte Carlo within sequential Monte Carlo methods (a technique known as sequential quasi Monte Carlo) in nonparametric mixtures for density estimation. We compare them to sequential and non sequential Monte Carlo algorithms. We highlight a critical distinction of the allocation variables exploration of the latent space under each of the three sampling approaches. This work has been presented at the *Practical Bayesian Nonparametrics* NIPS workshop [48].

7.1.4. Truncation error of a superposed gamma process in a decreasing order representation

Participant: Julyan Arbel.

Joint work with: Igor Prünster (University Bocconi, Milan).

Completely random measures (CRM) represent a key ingredient of a wealth of stochastic models, in particular in Bayesian Nonparametrics for defining prior distributions. CRMs can be represented as infinite random series of weighted point masses. A constructive representation due to Ferguson and Klass provides the jumps of the series in decreasing order. This feature is of primary interest when it comes to sampling since it minimizes the truncation error for a fixed truncation level of the series. We quantify the quality of the approximation in two ways. First, we derive a bound in probability for the truncation error. Second, we study a moment-matching criterion which consists in evaluating a measure of discrepancy between actual moments of the CRM and moments based on the simulation output. This work focuses on a general class of CRMs, namely the superposed gamma process, which suitably transformed have already been successfully implemented in Bayesian Nonparametrics. To this end, we show that the moments of this class of processes can be obtained analytically. This work has been presented at the *Advances in Approximate Bayesian Inference* NIPS workshop [47].

7.1.5. Non linear mapping by mixture of regressions with structured covariance matrix

Participant: Emeline Perthame.

Joint work with: Emilie Devijver (KU Leuven, Belgium) and Mélina Gallopin (Université Paris Sud).

In genomics, the relation between phenotypical responses and genes are complex and potentially non linear. Therefore, it could be interesting to provide biologists with statistical models that mimic and approximate these relations. In this paper, we focus on a dataset that relates genes expression to the sensitivity to alcohol of drosophila. In this framework of non linear regression, GLLiM (Gaussian Locally Linear Mapping) is an efficient tool to handle non linear mappings in high dimension. Indeed, this model based on a joint modeling of both responses and covariates by Gaussian mixture of regressions has demonstrated its performance in non linear prediction for multivariate responses when the number of covariates is large. This model also allows the addition of latent factors which have led to interesting interpretation of the latent factors in image analysis. Nevertheless, in genomics, biologists are more interested in graphical models, representing gene regulatory networks. For this reason, we developed an extension of GLLiM in which covariance matrices modeling the dependence structure of genes in each clusters are blocks diagonal, using tools derived for graphical models. This extension provides a new class of interpretable models that are suitable to genomics application fields while keeping interesting prediction properties.

7.1.6. Extended GLLiM model for a subclustering effect: Mixture of Gaussian Locally Linear Mapping (MoGLLiM)

Participant: Florence Forbes.

Joint work with: Naisyin Wang and Chun-Chen Tu from University of Michigan, Ann Arbor, USA.

The work of Chun-Chen Tu and Naisyin Wang pointed out a problem with the original GLLiM model that they propose to solve with a divide-remerge method. The proposal seems to be efficient on test data but the resulting procedure does not anymore correspond to the optimization of a single statistical model. The idea of this work is then to discuss the possibility to change the original GLLiM model in order to account for sub-clusters directly. A small change in the definition seems to have such an effect while remaining tractable. However, we will probably have to be careful with potential non-identifiability issue when dealing with clusters and sub-clusters.

7.2. Semi and non-parametric methods

7.2.1. Robust estimation for extremes

Participants: Clement Albert, Stephane Girard.

Joint work with: M. Stehlik (Johannes Kepler Universitat Linz, Austria and Universidad de Valparaiso, Chile) and A. Dutfoy (EDF R&D).

In the PhD thesis of Clément Albert (funded by EDF), we study the sensitivity of extreme-value methods to small changes in the data [46]. To reduce this sensitivity, robust methods are needed and, in [21], we proposed a novel method of heavy tails estimation based on a transformed score (the t-score). Based on a new score moment method, we derive the t-Hill estimator, which estimates the extreme value index of a distribution function with regularly varying tail. t-Hill estimator is distribution sensitive, thus it differs in e.g. Pareto and log-gamma case. Here, we study both forms of the estimator, i.e. t-Hill and t-lgHill. For both estimators we prove weak consistency in moving average settings as well as the asymptotic normality of t-lgHill estimator in the i.i.d. setting. In cases of contamination with heavier tails than the tail of original sample, t-Hill outperforms several robust tail estimators, especially in small sample situations. A simulation study emphasizes the fact that the level of contamination is playing a crucial role. We illustrate the developed methodology on a small sample data set of stake measurements from Guanaco glacier in Chile. This methodology is adapted to bounded distribution tails in [26] with an application to extreme snow loads in Slovakia.

7.2.2. Conditional extremal events

Participant: Stephane Girard.

Joint work with: L. Gardes (Univ. Strasbourg) and J. Elmethni (Univ. Paris 5)

The goal of the PhD theses of Alexandre Lekina and Jonathan El Methni was to contribute to the development of theoretical and algorithmic models to tackle conditional extreme value analysis, *ie* the situation where some covariate information X is recorded simultaneously with a quantity of interest Y. In such a case, the tail heaviness of Y depends on X, and thus the tail index as well as the extreme quantiles are also functions of the covariate. We combine nonparametric smoothing techniques [77] with extreme-value methods in order to obtain efficient estimators of the conditional tail index and conditional extreme quantiles. When the covariate is functional and random (random design) we focus on kernel methods [18].

Conditional extremes are studied in climatology where one is interested in how climate change over years might affect extreme temperatures or rainfalls. In this case, the covariate is univariate (time). Bivariate examples include the study of extreme rainfalls as a function of the geographical location. The application part of the study is joint work with the LTHE (Laboratoire d'étude des Transferts en Hydrologie et Environnement) located in Grenoble [31], [32].

7.2.3. Estimation of extreme risk measures

Participant: Stephane Girard.

Joint work with: A. Daouia (Univ. Toulouse), L. Gardes (Univ. Strasbourg) and G. Stupfler (Univ. Aix-Marseille).

One of the most popular risk measures is the Value-at-Risk (VaR) introduced in the 1990's. In statistical terms, the VaR at level $\alpha \in (0,1)$ corresponds to the upper α-quantile of the loss distribution. The Value-at-Risk however suffers from several weaknesses. First, it provides us only with a pointwise information: VaR(α) does not take into consideration what the loss will be beyond this quantile. Second, random loss variables with light-tailed distributions or heavy-tailed distributions may have the same Value-at-Risk. Finally, Value-at-Risk is not a coherent risk measure since it is not subadditive in general. A first coherent alternative risk measure is the Conditional Tail Expectation (CTE), also known as Tail-Value-at-Risk, Tail Conditional Expectation or Expected Shortfall in case of a continuous loss distribution. The CTE is defined as the expected loss given that the loss lies above the upper α-quantile of the loss distribution. This risk measure thus takes into account the whole information contained in the upper tail of the distribution. In [64], we investigate the extreme properties of a new risk measure (called the Conditional Tail Moment) which encompasses various risk measures, such as the CTE, as particular cases. We study the situation where some covariate information is available under some general conditions on the distribution tail. We thus has to deal with conditional extremes (see paragraph 7.2.2).

A second possible coherent alternative risk measure is based on expectiles [63]. Compared to quantiles, the family of expectiles is based on squared rather than absolute error loss minimization. The flexibility and virtues of these least squares analogues of quantiles are now well established in actuarial science, econometrics and statistical finance. Both quantiles and expectiles were embedded in the more general class of M-quantiles as the minimizers of a generic asymmetric convex loss function. It has been proved very recently that the only M-quantiles that are coherent risk measures are the expectiles.

7.2.4. Multivariate extremal events

Participants: Stephane Girard, Florence Forbes.

Joint work with: F. Durante (Univ. Bolzen-Bolzano, Italy) and G. Mazo (Univ. Catholique de Louvain, Belgique).

Copulas are a useful tool to model multivariate distributions [83]. However, while there exist various families of bivariate copulas, much fewer has been done when the dimension is higher. To this aim an interesting class of copulas based on products of transformed copulas has been proposed in the literature. The use of this class for practical high dimensional problems remains challenging. Constraints on the parameters and the product form render inference, and in particular the likelihood computation, difficult. As an alternative, we proposed a new class of copulas constructed by introducing a latent factor. Conditional independence with respect to this factor and the use of a nonparametric class of bivariate copulas lead to interesting properties like explicitness, flexibility and parsimony. In particular, various tail behaviours are exhibited, making possible the modeling of various extreme situations [17], [22].

7.2.5. Level sets estimation

Participant: Stephane Girard.

Joint work with: G. Stupfler (Univ. Aix-Marseille).

The boundary bounding the set of points is viewed as the larger level set of the points distribution. This is then an extreme quantile curve estimation problem. We proposed estimators based on projection as well as on kernel regression methods applied on the extreme values set, for particular set of points [10]. We also investigate the asymptotic properties of existing estimators when used in extreme situations. For instance, we have established in collaboration with G. Stupfler that the so-called geometric quantiles have very counter-intuitive properties in such situations [20] and thus should not be used to detect outliers.

7.2.6. Robust Sliced Inverse Regression.

Participants: Stephane Girard, Alessandro Chiancone, Florence Forbes.

This research theme was supported by a LabEx PERSYVAL-Lab project-team grant.

Sliced Inverse Regression (SIR) has been extensively used to reduce the dimension of the predictor space before performing regression. Recently it has been shown that this technique is, not surprisingly, sensitive to noise. Different approaches have thus been proposed to robustify SIR. In [14], we start considering an inverse problem proposed by R.D. Cook and we show that the framework can be extended to take into account a non-Gaussian noise. Generalized Student distributions are considered and all parameters are estimated via an EM algorithm. The algorithm is outlined and tested comparing the results with different approaches on simulated data. Results on a real dataset show the interest of this technique in presence of outliers.

7.2.7. Collaborative Sliced Inverse Regression.

Participants: Stephane Girard, Alessandro Chiancone.

This research theme was supported by a LabEx PERSYVAL-Lab project-team grant.

Joint work with: J. Chanussot (Gipsa-lab and Grenoble-INP).

In his PhD thesis work, Alessandro Chiancone studies the extension of the SIR method to different sub-populations. The idea is to assume that the dimension reduction subspace may not be the same for different clusters of the data [15]. One of the difficulty is that standard Sliced Inverse Regression (SIR) has requirements on the distribution of the predictors that are hard to check since they depend on unobserved variables. It has been shown that, if the distribution of the predictors is elliptical, then these requirements are satisfied. In case of mixture models, the ellipticity is violated and in addition there is no assurance of a single underlying regression model among the different components. Our approach clusterizes the predictors space to force the condition to hold on each cluster and includes a merging technique to look for different underlying models in the data. A study on simulated data as well as two real applications are provided. It appears that SIR, unsurprisingly, is not able to deal with a mixture of Gaussians involving different underlying models whereas our approach is able to correctly investigate the mixture.

7.2.8. Hapke's model parameter estimation from photometric measurements

Participants: Florence Forbes, Emeline Perthame.

Joint work with: Sylvain Douté (IPAG, Grenoble).

The Hapke's model is a widely used analytical model in planetology to describe the spectro-photometry of granular materials. It is a non linear model F that links a set of parameters x to a "theoretical" Bidirectional Reflectance Diffusion Function (BRDF). In practice, we assume that the observed BRDF Y is a noisy version of the "theoretical" one

$$Y = F(x) + \epsilon \tag{6}$$

where ϵ is a centered Gaussian noise with diagonal covariance matrix Σ. Then x is also assumed to be random with some prior distribution to be specified, e.g. uniform on the parameters range in [84]. The overall goal is to estimate the posterior distribution $p(x|y)$ for some observed BRDF y. Equation (5) defines the likelihood of the model which is $p(y|x) = \mathcal{N}(y; F(x), \Sigma)$. Then since F is non linear, it is not possible to obtain an analytical expression for $p(x|y)$. However, it is easy to simulate parameters x that follows the posterior distribution $p(x|y) \propto p(y|x)\ p(x)$ for instance using MCMC techniques [84]. If only point estimate are desired, the MAP can be used and evolutionary algorithms can then be used also using $p(y|x)\ p(x)$ as a fitness function. But obtaining such simulations is time consuming and has to be done for each observed value of y. In this work, we propose to use a locally linear mapping approximation and an inverse regression strategy to provide an analytical expression of $p(x|y)$. The idea is that the non linear F can be approximated by a number K of locally linear functions and that each of this function is easy to inverse. It follows that the inverse of F is also approximated as locally linear. Preliminary results were presented at the MultiPlaNet workshop in Orsay, December 14, 2016. They show that the proposed method does not fully reproduce the previous results obtained using MCMC techniques. Further investigations are required to understand the origin of the difference. Also ABC (approximate Bayes computation) methods will be considered as a subsequent step that may improved the current procedure while remaining computationally efficient.

7.2.9. *Prediction intervals for inverse regression models in high dimension*

Participant: Emeline Perthame.

Joint work with: Emilie Devijver (KU Leuven, Belgium).

Inverse regression, as a dimension reduction technique, is a reliable and efficient approach to handle large regression issues in high dimension, when the number of features exceeds the number of observations. Indeed, under some conditions, dealing with the inverse regression problem associated to a forward regression problem drastically reduces the number of parameters to estimate and make the problem tractable. However, regression models are often used to predict a new response from a new observed profile of covariates, and we may be interested in deriving confidence bands for the prediction to quantify the uncertainty around a predicted response. Theoretical results have already been derived for the well-known linear model, but recently, the curse of dimensionality has increased the interest of practitioners and theoreticians into generalization of those results on a high-dimension context. When both the responses and the covariates are multivariate, we derive in this work theoretical prediction bands for the inverse regression linear model and propose an analytical expression of these intervals. The feasibility, the confidence level and the accuracy of the proposed intervals are also analyzed through a simulation study.

7.2.10. *Multi sensor fusion for acoustic surveillance and monitoring*

Participants: Florence Forbes, Jean-Michel Becu.

Joint work with: Pascal Vouagner and Christophe Thirard from ACOEM company.

In the context of the DGA-rapid WIFUZ project with the ACOEM company, we addressed the issue of determining the localization of shots from multiple measurements coming from multiple sensors. We used Bayesian inversion and simulation techniques to recover multiple sources mimicking collaborative interaction between several vehicles. This project is at the intersection of data fusion, statistics, machine learning and acoustic signal processing. The general context is the surveillance and monitoring of a zone acoustic state from data acquired at a continuous rate by a set of sensors that are potentially mobile and of different nature. The overall objective is to develop a prototype for surveillance and monitoring that is able to combine multi sensor data coming from acoustic sensors (microphones and antennas) and optical sensors (infrared cameras) and to distribute the processing to multiple algorithmic blocs.

7.3. Graphical and Markov models

7.3.1. Conditional independence properties in compound multinomial distributions

Participant: Jean-Baptiste Durand.

Joint work with: Pierre Fernique (Inria, Virtual Plants) and Jean Peyhardi (Université de Montpellier).

We developed a unifying view of two families of multinomial distributions: the singular – for modeling univariate categorical data – and the non-singular – for modeling multivariate count data. In the latter model, we introduced sum-compound multinomial distributions that encompass re-parameterization of non-singular multinomial and negative multinomial distributions. The estimation properties within these compound distributions were obtained, thus generalizing know results in univariate distributions to the multivariate case. These distributions were used to address the inference of discrete-state models for tree-structured data. In particular, they were used to introduce parametric generation distributions in Markov-tree models [66].

7.3.2. Change-point models for tree-structured data

Participant: Jean-Baptiste Durand.

Joint work with: Pierre Fernique (Inria) and Yann Guédon (CIRAD), Inria Virtual Plants.

In the context of plant growth modelling, methods to identify subtrees of a tree or forest with similar attributes have been developed. They rely either on hidden Markov modelling or multiple change-point approaches. The latter are well-developed in the context of sequence analysis, but their extensions to tree-structured data are not straightforward. Their advantage on hidden Markov models is to relax the strong constraints regarding dependencies induced by parametric distributions and local parent-children dependencies. Heuristic approaches for change-point detection in trees were proposed and applied to the analysis of patchiness patterns (consisting of canopies made of clumps of either vegetative or flowering botanical units) in mango trees [43].

7.3.3. Hidden Markov models for the analysis of eye movements

Participants: Jean-Baptiste Durand, Brice Olivier.

This research theme is supported by a LabEx PERSYVAL-Lab project-team grant.

Joint work with: Marianne Clausel (LJK) Anne Guérin-Dugué (GIPSA-lab) and Benoit Lemaire (Laboratoire de Psychologie et Neurocognition)

In the last years, GIPSA-lab has developed computational models of information search in web-like materials, using data from both eye-tracking and electroencephalograms (EEGs). These data were obtained from experiments, in which subjects had to make some kinds of press reviews. In such tasks, reading process and decision making are closely related. Statistical analysis of such data aims at deciphering underlying dependency structures in these processes. Hidden Markov models (HMMs) have been used on eye movement series to infer phases in the reading process that can be interpreted as steps in the cognitive processes leading to decision. In HMMs, each phase is associated with a state of the Markov chain. The states are observed indirectly though eye-movements. Our approach was inspired by Simola et al. (2008), but we used hidden semi-Markov models for better characterization of phase length distributions. The estimated HMM highlighted contrasted reading strategies (ie, state transitions), with both individual and document-related variability. However, the characteristics of eye movements within each phase tended to be poorly discriminated. As a result, high uncertainty in the phase changes arose, and it could be difficult to relate phases to known patterns in EEGs.

This is why, as part of Brice Olivier's PhD thesis, we are developing integrated models coupling EEG and eye movements within one single HMM for better identification of the phases. Here, the coupling should incorporate some delay between the transitions in both (EEG and eye-movement) chains, since EEG patterns associated to cognitive processes occur lately with respect to eye-movement phases. Moreover, EEGs and scanpaths were recorded with different time resolutions, so that some resampling scheme must be added into the model, for the sake of synchronizing both processes.

To begin with, we first proved why HMM would be the best option in order to conduct this analysis and what could be the alternatives. A brief state of the art was made on models similar to HMMs. However, since our data is very specific, we needed to make use of unsupervised graphical generative models for the analysis of sequences which would keep a deep meaning. It resulted that Hidden semi-Markov model (HSMM) was the most powerful tool satisfying all our needs. Indeed, a HSMM is characterized by meaningful parameters such as an initial distribution, transition distributions, emission distributions and sojourn distributions, which allows us to directly characterize a reading strategy. Second, we found and improved an existing implementation of such a model. After searching for libraries to make inference in HSMM, the Vplants library embedded in the OpenAlea software turned out to be the most viable solution regarding the functionalities, though it was still incomplete. Consequently, we proposed improvements to this library and added functions in order to boost the likelihood of the data. This lead us to also propose a new library included in that software which is specific at the analysis of eye movements. Third, in order to improve and validate the interpretation of the reading strategies, we calculated indicators specific to each reading strategy. Fourth, since the parameters obtained from the model suggested individual and text variability, we first investigated text clustering to reduce the variability of the model. In order to do this, we supervised a group of 6 students to explore the text clustering component with the mission of clustering the texts by evolution of the semantic similarity throughout text. We therefore explored different methods for time series clustering and we retained the usage of Ascendant Hierarchical Clustering (AHC) using the Dynamic Time Warping (DTW) metric, which allows global dynamics of the time series to be captured, but not local dynamics. Plus, we preferred the simplicity and good understanding of the results using that method. Therefore, we deduced three text profiles giving meaning to the evolution of the semantic similarity: a step profile, a ramp profile, and a saw profile. With that new information in hand, we are now able to decompose our model over text profiles and hence, reduce its variability.

As discussed in the previous section, our work is focused on the standalone analysis of the eye-movements. We are currently polishing this phase of work. The common work and the goal for this coming year is to develop and implement a model for jointly analyzing eye-movements and EEGs in order to improve the discrimination of the reading strategies.

7.3.4. Lossy compression of tree structures

Participant: Jean-Baptiste Durand.

Joint work with: Christophe Godin (Inria, Virtual Plants) and Romain Azais (Inria BIGS)

In a previous work [79], a method to compress tree structures and to quantify their degree of self-nestedness was developed. 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 lossless 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. A lossy version of the algorithm consists in coding the nearest self-nested tree embedded in the initial tree. 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 obtained new theoretical results on the combinatorics of self-nested structures [60]. We improved this lossy compression method by computing a self-nested reduction of a tree that better approximates the initial tree. The algorithm has polynomial time complexity for trees with bounded outdegree. This approximation relies on an indel edit distance that allows (recursive) insertion and deletion of leaf vertices only. We showed using 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 [79] while the compression rates are equivalent. This procedure is also a keystone in our new topological clustering algorithm for trees. Perspectives of improving the time complexity of our algorithm include taking profit from one of its byproduct, which could be used as an indicator of both the number of potential candidates to explore and of the proximity of the tree to the nearest self-nested tree.

7.3.5. Learning the inherent probabilistic graphical structure of metadata

Participants: Thibaud Rahier, Stephane Girard, Florence Forbes.

Joint work with: Sylvain Marié, Schneider Electric.

The quality of prediction and inference on temporal data can be significantly improved by taking advantage of the associated metadata. However, metadata are often only partially structured and may contain missing values. In the context of T. Rahier's PhD with Schneider Electric, we first considered the problem of learning the inherent probabilistic graphical structure of metadata, which has two main benefits: (i) graphical models are very flexible and therefore enable the fusion of different types of data together (ii) the learned graphical model can be interrogated to perform tasks on metadata alone: variable clustering, conditional independence discovery or missing data replenishment. Bayesian Network (and more generally Probabilistic Graphical Model) structure learning is a tremendous mathematical challenge, that involves a NP-Hard optimisation problem. In the past year, we have explored many approaches to tackle this issue, and begun to develop a tailor-made algorithm, that exploits dependencies typically present in metadata, and that significantly speeds up the structure learning task and increases the chance of finding the optimal structure.

7.3.6. Robust Graph estimation

Participants: Karina Ashurbekova, Florence Forbes.

Joint work with: Sophie Achard, CNRS, Gipsa-lab.

In the face of increasingly high dimensional data and of trying to understand the dependency/association present in the data the literature on graphical modelling is growing rapidly and covers a range of applications (from bioinformatics e.g gene expression data to document modelling). A major limitation of recent work on using the (standard) Student t distribution for robust graphical modelling is the lack of independence and conditional independence of the Student t distribution, and estimation in this context (with the standard student t) is very difficult. We propose to develop and assess a generalized Student t from a new family (which has independence and conditional independence as special properties) for the general purpose of graphical modelling in high dimensional settings. Its main characteristic is to include multivariate heavy-tailed distributions with variable marginal amounts of tailweight that allow more complex dependencies than the standard case. We target an application to brain connectivity data for which standard Gaussian graphical models have been applied. Brain connectivity analysis consists in the study of multivariate time series representing local dynamics at each of multiple sites or sources throughout the whole human brain while functioning using for example functional magnetic resonance imaging (fMRI). The acquisition is difficult and often spikes are observed due to the movement of the subjects inside the scanner. In the case of identifying Gaussian graphical models, the glasso technique has been developed for estimating sparse graphs. However, this method can be severely impacted by the inclusion of only a few contaminated values, such as spikes that commonly occur in fMRI time series, and the resulting graph has the potential to contain false positive edges. Therefore, our goal was to assess the performance of more robust methods on such data.

7.4. Robust non Gaussian models

7.4.1. Robust Locally linear mapping with mixtures of Student distributions

Participants: Florence Forbes, Emeline Perthame, Brice Olivier.

The standard GLLiM model [6] for high dimensional regression assumes Gaussian noise models and is in its unconstrained version equivalent to a joint GMM. The fact that response and independent variables (X, Y) are jointly a mixture of Gaussian distribution is the key for all derivations in the model. In this work, we show that similar developments are possible based on a joint Student Mixture model, joint SMM. It follows a new model referred to as SLLiM for Student Locally linear mapping for which we investigate the robustness to outlying data in a high dimensional regression context [71]. The corresponding code is available on the CRAN in the *xLLiM* package.

7.4.2. Rectified binaural ratio: A complex T-distributed feature for robust sound localization

Participant: Florence Forbes.

Joint work with: Antoine Deleforge, Inria PANAMA team in Rennes.

Most existing methods in binaural sound source localization rely on some kind of aggregation of phase-and level-difference cues in the time-frequency plane. While different aggregation schemes exist, they are often heuristic and suffer in adverse noise conditions. In this work, we introduce the rectified binaural ratio as a new feature for sound source localization. We show that for Gaussian-process point source signals corrupted by stationary Gaussian noise, this ratio follows a complex t-distribution with explicit parameters. This new formulation provides a principled and statistically sound way to aggregate binaural features in the presence of noise. We subsequently derive two simple and efficient methods for robust relative transfer function and time-delay estimation. Experiments on heavily corrupted simulated and speech signals demonstrate the robustness of the proposed scheme. This work has been presented at the Eusipco conference in 2016 [30].

7.4.3. Statistical reconstruction methods for multi-energy tomography

Participants: Florence Forbes, Pierre-Antoine Rodesch.

Joint work with: Veronique Rebuffel from CEA Grenoble.

In the context of Pierre-Antoine Rodesh's PhD thesis, we investigate new statistical and optimization methods for tomographic reconstruction from non standard detectors providing multiple energy signals.

7.5. Statistical models for Neuroscience

7.5.1. Advanced statistical analysis of functional Arterial Spin Labelling data

Participants: Florence Forbes, Aina Frau Pascual.

Joint work with: Philippe Ciuciu from Team PARIETAL and Neurospin, CEA Saclay.

Arterial Spin Labelling (ASL) is a non-invasive perfusion MR imaging technique that can be also used to measure brain function (fASL for functional ASL). In contrast to BOLD fMRI, it gives a quantitative and absolute measure of cerebral blood flow (CBF), making this modality appealing for clinical neuroscience and patient's follow-up over longitudinal studies. However, its limited signal-to-noise ratio makes the analysis of fASL data challenging. In this work, we compared different approaches (GLM vs JDE) in the analysis of functional ASL data for the detection of evoked brain activity at the group level during visual and motor task performance. Our dataset has been collected at Neurospin on a 3T Tim Trio Siemens scanner (CEA Saclay, France), during the HEROES project (Inria Grant). It contains BOLD data (165 scans, TR=2.5s, TE=30ms, 3x3x3mm3) and functional pulsed ASL data (Q2TIPS PICORE scheme [Luh,00], 165 scans, TR=2.5s, TE=11ms, 3x3x7.5 mm3) of 13 right-handed subjects (7 men and 6 women) of age between 20 and 29. The experimental design consists of a mini-block paradigm of visual, motor and auditory tasks with 16 blocks of 15s each followed by 10s of rest. Data have been scaled, realigned, and normalized. For univariate analysis, the images have also been spatially smoothed with a Gaussian kernel of 5 mm full width half at maximum. Three data analysis approaches have been compared: (a) univariate General Linear Model (GLM) that considers canonical shapes for the perfusion and hemodynamic responses; (b) physiologically informed joint detection estimation (PI-JDE) [4] that jointly estimates effect maps and response functions in a multivariate manner in a Bayesian framework; (c) A restricted version of PI-JDE that considers fixed canonical shapes for the perfusion and hemodynamic responses (PRF and HRF, respectively), defining an intermediate approach between the first two. Since methods (b)-(c) embed adaptive spatial regularization, they do not require a preliminary smoothing of the data. Our results demonstrate that the PI-JDE multivariate approach is a competing alternative to GLM for the analysis of fASL: it recovers more localized and stronger effects. Our findings also replicate the state-of-the-art by showing more localized activation patterns in perfusion as compared to hemodynamics.

7.5.2. BOLD VEM multi session extension of the JDE approach

Participants: Florence Forbes, Aina Frau Pascual.

Joint work with: Philippe Ciuciu from Team PARIETAL and Neurospin, CEA Saclay.

The fast solution of the JDE approach for BOLD fMRI presented in [5] uses a variational expectation maximization (VEM) algorithm and considers a single session of BOLD data. This paper shows the faster performance of this algorithm with respect to the Markov Chain Monte Carlo (MCMC) approach presented in earlier work, with similar results. In fMRI, usually several sessions are acquired for the same subject to be able to compare them or combine them. In [73], a multiple-session extension of the JDE approach has been proposed to analyze several sessions together. The solution proposed uses MCMC and considers that the response levels have a mean value per condition and a common variance between sessions. In the context of Aina Frau's PhD, a VEM solution of this extension has been implemented. Experimental results have shown that the solution of the multiple-session VEM is not very different from the average of the results computed with single session VEM. For this reason, we proposed a heteroscedastic version of the multiple-session VEM. It amounts to considering session-specific variances. The goal is to be able to weight the importance of the different sessions so as to diminish the contribution of any potential noisy session to the final parameter estimates.

7.5.3. Estimating biophysical parameters from multimodal fMRI data

Participants: Florence Forbes, Pablo Mesejo Santiago.

Joint work with: Jan Warnking from Grenoble Institute of Neuroscience.

Functional Magnetic Resonance Imaging (fMRI) indirectly studies brain function. With Jan M. Warnking (Grenoble Institute of Neurosciences) we worked on the estimation of biophysical parameters from fMRI signals. We first used only BOLD signals, using a stochastic population-based optimization method to estimate 15 parameters without neither providing initial estimates nor computing gradients. Initial results were published at MICCAI 2015 and in the IEEE JSTSP journal [81], [82]. Also a MATLAB toolbox was released (see software section). The current ongoing work is to study the impact of the combination of different fMRI modalities in the estimation of this biophysical parameters. We can use 3 fMRI modalities (BOLD, ASL and MION) and 13 rats. We ran our optimizer with all possible combinations of modalities. The initial hypothesis was that as long as we introduce more fMRI modalities we would like to see more consistent estimates but we need to assess possible limits due to potential lack of data: only 13 rats, 6 of them without MION, and potential outliers among the rats that would better be excluded from the analysis.

7.5.4. Multi-subject joint parcelation detection estimation in functional MRI

Participant: Florence Forbes.

Joint work with: Lotfi Chaari, Mohanad Albughdadi, Jean-Yves Tourneret from IRIT-ENSEEIHT in Toulouse and Philippe Ciuciu from Neurospin, CEA Saclay.

fMRI experiments are usually conducted over a population of interest for investigating brain activity across different regions, stimuli and subjects. Multi-subject analysis usually proceeds in two steps: an intra-subject analysis is performed sequentially on each individual and then a group-level analysis is carried out to report significant results at the population level. This work considers an existing Joint Parcellation Detection Estimation (JPDE) model which performs joint hemodynamic parcellation, brain dynamics estimation and evoked activity detection. The hierarchy of the JPDE model is extended for multi-subject analysis in order to perform group-level parcellation. Then, the corresponding underlying dynamics is estimated in each parcel while the detection and estimation steps are iterated over each individual. Validation on synthetic and real fMRI data shows its robustness in inferring group-level parcellation and the corresponding hemodynamic profiles. This work has been presented at ISBI 2016 [42].

7.5.5. Automatic segmentation and characterization of brain tumors using robust multivariate clustering of multiparametric MRI

Participants: Florence Forbes, Alexis Arnaud.

Joint work with: Emmanuel Barbier and Benjamin Lemasson from Grenoble Institute of Neuroscience.

Brain tumor segmentation is a difficult task in the field of multiparametric MRI analysis because of the number of maps that are available. Furthermore, the characterization of brain tumors can be time-consuming, even for medical experts, and the reference method is biopsy which is a local and invasive technique. Because of this, it is important to develop automatic and non-invasive approaches in order to help the medical expert with these issues. In this study we use a robust statistical model-based method to classify multiparametric MRI of rat brains. The voxels are gather into classes resulting from multivariate multi-scaled Student distributions, which can accommodate outliers. First we adjust a mixture model on a reference group of rats to learn the MRI characteristics of healthy tissues. Second we use this model to delineate the brain tumors as atypical voxels in the data set of unhealthy rats. Third we adjust a new mixture model only on the atypical voxels to learn the MRI characteristics of tumorous tissues. Finally, we extract a fingerprint for each tumor type to make a tumor dictionary.

Our data set is composed of healthy rats (n=8 rats) and 4 groups of rats bearing a brain tumor model (n=8 per group). For each rat, we acquired 5 quantitative MRI parameters along 5 slices. And the proposed tumor dictionary reaches a rate of 75% of accurate prediction with a leave-one-out procedure.

7.5.6. Monitoring brain tumor evolution using multiparametric MRI

Participants: Florence Forbes, Alexis Arnaud.

Joint work with: Emmanuel Barbier, Nora Collomb and Benjamin Lemasson from Grenoble Institute of Neuroscience.

Analyzing brain tumor tissue composition can improve the handling of tumor growth and resistance to therapies. We showed on a 6 time point dataset of 8 rats that multiparametric MRI could be exploited via statistical clustering to quantify intra-lesional heterogeneity in space and time. More specifically, MRI can be used to map structural, eg diffusion, as well as functional, eg volume (BVf), vessel size (VSI), oxygen saturation of the tissue (StO2), characteristics. In previous work, these parameters were analyzed to show the great potential of multiparametric MRI (mpMRI) to monitor combined radio- and chemo-therapies. However, to exploit all the information contained in mpMRI while preserving information about tumor heterogeneity, new methods need to be developed. We demonstrated the ability of clustering analysis applied to longitudinal mpMRI to summarize and quantify intra-lesional heterogeneity during tumor growth. This study showed the interest of a clustering analysis on mpMRI data to monitor the evolution of brain tumor heterogeneity. It highlighted the type of tissue that mostly contributes to tumor development and could be used to refine the evaluation of therapies and to improve tumor prognosis.

7.5.7. Assessment of tissue injury in severe brain trauma

Participant: Florence Forbes.

Joint work with: Michel Dojat and Christophe Maggia from Grenoble Institute of Neuroscience and Senan Doyle from Pixyl.

Traumatic brain injury (TBI) remains a leading cause of death and disability among young people worldwide and current methods to predict long-term outcome are not strong. TBI initiates a cascade of events that can lead to secondary brain damage or exacerbate the primary injury, and these develop hours to days after the initial accident. The concept of secondary brain damage is the focus of modern TBI management in Intensive Care Units. The imbalance between oxygen supply to the brain tissue and utilization, i.e. brain tissue hypoxia, is considered the major cause for the development of secondary brain damage, and hence poor neurological outcome. Monitoring brain tissue oxygenation after TBI using brain tissue O_2 pressure (PbtO_2) probes surgically inserted into the parenchyma, may help clinicians to initiate adequate actions when episodes of brain ischemia/hypoxia are identified. The aggressive treatment of low PbtO_2 values ($<$ 15mmHg for more than 30 minutes) was associated with better outcome compared to standard therapy in some cohort studies of severe head-injury patients. However, another study was unable to find similar benefits to patient outcome. MRI is an excellent modality for estimating global and regional alterations in TBI and for following their longitudinal evolution. To assess the complexity of TBI, several morphological sequences are required for assessing volume loss. Moreover, diffusion tensor imaging (DTI) offers the most sensitive modality for the detection of changes in the acute phase of TBI and increases the accuracy of long-term outcome prediction compared to the available clinical/radiographic prognostic score. Mean Diffusivity (MD) or Apparent Diffusion Coefficient (ADC) have been widely used to determine the volume of ischemic tissue, and assess intra- and extracellular conditions. A reduction of MD is related to cytotoxic edema (intracellular) while an increase of MD indicates a vasogenic edema (extracellular). Changes of MD are expected with severe TBI. The volume of lesions on DTI shows a strong correlation with neurological outcome at patient discharge. We consider a clinically relevant criterion to be the volume of vulnerable brain lesions after TBI, as previously suggested. In consequence, we need an automatic segmentation method to assess the tissue damage in severe trauma, acute phase i.e. before 10 days after the event. Skull deformation, the presence of blood in the acute phase, the high variability of brain damage that excludes the use of anatomical *a priori* information, and the diffuse aspect of brain injury affecting potentially all brain structures, render TBI segmentation particularly demanding. The methods proposed in the literature are mainly concerned with volumetric changes following TBI and scarcely report lesion load. In this work, we report our methodological developments to assess lesion load in severe brain trauma in the entire brain. We use P-LOCUS to perform brain tissue segmentation and exclude voxels labeled as CSF, ventricle and hemorrhagic lesion. We propose a fusion of several atlases to parcel cortical, subcortical and WM structures into well identified regions where MD values can be expected to be homogenous. Abnormal voxels are detected in these regions by comparing MD values with normative values computed from healthy volunteers. The preliminary results, evaluated in a single center, are a first step in defining a robust methodology intended to be used in multi-center studies. This work has been published in [58].

7.5.8. Automatic multiple sclerosis lesion segmentation with P-Locus

Participant: Florence Forbes.

Joint work with: Michel Dojat from Grenoble Institute of Neuroscience and Senan Doyle from Pixyl.

P-LOCUS provides automatic quantitative neuroimaging biomarker extraction tools to aid diagnosis, prognosis and follow-up in multiple sclerosis studies. The software performs accurate and precise segmentation of multiple sclerosis lesions in a multi-stage process. In the first step, a weighted Gaussian tissue model is used to perform a robust segmentation. The algorithm avails of complementary information from multiple MR sequences, and includes additional estimated weight variables to account for the relative importance of each voxel. These estimated weights are used to define candidate lesion voxels that are not well described by a normal tissue model. In the second step, the candidate lesion regions are used to populate the weighted Gaussian model and guide convergence to an optimal solution. The segmentation is unsupervised, removing the need for a training dataset, and providing independence from specific scanner type and MRI scanner protocol. The procedure was applied to participate to the MSSEG Challenge at Miccai 2016 in Athen: Multiple Sclerosis Lesions Segmentation Challenge Using a Data Management and Processing Infrastructure [55].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

CIFRE PhD with SCHNEIDER (2015-2018). F. Forbes and S. Girard are the advisors of a CIFRE PhD (T. Rahier) with Schneider Electric. The other advisor is S. Marié from Schneider Electric. The goal is to develop specific data mining techniques able to merge and to take advantage of both structured and unstructured (meta)data collected by a wide variety of Schneider Electric sensors to improve the quality of insights that can be produced. The total financial support for MISTIS is of 165 keuros.

PhD contract with EDF (2016-2018). S. Girard is the advisor of a PhD (A. Clément) with EDF. The goal is to investigate sensitivity analysis and extrapolation limits in Extreme value theory with application to river flows analysis.

9. Partnerships and Cooperations

9.1. Regional Initiatives

- MISTIS participates in the weekly statistical seminar of Grenoble. Jean-Baptiste Durand is in charge of the organization and several lecturers have been invited in this context.
- F. Forbes and P. Mesejo are co-organizing a reading group on Deep Learning with R. Horaud and K. Alahari.

9.2. National Initiatives

9.2.1. Grenoble Idex projects

MISTIS is involved in a newly accepted transdiciplinary project **NeuroCoG** (December 2016). F. Forbes is also responsible for a workpackage in another project entitled "Institut des sciences des données".

9.2.2. Competitivity Clusters

The MINALOGIC VISION 4.0 project:MISTIS is involved in a new (October 2016) three-year *Pôle de competitivité Minalogic* project. The project is led by VI-Technology (http://www.vitechnology.com), a world leader in Automated Optical Inspection (AOI) of a broad range of electronic components. The other partners are the G-Scope Lab in Grenoble and ACTIA company based in Toulouse. Our goal is to exploit more intensively statistical techniques to exploit the large amount of data registered by AOI machines.

9.2.3. Defi Mastodons CNRS

Defi La qualité des données dans le Big Data (2016-17). S. Girard is involved in a 1-year project entitled “Classification de Données Hétérogènes avec valeurs manquantes appliquée au Traitement des Données Satellitaires en écologie et Cartographie du Paysage”, the other partners being members of Modal (Inria Lille Nord-Europe) or ENSAT-Toulouse. The total funding is 10 keuros.

9.2.4. Defi Imag’IN CNRS

Defi Imag’IN MultiPlanNet (2015-2016). This is a 2-year project to build a network for the analysis and fusion of multimodal data from planetology. There are 8 partners: IRCCYN Nantes, GIPSA-lab Grenoble, IPAG Grenoble, CEA Saclay, UPS Toulouse, LGL Lyon1, GEOPS University Orsay and Inria Mistis. F. Forbes is in charge of one work package entitled *Massive inversion of multimodal data*. Our contribution will be based on our previous work in the VAHINE project on hyperspectral images and recent developments on inverse regression methods. The CNRS support for the network is of 20 keuros.

9.2.5. GDR Madics

Apprentissage, opTimisation à Large-échelle et cAlcul diStribué (ATLAS). Mistis is participating to this action supported by the GDR in 2016 (3 keuros).

9.2.6. Networks

MSTGA and AIGM INRA (French National Institute for Agricultural Research) networks: F. Forbes is a member of the INRA network called AIGM (ex MSTGA) network since 2006, http://carlit.toulouse.inra.fr/AIGM, on Algorithmic issues for Inference in Graphical Models. It is funded by INRA MIA and RNSC/ISC Paris. This network gathers researchers from different disciplines. F. Forbes co-organized and hosted 2 of the network meetings in 2008 and 2015 in Grenoble.

9.3. International Initiatives

9.3.1. Inria International Labs

LIRIMA

Associate Team involved in the International Lab:

9.3.1.1. SIMERGE

Title: Statistical Inference for the Management of Extreme Risks and Global Epidemiology

International Partner (Institution - Laboratory - Researcher):

UGB (Senegal) - LERSTAD - Abdou Kâ Diongue

Starting year: 2015

See also: http://mistis.inrialpes.fr/simerge

The objective of the associate team is to federate some researchers from LERSTAD (Laboratoire d'Etudes et de Recherches en Statistiques et Développement, Université Gaston Berger) and MISTIS (Inria Grenoble Rhône-Alpes). The associate team will consolidate the existing collaborations between these two laboratories. Since 2010, the collaborations have been achieved through the co-advising of two PhD theses. They have led to three publications in international journals. The associate team will also involve statisticians from EQUIPPE laboratory (Economie QUantitative Intégration Politiques Publiques Econométrie, Université de Lille) and associated members of MODAL (Inria Lille Nord-Europe) as well as an epidemiologist from IRD (Institut de Recherche pour le Développement) at Dakar. We aim at developing two research themes: 1) Spatial extremes with application to management of extreme risks and 2) Classification with application to global epidemiology.

9.3.1.2. Informal International Partners

The context of our research is also the collaboration between MISTIS and a number of international partners such as the Statistics Department of University of Washington in Seattle, Université Gaston Berger in Senegal and Universities of Melbourne and Brisbane in Australia. In 2016, new collaborations had started with the statistics department of University of Michigan, in Ann Arbor, USA and with the statistics department of McGill University in Montreal, Canada.

The main active international collaborations in 2016 are with:

- F. Durante, Free University of Bozen-Bolzano, Italy.
- K. Qin and D. Wraith resp. from RMIT in Melbourne, Australia and Queensland University of Technology in Brisbane, Australia.
- E. Deme and S. Sylla from Gaston Berger university and IRD in Senegal.
- M. Stehlik from Johannes Kepler Universitat Linz, Austria and Universidad de Valparaiso, Chile.
- A. Nazin from Russian Academy of Science in Moscow, Russia.
- M. Houle from National Institute of Informatics, Tokyo, Japan.
- N. Wang and C-C. Tu from University of Michigan, Ann Arbor, USA.
- R. Steele, from McGill university, Montreal, Canada.

9.3.2. Participation in Other International Programs

Alexis Arnaud received an award from the MITACS program, for a 5 months visit to McGill university in Montreal.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

- Seydou Nourou Sylla (Université Gaston Berger, Sénégal) has been hosted by the MISTIS team for two months.
- Naisyin Wang and Chun-Chen Tu from University of Michigan, Ann Arbor, USA, have been hosted by the MISTIS team for one week.

9.4.2. Visits to International Teams

S. Girard went to univ. Gaston Berger in St Louis Senegal in the context of the SIMERGE associated team.

9.4.2.1. Research Stays Abroad

Alexis Arnaud spent 5 months at McGill university in Montreal.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Organizing Committees

- Stéphane Girard co-organized the workshop "Learning with functional data", held in Lille (October 2016), He was also a member of the organizing committee of “Journées MAS de la SMAI”, held in Grenoble (August 2016)
- Florence Forbes and Stéphane Girard co-organized a session “Dimension reduction for regression” at the ERCIM conference in Séville, Spain (December 2016).
- Julyan Arbel organized the Bayesian nonparametric prediction session at the International Society of Bayesian Analysis Conference, June 2016. He also co-organized the StaTalk Workshop on Bayesian nonparametrics, Collegio Carlo Alberto, Moncalieri, Italy, February 19.

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

- Stéphane Girard was the president of the scientific committee of the CIMPA conference “Méthodes statistiques pour l’évaluation des risques extrêmes”, held in Saint-Louis, Sénégal (April 2016), .
- Stéphane Girard was a member of the conference program committee of the “Mathematical Finance and Actuarial Sciences conference” organized by the AIMS (African Institute for Mathematical Sciences), Mbour, Sénégal (July 2016).

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- Stéphane Girard is Associate Editor of the *Statistics and Computing* journal since 2012 and Associate Editor of the *Journal of Multivariate Analysis* since 2016. He was co-editor of the book *Statistics for astrophysics, clustering and classification*, vol. 77, EDP sciences, 2016.

  He is also member of the Advisory Board of the *Dependence Modelling* journal since december 2014.
- F. Forbes is Associate Editor of the journal Frontiers in ICT: Computer Image Analysis since its creation in Sept. 2014. Computer Image Analysis is a new specialty section in the community-run openaccess journal Frontiers in ICT. This section is led by Specialty Chief Editors Drs Christian Barillot and Patrick Bouthemy.

10.1.3.2. Reviewer - Reviewing Activities

In 2016, S. Girard has been a reviewer for *Australian and New Zealand Journal of Statistics, Extremes* and *Dependence Modelling.*

In 2016, F. Forbes has been a reviewer for *Journal of Multivariate Analysis, Statistics and Computing, Computational Statistics and Data Analysis* .

In 2016, Julyan Arbel has been reviewer for NIPS 2016, ICML 2016, AISTATS 2016, the Annals of Statistics, Bayesian Analysis, Bernoulli, Biometrics, the Canadian Journal of Statistics, the Hacettepe Journal of Mathematics and Statistics, the Journal of Agricultural, Biological, and Environmental Statistics, SoftwareX, Statistics and Computing.

10.1.4. Invited Talks

Stéphane Girard has been invited to give a talk to the following conferences:

- "Extreme value modeling and water ressources" workshop (Aussois) [29],

- 3rd conference of the International Society for Non-Parametric Statistics (Avignon) [37],

- "Extremes - Copulas - Actuarial sciences" workshop (Luminy) [40],

- Statistics workshop at Tilburg University (Netherlands)

- ERCIM CFE-CMStatistics (Seville, Spain) [39].

Florence Forbes has been invited to give talks at :

- the 23th summer session of the Working Group on Model-based Clustering, Paris, July 18-23, 2016.

- the Fédération Rhône-Alpes-Auvergne day on multivariate data analysis in Grenoble, October 2016,

- the 11th Peyresq summer school on signal and image processing (July 2016): 5 hour lecture on Bayesian Analysis and applications [67].

- a special session on Dimension reduction for regression at the ERCIM CFE-CMStatistics conference, December 2016, in Seville, Spain [35],

- at the annual meeting of the MultiPlaNet project (Defi Imag'In CNRS) in Orsay in December 2016, on the inversion of the Hapke's model from photometric measurements.

Julyan Arbel has been invited to give talks at the following seminars and conferences:

- Rencontres Statistiques Lyonnaises, Institut Camille Jordan, November 23. Invited talk: Bayesian nonparametric inference for discovery probabilities.

- Séminaire de Statistique du LJK, Université Grenoble Alpes, November 17. Invited talk: Bayesian nonparametric inference for discovery probabilities.

- The Bayes Club, Korteweg-de Vries Institute for Mathematics, University of Amsterdam, October 7. Invited talk: Bayesian nonparametric inference for discovery probabilities.

- Séminaire de Statistique, Université Lille 3, October 6. Invited talk: Bayesian nonparametric inference for discovery probabilities.

- Séminaire de Proba-Stat, Université Paris 12 Créteil, October 4. Invited talk: Bayesian nonparametric inference for discovery probabilities.

- Séminaire de Proba-Stat, Université de Franche-Comté, Besancon, September 5. Invited talk: Bayesian nonparametric inference for discovery probabilities.

- ISBA World Meeting, Sardinia, Italy, June 13-17. Invited talk: Bayesian nonparametric inference for discovery probabilities.

- Mistis Seminar, Inria Grenoble, France, February 12. Talk: Infinite mixture models in Bayesian nonparametrics.

Julyan Arbel presented at the following contributed sessions in conferences and workshops:

- NIPS Meeting, Barcelona, Spain, Poster: Truncation error of a superposed gamma process in a decreasing order representation, Poster: Advances in Approximate Bayesian Inference workshop, Dec 9.

- NIPS Meeting, Barcelona, Spain, Sequential Quasi Monte Carlo for Dirichlet Process Mixture Models, Practical Bayesian Nonparametrics workshop, Dec 9.

- Journées MAS, Grenoble, France, August 29-31. Poster: Bayesian nonparametrics, why and how?

- Third Bayesian Young Statisticians Meeting, Florence, Italy, June 19-21. Talk: A moment-matching Ferguson & Klass algorithm.

- Journées de Statistique de la SFdS, Montpellier, France, May 30 - June 3. Talk: Bayesian nonparametric inference for discovery probabilities.

- StaTalk Workshop, Collegio Carlo Alberto, Moncalieri, Italy, February 19. Talk 1: A gentle introduction to Bayesian Nonparametrics. Talk 2: Species sampling models.

- MCMSki V, Lenzerheide, Switzerland, January 5-7. Invited talk: A moment-matching Ferguson & Klass algorithm.

Emeline Perthame has been invited to give a talk at:

- the statistics seminar at University of Caen in October 2016 on an *Inverse regression approach to robust non-linear high-to-low dimensional mapping*.

Gildas Mazo has been invited to give a talk at:

- a special session on Copulas at the ERCIM CFE-CMStatistics conference, December 2016, in Seville, Spain.

Alexis Arnaud gave a talk at:

- a GdR ISIS meeting on *Méthodes d'apprentissage statistiques et applications à la santé* 2016-10-21, Telecom Paris, on Automatic segmentation and characterization of brain tumors using robust multivariate clustering of multiparametric MRI.

10.1.5. Leadership within the Scientific Community

Stéphane Girard is at the head of the associate team (*Statistical Inference for the Management of Extreme Risks and Global Epidemiology*) created in 2015 between IISTIS and LERSTAD (Université Gaston Berger, Saint-Louis, Sénégal). The team is part of the LIRIMA (Laboratoire International de Recherche en Informatique et Mathématiques Appliquées), http://mistis.inrialpes.fr/simerge.

10.1.6. Scientific Expertise

- Stéphane Girard was in charge of evaluating research projects for the Research Foundation Flanders (FWO), Belgium.
- Stéphane Girard is a Voting Member for the International Society for NonParametric Statistics (ISNPS).

10.1.7. Research Administration

- Stéphane Girard has been at the head of the Probability and Statistics department of the LJK (Laboratoire Jean Kuntzmann) from September 2012 to September 2016.
- Grenoble Pole Cognition. F. Forbes is representing Inria and LJK in the pole.
- PRIMES Labex, Lyon. F. Forbes is a member of the strategic committee. F. Forbes is representing Inria.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master : Stéphane Girard, *Statistique Inférentielle Avancée*, 41 ETD, M1 level, Ensimag. Grenoble-INP, France.

Master : Stéphane Girard, *Introduction à la statistique des valeurs extrêmes*, 15 ETD, M2 level, Université Gaston Berger, Saint-Louis, Sénégal.

Licence : Alexis Arnaud, *Probability and statistics*, 56 ETD, L2 level, IUT2 Grenoble, Université Pierre Mendès France.

Master: Jean-Baptiste Durand, *Statistics and probability*, 192 ETD, M1 and M2 levels, Ensimag Grenoble INP, France. Head of the MSIAM M2 programme, in charge of the statistics and data science tracks ([12]).

J.-B. Durand is a faculty member at Ensimag, Grenoble INP.

J-M. Becu, C. Albert, B. Olivier are teaching at UGA.

Master and PhD course: Julyan Arbel gave a course on Bayesian statistics, 30 ETD, Collegio Carlo Alberto, Moncalieri, Turin, Italy.

10.2.2. Supervision

Aina Frau-Pascual, "*Statistical models for the analysis of ASL and BOLD functional magnetic resonance modalities to study brain function and disease*", defended on December 19, 2016, Université Grenoble-Alpes, supervised by Florence Forbes and Philippe Ciuciu (CEA, Inria PARIETAL).

Seydou Nourou Sylla, "*Modélisation et classification de données binaires en grande dimension - Application à l'autopsie verbale*", defended on December 21, 2016, Université Gaston Berger, Saint-Louis, Sénégal, supervised by Abdou Diongue (Université Gaston Berger, Sénégal) and Stéphane Girard.

Alessandro Chiancone, "*Réduction de dimension via Sliced Inverse Regression: Idées et nouvelles propositions*", defended on October 28, 2016, Université Grenoble-Alpes, supervised by Stéphane Girard and Jocelyn Chanussot (Grenoble INP).

PhD in progress: Thibaud Rahier, "*Data-mining pour la fusion de données structurées et non-structurées*", started on November 2015, Florence Forbes and Stéphane Girard.

PhD in progress: Clément Albert, "*Limites de crédibilité d'extrapolation des lois de valeurs extrêmes*", started on January 2016, Stéphane Girard.

PhD in progress: Maïlys Lopes, "*Télédétection en écologie du paysage : statistiques en grande dimension pour la multirésolution spatiale et la haute résolution temporelle*", started on November 2014, Stéphane Girard and Mathieu Fauvel (INRA Toulouse).

PhD in progress: Alexis Arnaud "*Multiparametric MRI statistical analysis for the identification and follow-up of brain tumors* ", October 2014, Florence Forbes and Emmanuel Barbier (GIN).

PhD in progress: Pierre-Antoine Rodesch, "*Spectral tomography and tomographic reconstruction algorithms*", October 2015, Florence Forbes and Veronique Rebuffel (CEA Grenoble).

PhD in progress: Brice Olivier, "*Joint analysis of eye-movements and EEGs using coupled hidden Markov and topic models*", October 2015, Jean-Baptiste Durand, Marianne Clausel and Anne Guérin-Dugué (Université Grenoble Alpes).

10.2.3. Juries

10.2.3.1. PhD

- Stéphane Girard has been reviewer of three PhD theses in 2016:

  - Cees de Valk, "*A large deviation approach to the statistics of extreme events*", Tilburg University, Netherlands, December 2016.

  - Nicolas Goix, "*Apprentissage automatique et extrêmes et pour la détection d'anomalies*", Telecom ParisTech, november 2016.

  - Anthony Zullo, "*Analyse de données fonctionnelles en télédétection hyperspectrale : application à l'étude des paysages agri-forestiers*", Univ. Toulouse, September 2016.

- S. Girard was a member of two PhD committees in 2016:

  - Quentin Sebille, “*Modélisation spatiale de valeurs extrêmes, application à l'étude de précipitations en France*, Univ. Lyon, december 2016.

  - Khalil Said, “*Mesures de risque multivariées et applications en science actuarielle*”, Univ. Lyon, december 2016.

- Florence Forbes has been reviewer of 1 PhD thesis in 2016:

  - Hong Phuong Dang, December 1st, 2016, Centrale Lille.

- F. Forbes was a member of one PhD committee in 2016:

  - Mohanad Albughdadi, September 2016, ENSHEEIT, Toulouse.

10.2.3.2. HDR

S. Girard was a member of the HDR committee of Mathieu Ribatet, Univ. Montpellier, November 2016.

F. Forbes was in the HDR committee of Sophie Achard, Univ. Grenoble Alpes, May 2016.

10.2.3.3. Other committees

- S. Girard is a member of the "Comité des Emplois Scientifiques" at Inria Grenoble Rhône-Alpes since 2015.
- F. Forbes is a member of the Committee for technological project and engineer candidate selection at Inria Grenoble Rhône-Alpes ("Commission du développement technologique ") since 2015.
- Since 2015, S. Girard is a member of the INRA committee (CSS MBIA) in charge of evaluating INRA researchers once a year in the MBIA dept of INRA.
- F. Forbes has been a member of 2 selection committees for Professors at Centrale-Supelec and Centrale Nantes and 1 selection committee for Assistant Professor at Paris-Sud University.

10.3. Popularization

- S. Girard presented his research on extreme-value analysis at the “Conférence ISN et enseignement”, March 2016, video. He also gave a talk at the Institut de Maitrise des Risques (IMdR) [38] on a similar topic.
- Julyan Arbel led the Math en Jeans teams at Lycée francais Jean Giono, Turin, working on various subjects spanning from statistics, machine learning, to combinatorics and games.

11. Bibliography

Major publications by the team in recent years

[1] C. Amblard, S. Girard.*Estimation procedures for a semiparametric family of bivariate copulas*, in "Journal of Computational and Graphical Statistics", 2005, vol. 14, n^{o} 2, p. 1–15.

[2] J. Blanchet, F. Forbes.*Triplet Markov fields for the supervised classification of complex structure data*, in "IEEE trans. on Pattern Analyis and Machine Intelligence", 2008, vol. 30(6), p. 1055–1067.

[3] C. Bouveyron, S. Girard, C. Schmid.*High dimensional data clustering*, in "Computational Statistics and Data Analysis", 2007, vol. 52, p. 502–519.

[4] C. Bouveyron, S. Girard, C. Schmid.*High dimensional discriminant analysis*, in "Communication in Statistics - Theory and Methods", 2007, vol. 36, n^{o} 14.

[5] L. CHAARI, T. VINCENT, F. FORBES, M. DOJAT, P. CIUCIU.*Fast joint detection-estimation of evoked brain activity in event-related fMRI using a variational approach*, in "IEEE Transactions on Medical Imaging", May 2013, vol. 32, n^{o} 5, p. 821-837 [*DOI :* 10.1109/TMI.2012.2225636], http://hal.inria.fr/inserm-00753873.

[6] A. DELEFORGE, F. FORBES, R. HORAUD.*High-Dimensional Regression with Gaussian Mixtures and Partially-Latent Response Variables*, in "Statistics and Computing", February 2014 [*DOI :* 10.1007/s11222-014-9461-5], https://hal.inria.fr/hal-00863468.

[7] F. FORBES, G. FORT.*Combining Monte Carlo and Mean field like methods for inference in hidden Markov Random Fields*, in "IEEE trans. Image Processing", 2007, vol. 16, n^{o} 3, p. 824-837.

[8] F. FORBES, D. WRAITH.*A new family of multivariate heavy-tailed distributions with variable marginal amounts of tailweights: Application to robust clustering*, in "Statistics and Computing", November 2014, vol. 24, n^{o} 6, p. 971-984 [*DOI :* 10.1007/s11222-013-9414-4], https://hal.inria.fr/hal-00823451.

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[10] S. GIRARD, P. JACOB.*Extreme values and Haar series estimates of point process boundaries*, in "Scandinavian Journal of Statistics", 2003, vol. 30, n^{o} 2, p. 369–384.

Publications of the year

Articles in International Peer-Reviewed Journal

[11] M. ALBUGHDADI, L. CHAARI, J.-Y. TOURNERET, F. FORBES, P. CIUCIU.*A Bayesian Non-Parametric Hidden Markov Random Model for Hemodynamic Brain Parcellation*, in "Signal Processing", 2017, https://hal.archives-ouvertes.fr/hal-01426385.

[12] M.-R. AMINI, J.-B. DURAND, O. GAUDOIN, E. GAUSSIER, A. IOUDITSKI.*Data Science: an international training program at master level*, in "Statistique et Enseignement (ISSN 2108-6745)", June 2016, vol. 7, n^{o} 1, p. 95-102, https://hal.inria.fr/hal-01342469.

[13] J. ARBEL, V. COSTEMALLE.*Estimation of immigration flows : reconciling two sources by a Bayesian approach*, in "Economie et Statistique", April 2016, https://hal.archives-ouvertes.fr/hal-01396606.

[14] A. CHIANCONE, F. FORBES, S. GIRARD.*Student Sliced Inverse Regression*, in "Computational Statistics and Data Analysis", August 2016 [*DOI :* 10.1016/j.csda.2016.08.004], https://hal.archives-ouvertes.fr/hal-01294982.

[15] A. CHIANCONE, S. GIRARD, J. CHANUSSOT.*Collaborative Sliced Inverse Regression*, in "Communication in Statistics - Theory and Methods", 2016 [*DOI :* 10.1080/03610926.2015.1116578], https://hal.inria.fr/hal-01158061.

[16] J.-B. DURAND, Y. GUÉDON.*Localizing the latent structure canonical uncertainty: entropy profiles for hidden Markov models*, in "Statistics and Computing", 2016, vol. 26, n^{o} 1, p. 549-567, The final publication is available at Springer via http://dx.doi.org/10.1007/s11222-014-9494-9 [*DOI :* 10.1007/s11222-014-9494-9], https://hal.inria.fr/hal-01090836.

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[19] I. D. GEBRU, X. ALAMEDA-PINEDA, F. FORBES, R. HORAUD.*EM Algorithms for Weighted-Data Clustering with Application to Audio-Visual Scene Analysis*, in "IEEE Transactions on Pattern Analysis and Machine Intelligence", December 2016, vol. 38, n^{o} 12, p. 2402 - 2415 [*DOI :* 10.1109/TPAMI.2016.2522425], https://hal.inria.fr/hal-01261374.

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Invited Conferences

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[40] S. GIRARD, A. DAOUIA, G. STUPFLER.*Estimation of tail risk based on extreme expectiles*, in "Workshop Extremes - Copulas - Actuarial science", Luminy, France, February 2016, https://hal.archives-ouvertes.fr/hal-01311778.

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Project-Team MORPHEO

Capture and Analysis of Shapes in Motion

IN COLLABORATION WITH: Laboratoire Jean Kuntzmann (LJK)

IN PARTNERSHIP WITH:
Institut polytechnique de Grenoble

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Vision, perception and multimedia interpretation

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Project-Team MORPHEO

Creation of the Team: 2011 March 01, updated into Project-Team: 2014 January 01

Keywords:

Computer Science and Digital Science:

5.1.8. - 3D User Interfaces
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5.4.4. - 3D and spatio-temporal reconstruction
5.4.5. - Object tracking and motion analysis
5.5.1. - Geometrical modeling
5.5.4. - Animation
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2.6.3. - Biological Imaging
2.8. - Sports, performance, motor skills
9.2.2. - Cinema, Television
9.2.3. - Video games
9.3. - Sports

1. Members

Research Scientists

Edmond Boyer [Team leader, Inria, Senior Researcher, HDR]
Julien Pansiot [Inria, Starting Research position]
Lionel Reveret [Inria, Researcher, until Jun 2016, HDR]
Stefanie Wuhrer [Inria, Researcher]

Faculty Members

Jean Sébastien Franco [INP Grenoble, Associate Professor]
Franck Hétroy-Wheeler [INP Grenoble, Associate Professor, HDR]

Technical Staff

Mickaël Heudre [Inria, until Sep 2016]

PhD Students

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Adnane Boukhayma [Inria, granted by Conseil Régional Rhône-Alpes]
Vincent Leroy [Inria]
Romain Rombourg [Univ. Grenoble Alpes]
Aurela Shehu [UNIV étrangère]
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Li Wang [Univ. Grenoble Alpes]
Jinlong Yang [Inria]
Victoria Fernandez Abrevaya [Univ. Grenoble Alpes, from Oct 2016]

Administrative Assistants

Julie Bourget [Inria, until Jul 2016]
Nathalie Gillot [Inria, from Sep 2016]

2. Overall Objectives

2.1. Overall Objectives

Morpheo's main objective is the ability to perceive and to interpret moving shapes using systems of multiple cameras for the analysis of animal motion, animation synthesis and immersive and interactive environments. Multiple camera systems allow dense information on both shapes and their motion to be recovered from visual cues. Such ability to perceive shapes in motion brings a rich domain for research investigations on how to model, understand and animate real dynamic shapes. In order to reach this objective, several scientific and technological challenges must be faced:

A first challenge is to be able to recover shape information from videos. Multiple camera setups allow to acquire shapes as well as their appearances with a reasonable level of precision. However most effective current approaches estimate static 3D shapes and the recovery of temporal information, such as motion, remains a challenging task. Another challenge in the acquisition process is the ability to handle heterogeneous sensors with different modalities as available nowadays: color cameras, time of flight cameras, stereo cameras and structured light scanners, etc.

A second challenge is the analysis of shapes. Few tools have been proposed for that purpose and recovering the intrinsic nature of shapes is an actual and active research domain. Of particular interest is the study of animal shapes and of their associated articulated structures. An important task is to automatically infer such properties from temporal sequences of 3D models as obtained with the previously mentioned acquisition systems. Another task is to build models for classes of shapes, such as animal species, that allow for both shape and pose variations.

A third challenge concerns the analysis of the motion of shapes that move and evolve, typically humans. This has been an area of interest for decades and the challenging innovation is to consider for this purpose dense motion fields, obtained from temporally consistent 3D models, instead of traditional sparse point trajectories obtained by tracking particular features on shapes, e.g. motion capture systems. The interest is to provide full information on both motions and shapes and the ability to correlate these information.The main tasks that arise in this context are first to find relevant indices to describe the dynamic evolutions of shapes and second to build compact representations for classes of movements.

A fourth challenge tackled by Morpheo is immersive and interactive systems. Such systems rely on real time modeling, either for shapes, motion or actions. Most methods of shape and motion retrieval turn out to be fairly complex, and quickly topple hardware processing or bandwidth limitations, even with a limited number of cameras. Achieving interactivity thus calls for scalable methods and research of specific distribution and parallelization strategies.

3. Research Program

3.1. Shape Acquisition

Multiple camera setups allow to acquire shapes, i.e. geometry, as well as their appearances, i.e. photometry, with a reasonable level of precision. However fundamental limitations still exist, in particular today's state-of-the-art approaches do not fully exploit the redundancy of information over temporal sequences of visual observations. Despite an increasing interest of the computer vision communities in the past years, the problem is still far from solved other than in specific situations with restrictive assumptions and configurations. Our goal in this research axis is to fully leverage temporal aspects of the acquisition process and to open the acquisition process to different modalities, in particular Xrays.

3.2. Generative / discriminative inference

Acquisition of 4D Models can often be conveniently formulated as an estimation or learning problem. Various generative models can be proposed for the problems of shape and appearance modeling over time sequences, and motion segmentation. The idea of these generative models is to predict the noisy measurements (e.g. pixel values, measured 3D points or speed quantities) from a set of parameters describing the unobserved scene state (e.g. shape and appearance), which in turn can be inverted with various inference algorithms. The advantages of this type of modeling are numerous to deal with noisy measurements, explicitly model dependencies between model parameters, hidden variables and observed quantities, and relevant priors over parameters; sensor models for different modalities can also easily be seamlessly integrated and jointly used, which remains central to our goals. A limitation of such algorithms is that classical algorithms to solve them rely on local iterative convergence schemes subject to local minima, or global restart schemes which avert this problem but with a significant computational penalty. This is why we also consider discriminative and deep learning approaches, which allow to formulate the parameter estimation as a direct regression from input quantities or pixel values, whose parameters are learned given a training set. This has the advantage of directly computing a solution from inputs, with robustness and speed benefits, as a standalone estimation algorithm or to initialize local convergence schemes based on generative modeling. A number of the approaches we propose thus leverage the advantages of both generative and such discriminative approaches.

3.3. Shape Analysis

Shape analysis has received much attention from the scientific community and recovering the intrinsic nature of shapes is currently an active research domain. Of particular interest is the study of human and animal shapes and their associated articulated underlying structures, i.e. skeletons, since applications are numerous, either in the entertainment industry or for medical applications, among others. Our main goals in this research axis are : the understanding of a shape's global structure, and a pose-independent classification of shapes.

3.4. Shape Tracking

Recovering the temporal evolution of a deformable surface is a fundamental task in computer vision, with a large variety of applications ranging from the motion capture of articulated shapes, such as human bodies, to the deformation of complex surfaces such as clothes. Methods that solve for this problem usually infer surface evolutions from motion or geometric cues. This information can be provided by motion capture systems or one of the numerous available static 3D acquisition modalities. In this inference, methods are faced with the challenging estimation of the time-consistent deformation of a surface from cues that can be sparse and noisy. Such an estimation is an ill posed problem that requires prior knowledge on the deformation to be introduced in order to limit the range of possible solutions. Our goal is to devise robust and accurate solutions based on new deformation models that fully exploit the geometric and photometric information available.

3.5. Dynamic Motion Modeling

Multiple views systems can significantly change the paradigm of motion capture. Traditional motion capture systems provide 3D trajectories of a sparse set of markers fixed on the subject. These trajectories can be transformed into motion parameters on articulated limbs with the help of prior models of the skeletal structure. However, such skeletal models are mainly robotical abstractions that do not describe the true morphology and anatomical motions of humans and animals. On the other hand, 4D models (temporally consistent mesh sequences) provide dense motion information on body's shape while requiring less prior assumption. They represent therefore a new rich source of information on human and animal shape movements. The analysis of such data has already received some attention but most existing works model motion through static poses and do not consider yet dynamic information. Such information (e.g. trajectories and speed) is anyway required to analyse walking or running sequences. We will investigate this research direction with the aim to propose and study new dynamic models.

3.6. Shape Animation

3D animation is a crucial part of digital media production with numerous applications, in particular in the game and motion picture industry. Recent evolutions in computer animation consider real videos for both the creation and the animation of characters. The advantage of this strategy is twofold: it reduces the creation cost and increases realism by considering only real data. Furthermore, it allows to create new motions, for real characters, by recombining recorded elementary movements. In addition to enable new media contents to be produced, it also allows to automatically extend moving shape datasets with fully controllable new motions. This ability appears to be of great importance with the recent advent of deep learning techniques and the associated need for large learning datasets. In this research direction, we will investigate how to create new dynamic scenes using recorded events.

4. Application Domains

4.1. 4D modeling

Modeling shapes that evolve over time, analyzing and interpreting their motion has been a subject of increasing interest of many research communities including the computer vision, the computer graphics and the medical imaging communities. Recent evolutions in acquisition technologies including 3D depth cameras (Time-of-Flight and Kinect), multi-camera systems, marker based motion capture systems, ultrasound and CT scans have made those communities consider capturing the real scene and their dynamics, create 4D spatio-temporal models, analyze and interpret them. A number of applications including dense motion capture, dynamic shape modeling and animation, temporally consistent 3D reconstruction, motion analyzes and interpretation have therefore emerged.

4.2. Shape Analysis

Most existing shape analysis tools are local, in the sense that they give local insight about an object's geometry or purpose. The use of both geometry and motion cues makes it possible to recover more global information, in order to get extensive knowledge about a shape. For instance, motion can help to decompose a 3D model of a character into semantically significant parts, such as legs, arms, torso and head. Possible applications of such high-level shape understanding include accurate feature computation, comparison between models to detect defects or medical pathologies, and the design of new biometric models or new anthropometric datasets.

4.3. Human Motion Analysis

The recovery of dense motion information enables the combined analyses of shapes and their motions. Typical examples include the estimation of mean shapes given a set of 3D models or the identification of abnormal deformations of a shape given its typical evolutions. The interest arises in several application domains where temporal surface deformations need to be captured and analysed. It includes human body analyses for which potential applications are anyway numerous and important, from the identification of pathologies to the design of new prostheses.

4.4. Interaction

The ability to build models of humans in real time allows to develop interactive applications where users interact with virtual worlds. The recent evolutions of HMDs, e.g. Oculus Rift, HTC Vibe and Microsoft Hololens, offer now efficient solutions to visualize virtual worlds, which dramatically increases the need for new contents as well as new interactive and immersive solutions. Challenging issues in this domain include the development of real time applications for interactivity and the design of new interactive applications such as virtual fitting rooms.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

The work on estimating the visual contrast on a 3D mesh has been awarded the best paper award at the Pacific Graphics 2016 conference.

BEST PAPERS AWARDS :

[] **Computer Graphics Forum**. G. NADER, K. WANG, F. HÉTROY-WHEELER, F. DUPONT.

6. New Software and Platforms

6.1. Kinovis: 4D repository

FUNCTIONAL DESCRIPTION

This website is now part of the Kinovis platform webiste. It hosts dynamic mesh sequences reconstructed from images captured using a multi-camera set up. Such mesh-sequences offer a new promising vision of virtual reality, by capturing real actors and their interactions. The texture information is trivially mapped to the reconstructed geometry, by back-projecting from the images. These sequences can be seen from arbitrary viewing angles as the user navigates in 4D (3D geometry + time) . Different sequences of human / non-human interaction can be browsed and downloaded from the data section.

- Contact: Edmond Boyer
- URL: http://kinovis.inrialpes.fr/4d-repository/

6.2. Lucy Viewer

KEYWORDS: Data visualization - 4D - Multi-Cameras

FUNCTIONAL DESCRIPTION

Lucy Viewer is an interactive viewing software for 4D models, i.e, dynamic three-dimensional scenes that evolve over time. Each 4D model is a sequence of meshes with associated texture information from the original real images.

- Participants: Mickaël Heudre, Jean-Sébastien Franco and Edmond Boyer
- Contact: Edmond Boyer
- URL: http://kinovis.inrialpes.fr/lucyviewer/

6.3. QuickCSG

KEYWORDS: 3D modeling - CAD - 3D reconstruction - Geometric algorithms

FUNCTIONAL DESCRIPTION QuickCSG is a library and command-line application that computes boolean operations between polyhedra. It is able to directly compute resulting solids from an arbitrary number of inputs and for an arbitrary boolean combination function, with state of the art execution times.

- Participants: Matthijs Douze, Jean-Sébastien Franco and Bruno Raffin
- Partner: INP Grenoble
- Contact: Matthijs Douze
- URL: http://kinovis.inrialpes.fr/quickcsg/

6.4. Shape Tracking

FUNCTIONAL DESCRIPTION

We are developing a software suite to track shapes over temporal sequences. The motivation is to provide temporally coherent 4D Models, i.e. 3D models and their evolutions over time , as required by motion related applications such as motion analysis. This software takes as input a temporal sequence of 3D models in addition to a template and estimate the template deformations over the sequence that fit the observed 3D models.

- Contact: Edmond Boyer

6.5. 3DtLaplace

KEYWORDS: Laplace operator - Mesh sequence
FUNCTIONAL DESCRIPTION This software computes a discrete 3D+t Laplace operator for temporally mesh sequences.

- Participants: Victoria Fernández-Abrevaya, Franck Hétroy-Wheeler and Stefanie Wuhrer
- Partner: INP Grenoble
- Contact: Victoria Fernández-Abrevaya
- URL: http://3dtlaplace.gforge.inria.fr/

6.6. CVTGenerator

KEYWORDS: Mesh - Centroidal Voronoi tessellation - Implicit surface
FUNCTIONAL DESCRIPTION CVTGenerator is a program that builds Centroidal Voronoi Tessellations of any 3D meshes and implicit surfaces.

- Participants: Edmond Boyer, Franck Hétroy-Wheeler and Li Wang
- Partner: INP Grenoble
- Contact: Li Wang
- URL: http://cvt.gforge.inria.fr/

6.7. Platforms

6.7.1. Platform Kinovis

Kinovis (http://kinovis.inrialpes.fr/) is a multi-camera acquisition project that was was selected within the call for proposals ”Equipements d’Excellence” of the program “Investissement d’Avenir˝ funded by the French government. The project involves 2 institutes: the Inria Grenoble Rhône-Alpes, the université Joseph Fourier and 4 laboratories: the LJK (laboratoire Jean Kuntzmann - applied mathematics), the LIG (laboratoire d’informatique de Grenoble - Computer Science), the Gipsa lab (Signal, Speech and Image processing) and the LADAF (Grenoble Hospitals - Anatomy). The Kinovis environment is composed of 2 complementary platforms. A first platform located at Inria Grenoble with a 10mx10m acquisition surface is equipped with 68 color cameras and 20 IR motion capture (mocap) cameras. It is the evolution of the Grimage platform towards the production of better models of more complex dynamic scenes. A second platform located at Grenoble Hospitals, within the LADAF anatomy laboratory, is equipped with 10 color and 2 X-ray cameras to enable combined analysis of internal and external shape structures, typically skeleton and bodies of animals. Installation works of both platforms started in 2013 and are now finished. Both platforms have already demonstrated their potential through a range of projects lead by the team and externally. Members of Morpheo are highly involved in this project. Edmond Boyer is coordinating this project and Lionel Reveret is in charge of the LADAF platform. Mickaël Heudre and Julien Pansiot were managing the technical resources of both platforms.

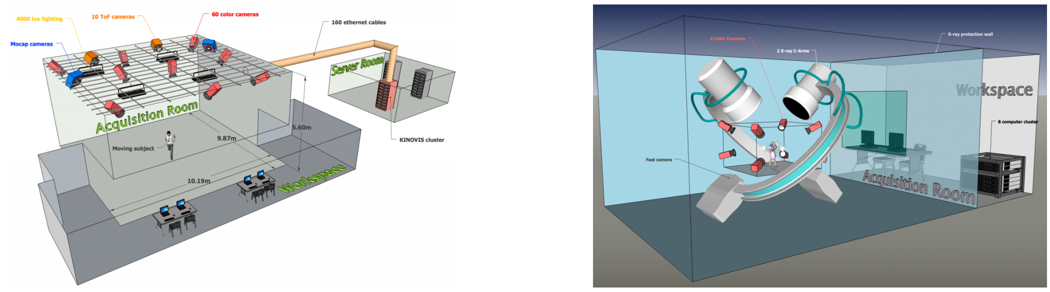

Figure 1. Kinovis platforms: on the left the Inria platform; on the right Grenoble Hospital platform.

7. New Results

7.1. Cotemporal Multi-View Video Segmentation

We address the problem of multi-view video segmentation of dynamic scenes in general and outdoor environments with possibly moving cameras. Multi-view methods for dynamic scenes usually rely on geometric calibration to impose spatial shape constraints between viewpoints. In this paper, we show that the calibration constraint can be relaxed while still getting competitive segmentation results using multi-view constraints. We introduce new multi-view cotemporality constraints through motion correlation cues, in addition to common appearance features used by co-segmentation methods to identify co-instances of objects. We also take advantage of learning based segmentation strategies by casting the problem as the selection of monocular proposals that satisfy multi-view constraints. This yields a fully automated method that can segment subjects of interest without any particular pre-processing stage, as depicted in Figure 2. Results on several challenging outdoor datasets demonstrate the feasibility and robustness of our approach.

This work has been presented at the International Conference on 3D Vision (3DV) 2016 [9].

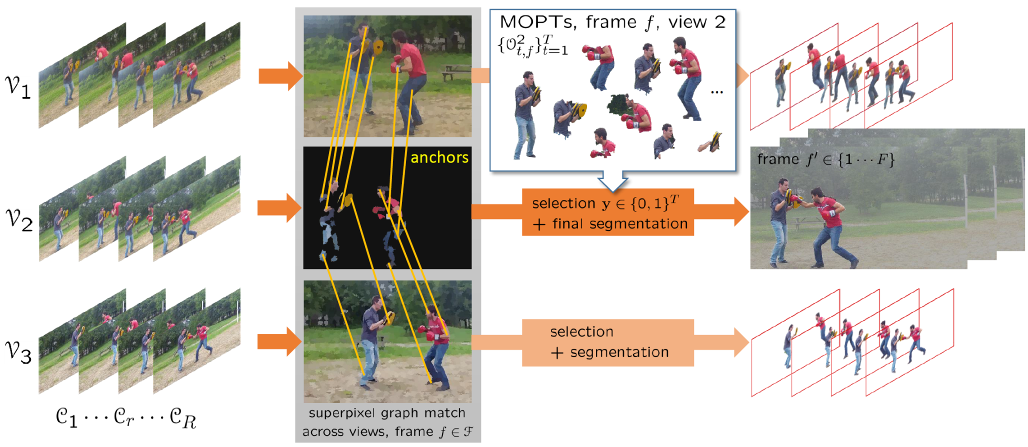

Figure 2. Overview of multiview segmentation pipeline

7.2. Volumetric Shape Reconstruction from Implicit Forms

In this work we evaluate volumetric shape reconstruction methods that consider as input implicit forms in 3D. Many visual applications build implicit representations of shapes that are converted into explicit shape representations using geometric tools such as the Marching Cubes algorithm. This is the case with image based reconstructions that produce point clouds from which implicit functions are computed, with for instance a Poisson reconstruction approach. While the Marching Cubes method is a versatile solution with proven efficiency, alternative solutions exist with different and complementary properties that are of interest for shape modeling. In this paper, we propose a novel strategy that builds on Centroidal Voronoi Tessellations (CVTs). These tessellations provide volumetric and surface representations with strong regularities in addition to provably more accurate approximations of the implicit forms considered. In order to compare the existing strategies, we present an extensive evaluation that analyzes various properties of the main strategies for implicit to explicit volumetric conversions: Marching cubes, Delaunay refinement and CVTs, including accuracy and shape quality of the resulting shape mesh.

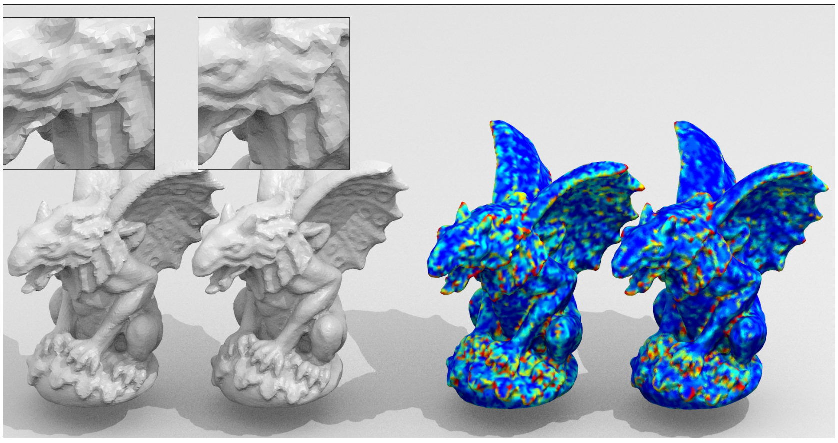

Figure 3. Poisson volumetric reconstructions from a Gargoyle point cloud with Marching Cubes (left) and CVT (right) [16]. Distances to the implicit form are color encoded on the right, from low (blue) to high (red).

This work has been presented at the ECCV 2016 conference [16].

7.3. Bayesian 3D imaging from X-rays and video

A new method for estimating 3D dense attenuation of moving samples such as body parts from multiple video and a single planar X-ray device has been devised [12]. Most dense modeling methods consider samples observed with a moving X-ray device and cannot easily handle moving samples. We proposed a novel method that uses a surface motion capture system associated to a single low-cost/low-dose planar X-ray imaging device for dense in-depth attenuation information. Our key contribution is to rely on Bayesian inference to solve for a dense attenuation volume given planar radioscopic images of a moving sample. The approach enables multiple sources of noise to be considered and takes advantage of limited prior information to solve an otherwise ill-posed problem. Results show that the proposed strategy is able to reconstruct dense volumetric attenuation models from a very limited number of radiographic views over time on simulated and in-vivo data, as illustrated in Figure 4.

7.4. Robust Multilinear Model Learning Framework for 3D Faces

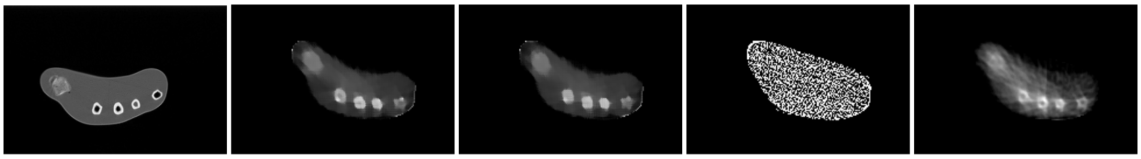

Figure 4. Results of the proposed method on a forearm phantom (2 selected slices). Left-to-right: ground-truth CT scan, proposed method, without optical flow, without TVL_1prior, ART. Without optical flow, artefacts are visible, for example in the bone cavities. The ART method produces much noisier results.

Statistical models are widely used to represent the variations of 3D human faces. Multilinear models in particular are common as they decouple shape changes due to identity and expression. Existing methods to learn a multilinear face model degrade if not every person is captured in every expression, if face scans are noisy or partially occluded, if expressions are erroneously labeled, or if the vertex correspondence is inaccurate. These limitations impose requirements on the training data that disqualify large amounts of available 3D face data from being usable to learn a multilinear model. To overcome this, we have developed an effective framework to robustly learn a multilinear model from 3D face databases with missing data, corrupt data, wrong semantic correspondence, and inaccurate vertex correspondence. To achieve this robustness to erroneous training data, our framework jointly learns a multilinear model and fixes the data. This framework is significantly more efficient than prior methods based on linear statistical models. This work was presented at CVPR 2016 [7].

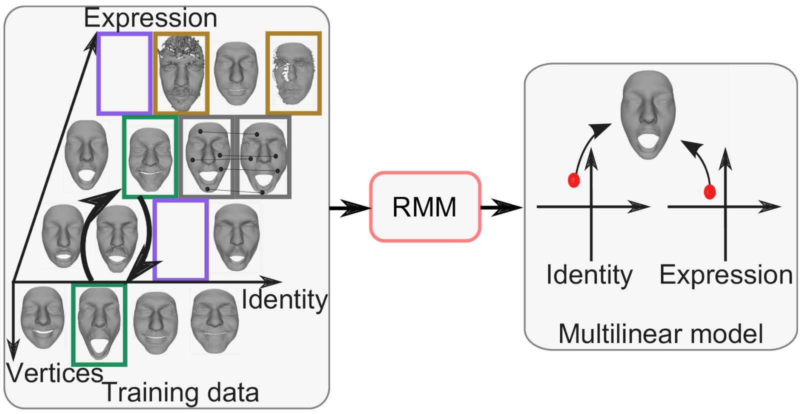

Figure 5. Overview of our robust multilinear model (RMM) learning framework that is robust to missing data (purple), corrupt data (brown), wrong semantic correspondence (green), and inaccurate vertex correspondence (gray).

7.5. Segmentation of Tree Seedling Point Clouds into Elementary Units

We propose a new semi-automatic method to cluster TLS data into meaningful sets of points to extract plant components. The approach is designed for small plants with distinguishable branches and leaves, such as tree seedlings. It first creates a graph by connecting each point to its most relevant neighbours, then embeds the graph into a spectral space, and finally segments the embedding into clusters of points. The process can then be iterated on each cluster separately. The main idea underlying the approach is that the spectral embedding of the graph aligns the points along the shape's principal directions. A quantitative evaluation of the segmentation accuracy, as well as of leaf area estimates, is provided on a poplar seedling mock-up. It shows that the segmentation is robust with false positive and false negative rates around 1%. Qualitative results on four contrasting plant species with three different scan resolution levels each are also shown in the paper, which has been published in the International Journal of Remote Sensing [2].

7.6. Estimation of Human Body Shape in Motion with Wide Clothing

Estimating 3D human body shape in motion from a sequence of unstructured oriented 3D point clouds is important for many applications. We propose the first automatic method to solve this problem that works in the presence of loose clothing. The problem is formulated as an optimization problem that solves for identity and posture parameters in a shape space capturing likely body shape variations. The automation is achieved by leveraging a recent robust pose detection method Stitched Puppet. To account for clothing, we take advantage of motion cues by encouraging the estimated body shape to be inside the observations. The method is evaluated on a new benchmark containing different subjects, motions, and clothing styles that allows to quantitatively measure the accuracy of body shape estimates. Furthermore, we compare our results to existing methods that require manual input and demonstrate that results of similar visual quality can be obtained.

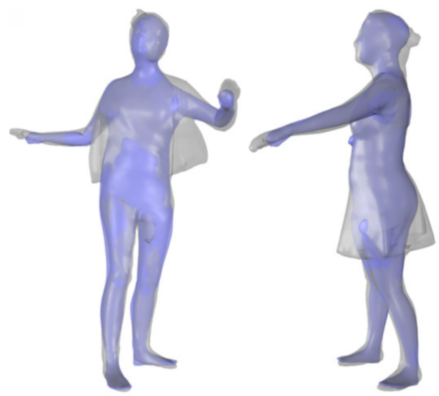

Figure 6. Two frames of an input point cloud sequence (in gray) with the estimated body shape shown in blue [14].

This work has been presented at the ECCV 2016 conference [14].

7.7. Computing Temporal Alignments of Human Motion Sequences in Wide Clothing using Geodesic Patches

In this work, we address the problem of temporal alignment of surfaces for subjects dressed in wide clothing, as acquired by calibrated multi-camera systems. Most existing methods solve the alignment by fitting a single surface template to each instant's 3D observations, relying on a dense point-to-point correspondence scheme, e.g. by matching individual surface points based on local geometric features or proximity. The wide clothing situation yields more geometric and topological difficulties in observed sequences, such as apparent merging of surface components, misreconstructions, and partial surface observation, resulting in overly sparse, erroneous point-to-point correspondences, and thus alignment failures. To resolve these issues, we propose an alignment framework where point-to-point correspondences are obtained by growing isometric patches from a set of reliably obtained body landmarks. This correspondence decreases the reliance on local

geometric features subject to instability, instead emphasizing the surface neighborhood coherence of matches, while improving density given sufficient landmark coverage. We validate and verify the resulting improved alignment performance in our experiments.
This work has been presented at the International Conference on 3D Vision (3DV) 2016 [13].

7.8. A 3D+t Laplace Operator for Temporal Mesh Sequences

The Laplace operator plays a fundamental role in geometry processing. Several discrete versions have been proposed for 3D meshes and point clouds, among others. We have defined a discrete Laplace operator for temporally coherent mesh sequences, which allows to process mesh animations in a simple yet efficient way. This operator is a discretization of the Laplace-Beltrami operator using Discrete Exterior Calculus on CW complexes embedded in a four-dimensional space. A parameter is introduced to tune the influence of the motion with respect to the geometry. This enables straightforward generalization of existing Laplacian static mesh processing works to mesh sequences. An application to spacetime editing has been provided as example.

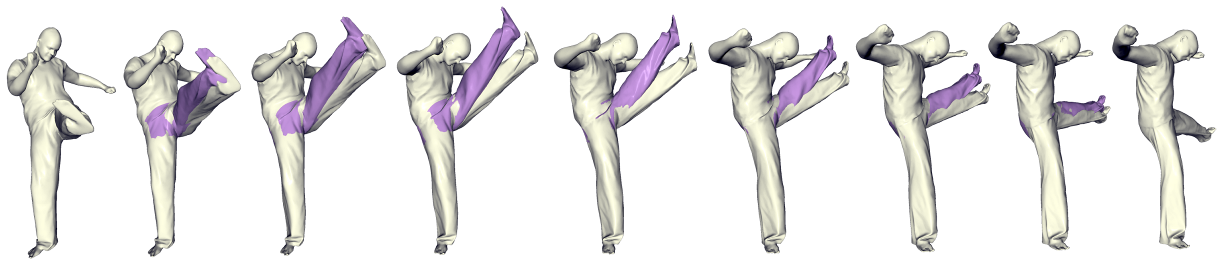

Figure 7. Spacetime editing of a temporal mesh sequence using the proposed 3D+t Laplace operator [1].

This work has been published in Computer & Graphics [1] and presented at the Shape Modeling International (SMI) 2016 conference.

7.9. Volumetric 3D Tracking by Detection

In this collaboration with TU Munich, we investigated a new solutions for 3D tracking by detection based on fully volumetric representations. On one hand, 3D tracking by detection has shown robust use in the context of interaction (Kinect) and surface tracking. On the other hand, volumetric representations have recently been proven efficient both for building 3D features and for addressing the 3D tracking problem. We leveraged these benefits by unifying both families of approaches into a single, fully volumetric tracking-by-detection framework. We used a centroidal Voronoi tessellation (CVT) representation to compactly tessellate shapes with optimal discretization, construct a feature space, and perform the tracking according to the correspondences provided by trained random forests (see figure 8). Our results show improved tracking and training computational efficiency and improved memory performance. This in turn enables the use of larger training databases than state of the art approaches, which we leveraged by proposing a cross-tracking subject training scheme to benefit from all subject sequences for all tracking situations, thus yielding better detection and less overfitting. The approach has been presented at CVPR 2016 [10].

7.10. Eigen Appearance Maps of Dynamic Shapes

In this work, we considered the problem of building efficient appearance rep- resentations of shapes observed from multiple viewpoints and in several movements. Multi-view systems now allow the acquisition of spatio-temporal models of such moving objects. While efficient geometric representations for these models have been

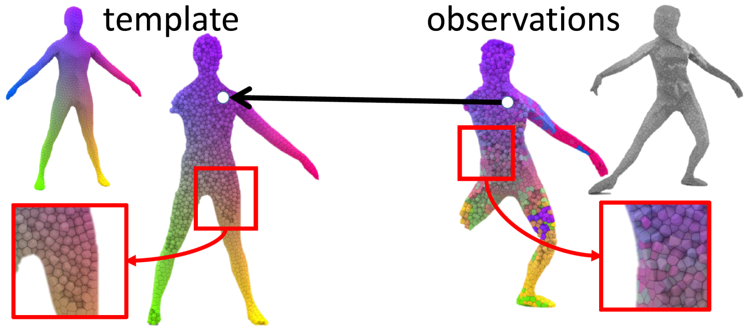

Figure 8. 3D shapes are represented using centroidal Voronoi tessellations. The volumetric cells of the observations are matched to cells of the template.

widely studied, appearance information, as provided by the observed images, is mainly considered on a per frame basis, and no global strategy yet addresses the case where several temporal sequences of a shape are available. We proposed a per subject representation that builds on PCA to identify the underlying manifold structure of the appearance information relative to a shape. The resulting eigen representation encodes shape appearance variabilities due to viewpoint and motion, with Eigen textures, and due to local inaccuracies in the geometric model, with Eigen warps. In addition to providing compact representations, such decompositions also allow for appearance interpolation and appearance completion. We evaluated their performances over different characters and with respect to their ability to reproduce compelling appearances in a compact way. This work was presented at ECCV 2016.

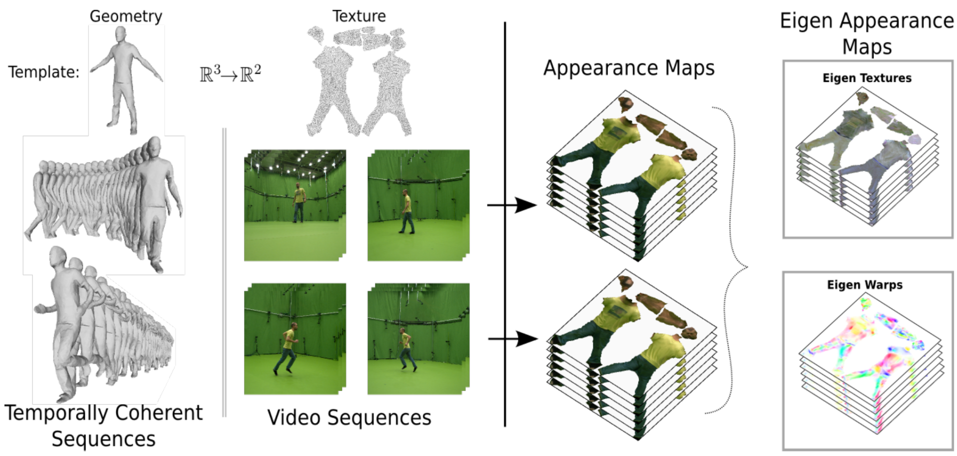

Figure 9. Given time consistent shape models and their appearance maps, our method exploits the manifold structure of these appearance information through PCA decomposition to generate the Eigen appearance maps relative to a shape.

7.11. Visual Contrast Sensitivity and Discrimination for 3D Meshes

In this work, we first introduce an algorithm for estimating the visual contrast on a 3D mesh. We then perform a series of psychophysical experiments to study the effects of contrast sensitivity and contrast discrimination of the human visual system for the task of differentiating between two contrasts on a 3D mesh. The results of these experiments allow us to propose a perceptual model that is able to predict whether a change in local contrast on 3D mesh, induced by a local geometric distortion, is visible or not. Finally, we illustrate the utility of the proposed perceptual model in a number of applications: we compute the Just Noticeable Distortion (JND) profile for smooth-shaded 3D meshes and use the model to guide mesh processing algorithms.
This work has been published in Computer Graphics Forum [] and has received the best paper award at the Pacific Graphics 2016 conference.

8. Bilateral Contracts and Grants with Industry

8.1. QuickCSG Contract with undisclosed industrial partner

QuickCSG software was licensed in October 2015 to an industrial partner whose name is contractually kept undisclosed for a finite time period. Integration of QuickCSG into the partner's software is continuing and is scheduled to be sold with this industrial partner's products. An additional support contract has been signed with this partner for the purpose of the transfer.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. ARC6 project PADME – Perceptual quality Assessment of Dynamic MEshes and its applications

In this project, we propose to use a new and experimental "bottom-up" approach to study an interdisciplinary problem, namely the objective perceptual quality assessment of 3D dynamic meshes (i.e., shapes in motion with temporal coherence). The objectives of the proposed project are threefold:

1. to understand the HVS (human visual system) features when observing 3D animated meshes, through a series of psychophysical experiments;
2. to develop an efficient and open-source objective quality metric for dynamic meshes based on the results of the above experiments;
3. to apply the learned HVS features and the derived metric to the application of compression and/or watermarking of animated meshes.

This work is funded by the Rhône-Alpes région through an ARC6 grant for the period 2013-2016. The three partners are LIRIS (University Lyon 1, Florent Dupont), GIPSA-Lab (CNRS, Kai Wang) and LJK (University of Grenoble, Franck Hétroy-Wheeler). A PhD student, Georges Nader, is working on this project.

9.2. National Initiatives

9.2.1. Persyval-Lab exploratory project Carambole

The Carambole projects initiates a new collaboration between the Morpheo team and biophysicists from University Paris Diderot. The objectives are to develop hardware and software to help tracking feature points on a leaf of Averrhoa Carambola during its growth with a multi-camera system and to measure their 3D motion. Averrhoa carambola is of special interest because of the distinctive nutation balancing motion of a leaf during its growth.

This exploratory project is funded for 18 months in 2016 and 2017 by the Persyval-Lab LabEx.

9.2.2. ANR

9.2.2.1. ANR project Achmov – Accurate Human Modeling in Videos

The technological advancements made over the past decade now allow the acquisition of vast amounts of visual information through the use of image capturing devices like digital cameras or camcorders. A central subject of interest in video are the humans, their motions, actions or expressions, the way they collaborate and communicate. The goal of ACHMOV is to extract detailed representations of multiple interacting humans in real-world environments in an integrated fashion through a synergy between detection, figure-ground segmentation and body part labeling, accurate 3D geometric methods for kinematic and shape modeling, and large-scale statistical learning techniques. By integrating the complementary expertise of two teams (one French, MORPHEO and one Romanian, CLVP), with solid prior track records in the field, there are considerable opportunities to move towards processing complex real world scenes of multiple interacting people, and be able to extract rich semantic representations with high fidelity. This would enable interpretation, recognition and synthesis at unprecedented levels of accuracy and in considerably more realistic setups than currently considered. This project is currently ongoing with 2 PhDs on the Inria side: Vincent Leroy and Jinlong Yang.

9.2.3. Competitivity Clusters

9.2.3.1. FUI project Creamove

Creamove is a collaboration between the Morpheo team of the Inria Grenoble Rhône-Alpes, the 4D View Solution company specialized in multi-camera acquisition systems, the SIP company specialized in multi-media and interactive applications and a choreographer. The objective is to develop new interactive and artistic applications where humans can interact in 3D with virtual characters built from real videos. Dancer performances will be pre-recorded in 3D and used on-line to design new movement sequences based on inputs coming from human bodies captured in real time. Website: http://www.creamove.fr.

9.3. International Initiatives

9.3.1. Inria International Partners

9.3.1.1. Declared Inria International Partners

9.3.1.1.1. Joint projects with the Forestry Commission, UK

A common project with an ecophysiologist from the British Forestry Commission, Eric Casella, is currently carried out. It aims at reconstructing accurate virtual models of forest trees, for biomass measurement purposes. This project is called Digitree and is funded by the University of Grenoble Alpes, through the AGIR framework. A PhD student, Romain Rombourg, is working on it. Two presentations related to this project have been made this year at the FSPMA conference [15], [21].

The long term collaboration with TU Munich and Slobodan Ilic on human motion capture is ongoing with the work of Paul Huang [10] that was published at CVPR this year. The work contributes with an approach that combines detection by learning with traditional generative tracking approaches.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Selection

10.1.1.1. Chair of Conference Program Committees

- Edmond Boyer was area chair for CVPR 2016 and BMVC 2016.

10.1.1.2. Member of the Conference Program Committees

- Franck Hétroy-Wheeler was part of the IPC for Eurographics 2016 (short papers).
- Stefanie Wuhrer was PC member for the Eurographics Workshop 3DOR

10.1.1.3. Reviewer

- Edmond Boyer has reviewed for: ECCV 2016, SIGGRAPH 2016, 3DV 2016, RFIA 2016, ORASIS 2015.
- Jean-Sébastien Franco has reviewed for: ECCV 2016, SIGGRAPH 2016, 3DV 2016, RFIA 2016
- Franck Hétroy-Wheeler has reviewed for: Eurographics 2016 (short papers), 3DV 2016.
- Stefanie Wuhrer has reviewed for CVPR 2016 and ECCV 2016

10.1.2. Journal

10.1.2.1. Member of the Editorial Boards

- Edmond Boyer is associate editor of IJCV.

10.1.2.2. Reviewer - Reviewing Activities

- Edmond Boyer has reviewed for: IEEE Transactions on PAMI.
- Franck Hétroy-Wheeler has reviewed for: Journal of Mathematical Imaging and Vision, The Visual Computer, Journal of Imaging.
- Julien Pansiot has reviewed for: MobiHealth 2016, J. 3D Research 2016, IOP SMS 2016, TPAMI 2016, IJCV 2016.

10.1.3. Invited Talks

- Edmond Boyer gave invited talks at: CVPR area chair meeting and ETH Zurich.

10.1.4. Scientific Expertise

- Edmond Boyer evaluated projects for: EPSRC (UK's agency for funding research) and FWF (Austrian Science Fund agency).

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master: Edmond Boyer, 3D Modeling, 18h, M2R GVR, Université Joseph Fourier Grenoble.

Master: Edmond Boyer, Introduction to Visual Computing, 30h, M1 MoSig, Université Joseph Fourier Grenoble.

Master: J.S. Franco, co-responsability of the Graphics, Vision, Robotics specialty of the Mosig Masters program, Second year Masters, Grenoble INP, Université Joseph Fourier.

Licence: F. Hétroy-Wheeler, Algorithmics and data structures, 59h, Ensimag 1st year, Grenoble INP.

Licence: F. Hétroy-Wheeler, Algorithmics and programming, 45h, Ensimag dual education through apprenticeship 1st year, Grenoble INP.

Master: F. Hétroy-Wheeler, Image projects, 25h, Ensimag 2nd year, Grenoble INP.

Master: F. Hétroy-Wheeler, Surface modelling, 24h, Ensimag 3rd year, Grenoble INP.

Master: F. Hétroy-Wheeler, 3D graphics, 11h, Master of Science in Informatics, Université Grenoble Alpes.

Master: F. Hétroy-Wheeler, Geometric modelling, 42h, Master of Science in Industrial and Applied Mathematics, Université Grenoble Alpes.

Master: F. Hétroy-Wheeler, co-responsability of the Mathematical Modeling, Image and Simulation (MMIS) track of Ensimag, Grenoble INP.

Master: J. Pansiot, Introduction to Computer Vision, 27h, Ensimag 3rd year, Grenoble INP.

Master: S. Wuhrer, 3D graphics, 13h, Master of Science in Informatics, Université Grenoble Alpes.

10.2.2. Supervision

PhD in progress : Benjamin Allain, Geometry and Appearance Analysis of Deformable 3D shapes, Université de Grenoble Alpes, started 01/10/2012, supervised by J.S. Franco and E. Boyer.

PhD in progress :Victoria Fernandez Abrevaya, 3D Dynamic Human Motion Representations, Université de Grenoble Alpes, started 01/10/2016, supervised by Stefanie Wuhrer and Edmond Boyer.

PhD: Timo Bolkart, Statistical analysis of 3D human faces is motion, Saarland University, started 01/01/2012, defended 14/06/2016, supervised by Stefanie Wuhrer.

PhD in progress: Adnane Boukhayma, 4D model synthesis, Universiteé de Grenoble Alpes, started 01/10/2013, supervised by Edmond Boyer.

PhD in progress : Vincent Leroy, 4D Multi-View Reconstruction from Photometric Information, Université de Grenoble, started 01/10/2015, supervised by J.S. Franco and E. Boyer.

PhD: Georges Nader, Calcul du seuil de visibilité d'une distorsion géométrique locale sur un maillage et ses applications, Université Claude Bernard - Lyon 1, defended 22/11/2016, supervised by Florent Dupont, Kai Wang and Franck Hétroy-Wheeler.

PhD in progress: Romain Rombourg, Digital tree: from the acquisition to a high-level geometric model, Université Grenoble Alpes, started 01/10/2015, supervised by Franck Hétroy-Wheeler and Eric Casella.

PhD in progress: Aurela Shehu, Geometric processing of near-isometrically deforming surfaces, Saarland University, started 01/04/2012, defended 14/06/2016, supervised by Stefanie Wuhrer.

PhD : Vagia Tsiminaki, Appearance Modelling and Time Refinement in 3D Videos, Université de Grenoble Alpes, started 01/10/2012, defended 14/12/2016, supervised by J.S. Franco and E. Boyer.

PhD in progress: Li Wang, Transport optimal pour l'analyse de formes en mouvement, Université de Grenoble Alpes, started 01/10/2013, supervised by Edmond Boyer and Franck Hétroy-Wheeler.

PhD in progress : Jinlong Yang, Learning shape spaces of dressed 3D human models in motion, Université de Grenoble Alpes, started 01/10/2015, supervised by Franck Hétroy-Wheeler and Stefanie Wuhrer.

10.2.3. Juries

- Edmond Boyer was reviewer of the PhD thesis of: Ludovic Blache (université de Reims Champagne Ardenne), Timo Bolkart (Saarland University) and Vincent Jantet (ETH Zurich).
- Franck Hétroy-Wheeler is a member of the PhD monitoring committee of Van Tho Nguyen (University of Lorraine, INRA Nancy and Office National des Forêts).

10.3. Popularization

Morpheo members have demonstrated the Kinovis platform to the general public on numerous occasions, and most notably for the "Fête de la Science".

11. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journal

[1] V. FERNÁNDEZ ABREVAYA, S. MANANDHAR, F. HÉTROY-WHEELER, S. WUHRER.*A 3D+t Laplace operator for temporal mesh sequences*, in "Computers and Graphics", August 2016, vol. 58, 11 [*DOI :* 10.1016/J.CAG.2016.05.018], https://hal.inria.fr/hal-01318763.

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[21] R. ROMBOURG, E. CASELLA, F. HÉTROY-WHEELER, H. MCKAY.*A point-cloud classification method to assess biases in tLiDAR-based forest canopy gap fraction estimates*, November 2016, International Conference on Functional-Structural Plant Growth Modeling, Simulation, Visualization and Applications (FSPMA), Poster, https://hal.inria.fr/hal-01399489.

Project-Team NANO-D

Algorithms for Modeling and Simulation of Nanosystems

IN COLLABORATION WITH: Laboratoire Jean Kuntzmann (LJK)

IN PARTNERSHIP WITH:
CNRS

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Numerical schemes and simulations

Table of contents

Project-Team NANO-D

Creation of the Team: 2008 January 01, updated into Project-Team: 2014 July 01

Keywords:

Computer Science and Digital Science:

6. - Modeling, simulation and control
6.2. - Scientific Computing, Numerical Analysis & Optimization
8.2. - Machine learning

Other Research Topics and Application Domains:

1. - Life sciences
1.1. - Biology
2. - Health
5.3. - Nanotechnology
5.5. - Materials

1. Members

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Sergey Grudinin [CNRS, Researcher]
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2. Overall Objectives

2.1. Overview

During the twentieth century, the development of macroscopic engineering has been largely stimulated by progress in numerical design and prototyping: cars, planes, boats, and many other manufactured objects are nowadays designed and tested on computers. Digital prototypes have progressively replaced actual ones, and effective computer-aided engineering tools have helped cut costs and reduce production cycles of these macroscopic systems.

The twenty-first century is most likely to see a similar development at the atomic scale. Indeed, the recent years have seen tremendous progress in nanotechnology - in particular in the ability to control matter at the atomic scale. The nanoscience revolution is already impacting numerous fields, including electronics and semiconductors, textiles, energy, food, drug delivery, chemicals, materials, the automotive industry, aerospace and defense, medical devices and therapeutics, medical diagnostics, etc. According to some estimates, the world market for nanotechnology-related products and services will reach one trillion dollars by 2015. Nano-engineering groups are multiplying throughout the world, both in academia and in the industry: in the USA, the MIT has a “NanoEngineering” research group, Sandia National Laboratories created a “National Institute for Nano Engineering”, to name a few; China founded a “National Center for Nano Engineering” in 2003, etc. Europe is also a significant force in public funding of nanoscience and nanotechnology.

Similar to what has happened with macroscopic engineering, powerful and generic computational tools will be employed to engineer complex nanosystems, through modeling and simulation.

Modeling and simulation of natural or artificial nanosystems is still a challenging problem, however, for at least three reasons: (a) the number of involved atoms may be extremely large (liposomes, proteins, viruses, DNA, cell membrane, etc.); (b) some chemical, physical or biological phenomena have large durations (e.g., the folding of some proteins); and (c) the underlying physico-chemistry of some phenomena can only be described by quantum chemistry (local chemical reactions, isomerizations, metallic atoms, etc.). The large cost of modeling and simulation constitutes a major impediment to the development of nanotechnology.

The NANO-D team aims at developing efficient computational methods for modeling and simulation of complex nanosystems, both natural (e.g., the ATPase engine and other complex molecular mechanisms found in biology) and artificial (e.g., NEMS - Nano Electro-Mechanical Systems).

In particular, the group develops novel multiscale, adaptive modeling and simulation methods, which automatically focus computational resources on the most relevant parts of the nanosystems under study.

2.2. Research axes

The goal of the NANO-D group is to help current and future designers of *nanosystems*, i.e. systems studied or designed at the atomic scale (whether natural or artificial, independently of the application domain, including structural biology, material science, chemistry, etc.) by developing the **foundations of a software application which will run on a desktop computer, and will allow for efficient analysis, design, modeling and simulation of nanosystems**.

To achieve this, we will be developing a series of **adaptive methods and algorithms** that allow users to focus computational resources on the parts of the models that they want to simulate, and that allow to finely trade between speed and precision.

In parallel, we will develop the architecture of a new desktop application for virtual prototyping of nanosystems, and will integrate all our algorithms into this application. Furthermore, the architecture of this platform will be open, so that independent developers may add modules, for **multiple application domains** (physics, biology, chemistry, materials, electronics, etc.). With this open platform, we will attempt to federate the research performed in computational nanoscience throughout the world.

This application is called **SAMSON: "Software for Adaptive Modeling and Simulation Of Nanosystems"**.

Our two research axes are:

1. **Developing adaptive algorithms for simulating nanosystems**
   - **Defining adaptive Hamiltonians**: In order to be able to perform simulations with good mathematical properties, we are expanding on our recent work on *adaptively restrained Hamiltonians* [22], *i.e.* modified Hamiltonian representations of molecular systems that are able to switch degrees of freedom on and off during a simulation. These will allow us to finely trade between precision and computational performance, by choosing arbitrarily the number of degrees of freedom. Even though we have already obtained some promising results in this domain, our goal is to develop several different simplification methods.
   - **Developing algorithms for incremental potential update**: In order to benefit from performing adaptive particle simulations, we need to develop a series of algorithms that will take advantage of the fact that some (potentially relative) atomic positions are frozen. We have already demonstrated how this is possible for torsion-angle quasi-static simulation of classical bio-molecular force-fields [67], for neighbor search between large rigid molecules [21], and for bond-order reactive force-fields [25]. We are developing new algorithms for incremental neighbor search, energy and force updates corresponding to the adaptive Hamiltonians that we are defining.
2. **Developing algorithms for modeling molecular interactions**
   - **Developing knowledge-driven methods, potentials and algorithms**: Over time, more and more experimental information becomes available. One can use this information to predict and discover new types of molecular interactions and various mechanisms or molecular organization. For example, currently there are more than 50,000 protein structures of a high resolution stored in the Protein Data Bank [23] and over 500,000 structures of small molecules stored in the Cambridge Structural Database [17]. We are developing algorithms for protein-protein interactions and protein-ligand interactions.
   - **Developing parametrization algorithms for interaction potentials**: Molecular models typically require their own potential energy function (or a *forcefield*) to be assigned. However, the development of a new potential function is a very difficult and sometimes challenging task [43]. Therefore, we are developing algorithms for automatic parametrization of new potential functions for some particular representations of a molecular system.
   - **Developing algorithms for exhaustive sampling**: Some application domains, such as computational docking, cryo-EM rigid-body fitting, etc., require sampling in a low-dimensional space. For such applications it is advantageous to perform an exhaustive search rather than accelerated sampling [64]. Therefore, we are developing fast search methods to perform exhaustive search.

3. Research Program

3.1. The need for practical design of nanosystems

Computing has long been an essential tool of engineering. During the twentieth century, the development of macroscopic engineering has been largely stimulated by progress in numerical design and prototyping. Cars, planes, boats, and many other manufactured objects are nowadays, for the most part, designed and tested on computers. Digital prototypes have progressively replaced actual ones, and effective computer-aided engineering tools (e.g., CATIA, SolidWorks, T-FLEX CAD, Alibre Design, TopSolid, etc.) have helped cut costs and reduce production cycles of macroscopic systems [66].

The twenty-first century is most likely to see a similar development at the atomic scale. Indeed, the recent years have seen tremendous progress in nanotechnology. The magazine Science, for example, recently featured a paper demonstrating an example of DNA nanotechnology, where DNA strands are stacked together through programmable self-assembly [35]. In February 2007, the cover of Nature Nanotechnology showed a "nano-wheel" composed of a few atoms only. Several nanosystems have already been demonstrated, including a *de-novo* computationally designed protein interface [37], a wheelbarrow molecule [44], a nano-car [70], a Morse molecule [18], etc. Typically, these designs are optimized using semi-empirical quantum mechanics calculations, such as the semi-empirical ASED+ calculation technique [19].

While impressive, these are but two examples of the nanoscience revolution already impacting numerous fields, including electronics and semiconductors [53], textiles [52], [40], energy [55], food [29], drug delivery [39], [72], chemicals [41], materials [30], the automotive industry [16], aerospace and defense [38], medical devices and therapeutics [33], medical diagnostics [73], etc. According to some estimates, the world market for nanotechnology-related products and services will reach one trillion dollars by 2015 [65]. Nano-engineering groups are multiplying throughout the world, both in academia and in the industry: in the USA, the MIT has a "NanoEngineering" research group, Sandia National Laboratories created a "National Institute for Nano Engineering", to name a few; China founded a "National Center for Nano Engineering" in 2003, etc. Europe is also a significant force in public funding of nanoscience and nanotechnology and, in Europe, Grenoble and the Rhone-Alpes area gather numerous institutions and organizations related to nanoscience.

Of course, not all small systems that currently fall under the label "nano" have mechanical, electronic, optical properties similar to the examples given above. Furthermore, current construction capabilities lack behind some of the theoretical designs which have been proposed, such as the planetary gear designed by Eric Drexler at Nanorex. However, the trend is clearly for adding more and more functionality to nanosystems. While designing nanosystems is still very much an art mostly performed by physicists, chemists and biologists in labs throughout the world, there is absolutely no doubt that fundamental engineering practices will progressively emerge, and that these practices will be turned into quantitative rules and methods. Similar to what has happened with macroscopic engineering, powerful and generic software will then be employed to engineer complex nanosystems.

3.2. Challenges of practical nanosystem design

As with macrosystems, designing nanosystems will involve modeling and simulation within software applications: modeling, especially structural modeling, will be concerned with the creation of potentially complex chemical structures such as the examples above, using a graphical user interface, parsers, scripts, builders, etc.; simulation will be employed to predict some properties of the constructed models, including mechanical properties, electronic properties, chemical properties, etc.

In general, design may be considered as an "inverse simulation problem". Indeed, designed systems often need to be optimized so that their properties — predicted by simulation — satisfy specific objectives and constraints (e.g. a car should have a low drag coefficient, a drug should have a high affinity and selectivity to a target protein, a nano-wheel should roll when pushed, etc.). Being the main technique employed to predict properties, simulation is essential to the design process. At the nanoscale, simulation is even more important. Indeed, physics significantly constrains atomic structures (e.g. arbitrary inter-atomic distances cannot exist), so that a tentative atomic shape should be checked for plausibility much earlier in the design process (e.g. remove atomic clashes, prevent unrealistic, high-energy configurations, etc.). For nanosystems, thus, efficient simulation algorithms are required both when modeling structures and when predicting systems properties. Precisely, an effective software tool to design nanosystems should (a) allow for interactive physically-based modeling, where all user actions (e.g. displacing atoms, modifying the system's topology, etc.) are automatically followed by a few steps of energy minimization to help the user build plausible structures, even for large number of atoms, and (b) be able to predict systems properties, through a series of increasingly complex simulations.

3.3. Current simulation approaches

Even though the growing need for effective nanosystem design will still increase the demand for simulation, a lot of research has already gone into the development of efficient simulation algorithms. Typically, two approaches are used: (a) increasing the computational resources (use super-computers, computer clusters, grids, develop parallel computing approaches, etc.), or (b) simulating simplified physics and/or models. Even though the first strategy is sometimes favored, it is expensive and, it could be argued, inefficient: only a few supercomputers exist, not everyone is willing to share idle time from their personal computer, etc. Surely, we would see much less creativity in cars, planes, and manufactured objects all around if they had to be designed on one of these scarce super-resources.

The second strategy has received a lot of attention. Typical approaches to speed up molecular mechanics simulation include lattice simulations [75], removing some degrees of freedom (e.g. keeping torsion angles only [51], [71]), coarse-graining [74], [68], [20], [69], multiple time step methods [61], [62], fast multipole methods [34], parallelization [46], averaging [28], multi-scale modeling [27], [24], reactive force fields [26], [78], interactive multiplayer games for predicting protein structures [32], etc. Until recently, quantum mechanics methods, as well as mixed quantum / molecular mechanics methods were still extremely slow. One breakthrough has consisted in the discovery of linear-scaling, divide-and-conquer quantum mechanics methods [76], [77].

Overall, the computational community has already produced a variety of sophisticated simulation packages, for both classical and quantum simulation: ABINIT, AMBER, CHARMM, Desmond, GROMOS and GROMACS, LAMMPS, NAMD, ROSETTA, SIESTA, TINKER, VASP, YASARA, etc. Some of these tools are open source, while some others are available commercially, sometimes via integrating applications: Ascalaph Designer, BOSS, Discovery Studio, Materials Studio, Maestro, MedeA, MOE, NanoEngineer-1, Spartan, etc. Other tools are mostly concerned with visualization, but may sometimes be connected to simulation packages: Avogadro, PyMol, VMD, Zodiac, etc. The nanoHUB network also includes a rich set of tools related to computational nanoscience.

To the best of our knowledge, however, all methods which attempt to speed up dynamics simulations perform a priori simplification assumptions, which might bias the study of the simulated phenomenon. A few recent, interesting approaches have managed to combine several levels of description (e.g. atomistic and coarse-grained) into a single simulation, and have molecules switch between levels during simulation, including the adaptive resolution method [57], [58], [59], [60], the adaptive multiscale method [54], and the adaptive partitioning of the Lagrangian method [42]. Although these approaches have demonstrated some convincing applications, they all suffer from a number of limitations stemming from the fact that they are either ad hoc methods tuned to fix specific problems (e.g. fix density problems in regions where the level of description changes), or mathematically founded methods that necessitate to “calibrate” potentials so that they can be mixed (i.e. all potentials have to agree on a reference point). In general, multi-scale methods, even when they do not allow molecules to switch between levels of detail during simulation, have to solve the problem of rigorously combining multiple levels of description (i.e. preserve statistics, etc.), of assigning appropriate levels to different parts of the simulated system (“simplify as much as possible, but not too much”), and of determining computable mappings between levels of description (especially, adding back detail when going from coarse-grained descriptions to fine-grained descriptions).

3.4. Research axes

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4. Application Domains

4.1. Overview

NANO-D is *a priori* concerned with all applications domains involving atomistic representations, including chemistry, physics, electronics, material science, biology, etc.

Historically, though, our first applications have been in biology, as the next two sections detail. Thanks to the development of algorithms to efficiently simulate reactive force fields, as well as to perform interactive quantum mechanical calculations, however, we now have the possibility to address problems in chemistry, and physics.

4.2. Structural Biology

Structural biology is a branch of molecular biology, biochemistry, and biophysics concerned with the molecular structure of biological macromolecules, especially proteins and nucleic acids. Structural biology studies how these macromolecules acquire the structures they have, and how alterations in their structures affect their function. The methods that structural biologists use to determine the structure typically involve measurements on vast numbers of identical molecules at the same time, such as X-Ray crystallography, NMR, cryo-electron microscopy, etc. In many cases these methods do not directly provide the structural answer, therefore new combinations of methods and modeling techniques are often required to advance further.

We develop a set of tools that help biologists to model structural features and motifs not resolved experimentally and to understand the function of different structural fragments.

- Symmetry is a frequent structural trait in molecular systems. For example, most of the water-soluble and membrane proteins found in living cells are composed of symmetrical subunits, and nearly all structural proteins form long oligomeric chains of identical subunits. Only a limited number of symmetry groups is allowed in crystallography, and thus, in many cases the native macromolecular conformation is not present on high-resolution X-ray structures. Therefore, to understand the realistic macromolecular packing, modeling techniques are required.
- Many biological experiments are rather costly and time-demanding. For instance, the complexity of mutagenesis experiments grows exponentially with the number of mutations tried simultaneously. In other experiments, many candidates are tried to obtain a desired function. For example, about 250,000 candidates were tested for the recently discovered antibiotic Platensimycin. Therefore, there is a vast need in advance modeling techniques that can predict interactions and foresee the function of new structures.
- Structure of many macromolecules is still unknown. For other complexes, it is known only partially. Thus, software tools and new algorithms are needed by biologists to model missing structural fragments or predict the structure of those molecule, where there is no experimental structural information available.

4.3. Pharmaceutics and Drug Design

Drug design is the inventive process of finding new medications based on the knowledge of the biological target. The drug is most commonly an organic small molecule which activates or inhibits the function of a biomolecule such as a protein, which in turn results in a therapeutic benefit to the patient. In the most basic sense, drug design involves design of small molecules that are complementary in shape and charge to the biomolecular target to which they interact and therefore will bind to it. Drug design frequently relies on computer modeling techniques. This type of modeling is often referred to as computer-aided drug design.

Structure-based drug design attempts to use the structure of proteins as a basis for designing new ligands by applying accepted principles of molecular recognition. The basic assumption underlying structure-based drug design is that a good ligand molecule should bind tightly to its target. Thus, one of the most important principles for designing or obtaining potential new ligands is to predict the binding affinity of a certain ligand to its target and use it as a criterion for selection.

We develop new methods to estimate the binding affinity using an approximation to the binding free energy. This approximation is assumed to depend on various structural characteristics of a representative set of native complexes with their structure solved to a high resolution. We study and verify different structural characteristics, such as radial distribution functions, and their affect on the binding free energy approximation.

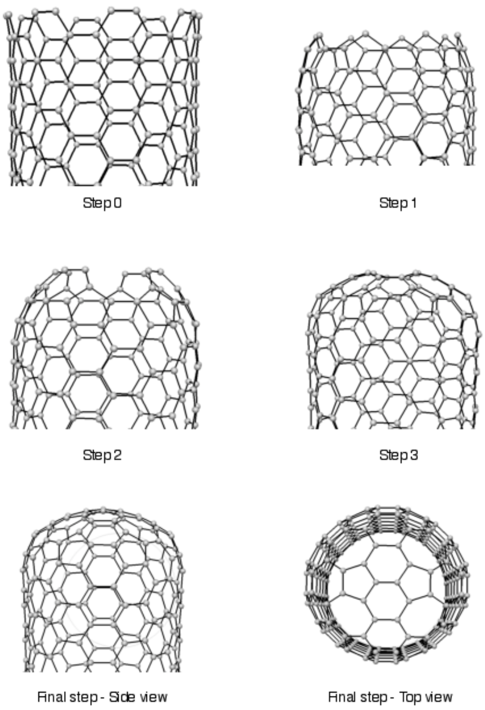

Figure 1. Snapshots of a nanotube capping process with the adaptive interactive modeler. Thanks to the adaptive methodology, this operation can be done in a few minutes.

4.4. Nano-engineering

In general, we want to develop methods to ease nano-engineering of artificial nanosystems, such as the ones described above (DNA nanotechnology, nano-mechanisms, etc.). We have shown, for example, that our incremental and adaptive algorithms allow us to easily edit and model complex shapes, such as a nanotube (Fig. 1) and the "nano-pillow" below (Fig. 2). Please read more about the SAMSON software platform for more examples.

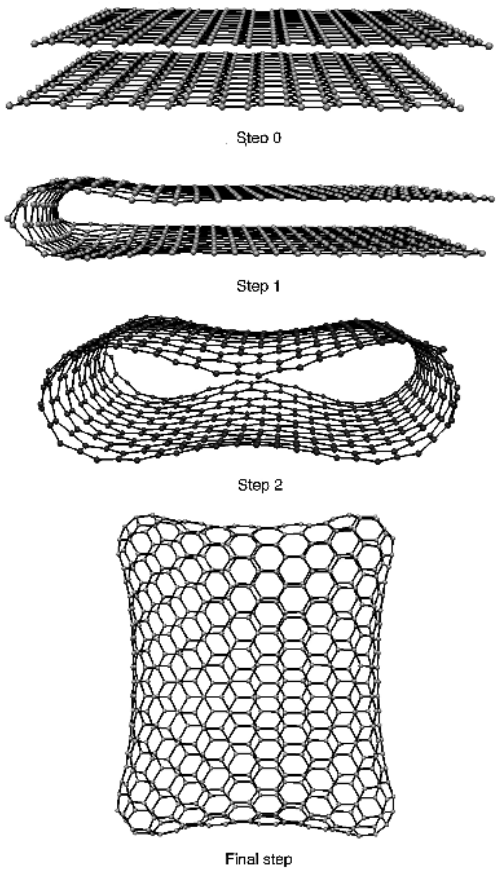

Figure 2. Different steps to prototype a "nano-pillow" with the adaptive interactive modeler.

5. New Software and Platforms

5.1. SAMSON

Software for Adaptive Modeling and Simulation Of Nanosystems
KEYWORDS: Bioinformatics - Simulation - Nanosystems - Structural Biology - Chemistry
SCIENTIFIC DESCRIPTION

Please refer to https://www.samson-connect.net
FUNCTIONAL DESCRIPTION

SAMSON is a software platform for real-time modelling and simulation of natural or artificial nanosystems. The objective is to make SAMSON a generic application for computer-aided design of nanosystems, similar to existing applications for macrosystem prototyping (CATIA, SolidWorks, etc.).

- Contact: Stéphane Redon
- URL: http://www.samson-connect.net/

6. New Results

6.1. Development of a novel minimization method

Participants: Clement Beitone, Stephane Redon.

Finding the optimized configuration of a system of particles so that it minimizes the energy of the system is a very common task in the field of particles simulation. More precisely, we are interested in finding the closest atomic structure located at a minima on the Potential Energy Surface (PES) starting from a given initial configuration. Achieving faster but reliable minimizations of such systems help to enhance a wide range of applications in molecular dynamics. To improve the efficiency of the convergence some authors have proposed alternative methods to the steepest descent algorithm; for example, the conjugate gradient technique or the Fast Inertial Relaxation Engine (FIRE).

In this work, we are developing a novel method that helps to increase the efficiency and the reliability of existing optimizers, *e.g.* FIRE and Interactive Modelling (IM).

We have implemented the modified versions of these algorithms along with others optimization algorithms like L-BFGS and Conjugate Gradient as state updaters in SAMSON. To assess the efficiency of the proposed approaches we have developed an App in SAMSON that allows us to reliably and conveniently probe several criteria during the minimization process (Figure 3).

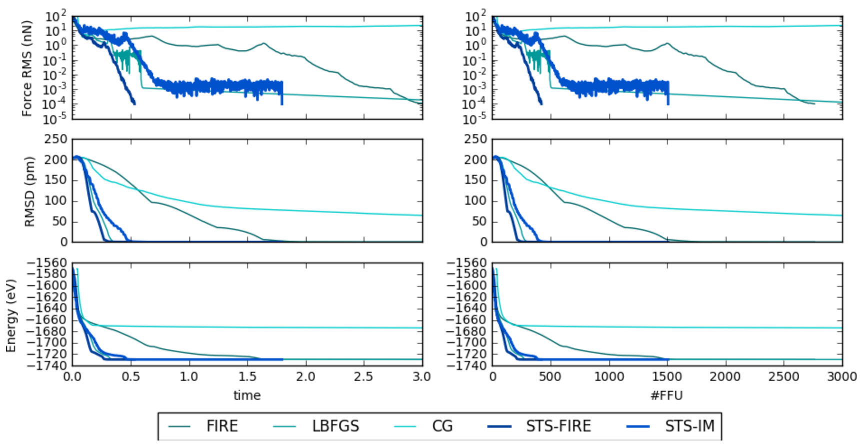

Figure 3. Comparison of different optimizers with the proposed methods on the fullerene C240. For this experiment the force field used to model the interactions between the atoms is the Brenner potential.

6.2. Parallel algorithms for adaptive molecular dynamics simulations

Participants: Dmitriy Marin, Stephane Redon.

We have developed a parallel implementation of Adaptively Restrained Particle Simulations (ARPS) in LAMMPS Molecular Dynamics Simulator with the usage of Kokkos [0] package. The main idea of the ARPS method [22] is to speed up particle simulations by adaptively switching on and off positional degrees of freedom, while letting momenta evolve; this is done by using adaptively restrained Hamiltonian. The developed parallel implementation allows us to run LAMMPS with ARPS integrator on central processing units (CPU), graphics processing units (GPU), or many integrated core architecture (MIC). We modified the ARPS algorithm for efficient usage of GPU and many-core CPU, e.g. all computations were parallelized for efficient calculations on computational device; communications between host and device were decreased.

To measure speed up of the developed parallel implementation we used several benchmarks and heterogeneous computational systems with next parameters: 2x CPU Intel Xeon E5-2680 v3 (24 cores in total), GPU Nvidia Quadro K4200, GPU Nvidia Tesla K20c. Results on the speed up in comparison with serial ARPS code for one of the benchmarks (Lennard–Jones liquid, 515K atoms, ~1% of particles switches their state at each timestep from active to restrained or from restrained to active) are shown in Figure 4. It can be seen, that for small number of CPU cores the speed up is almost constant for all the percentage of active atoms in the system. But for large number of CPU cores and for GPUs the speed up is decreasing with decreasing percentage of active atoms, because of divergence of threads and limited occupancy. The achieved speed up on 20 CPU-cores is up to 14 times, on GPU Nvidia Tesla K20c is up to 24 times.

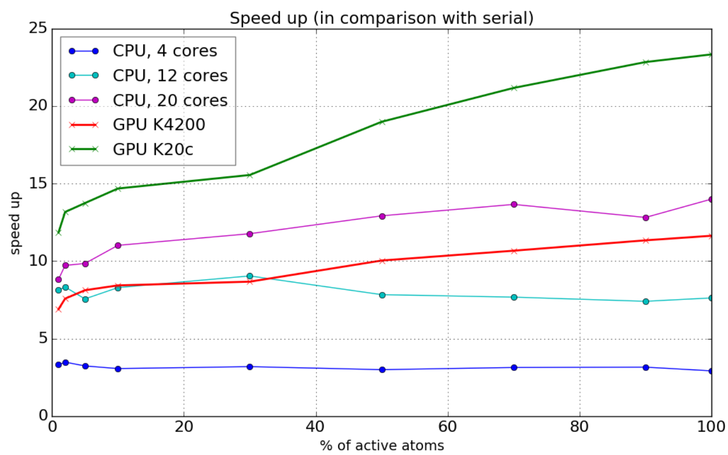

Figure 4. The parallel ARPS results

6.3. Adaptive Algorithms for Orbital-Free Density Functional Theory

Participants: Francois Rousse, Stephane Redon.

[0]The Kokkos package is based on Kokkos library, which is a templated C++ library that provides two key abstractions: it allows a single implementation of an application kernel to run efficiently on different hardware, such as a many-core CPU, GPU, or MIC; it provides data abstractions to adjust (at compile time) the memory layout of basic data structures — like 2d and 3d arrays — for performance optimization on different platforms. These abstractions are set at build time (during compilation of LAMMPS).

The SAMSON App developed to simulate molecular systems with an adaptive version of OF-DFT has been continued. It has been tested on several small systems : atoms, dimers, etc. The errors found on the energies and the bond length found were coherent with the predictive characteristics of OF-DFT and with other OF-DFT softwares like PROFESS.

The pseudopotentials computed by the Carter Group of Princeton (who developed PROFESS) have been implemented in the SAMSON App. The electronic densities became smoother and the predictions were improved, but it restricted the applicability of the SAMSON App since the pseudopotentials were computed only for the elements of the columns III (like aluminum) and V (like Potassium) of the periodic table.

Several optimization algorithms have been tried : projected gradient, Primal-Dual, Lagrangian multiplier improved with a penalization, different nonlinear conjugate gradient minimization algorithms ... None of them showed a clear superiority on the other in both stability and speed. Currently, we use the projected gradient since it is the most stable.

We have implemented an interaction model in SAMSON based on the OF-DFT code and tested its ability to predict the geometry of system on a small crystal of aluminum. The crystal contracted itself, which is coherent with the OF-DFT theory, since it tends to underestimate bond lengths, and with the surface tension, since it tends to minimize the surface of the system. The next step will be to make this interaction model adaptive and measure how much time is gained.

6.4. A crystal creator app

Participants: Francois Rousse, Stephane Redon.

We developed a new SAMSON Element able to generate models of crystals. The user can either write its own unit cell or load it from a CIF file ("Crystallographic Information File"). Once written or imported, this unit cell can be replicated again in every direction to generate a whole crystal. As the important characteristics of crystals often comes from the defects, the replacements and the insertions, these repetitions of unit cells are not mere copies but are whole new unit cells generated again each time. Thus a crystal with enough unit cells shall have the right proportion of elements, with the right amount of defects, replacements and insertions, randomly disposed. In the document view, the unit cells are separated to ease the manipulation of the crystal. Last, it allows the user to cut the crystal on the planes given by Miller indexes.

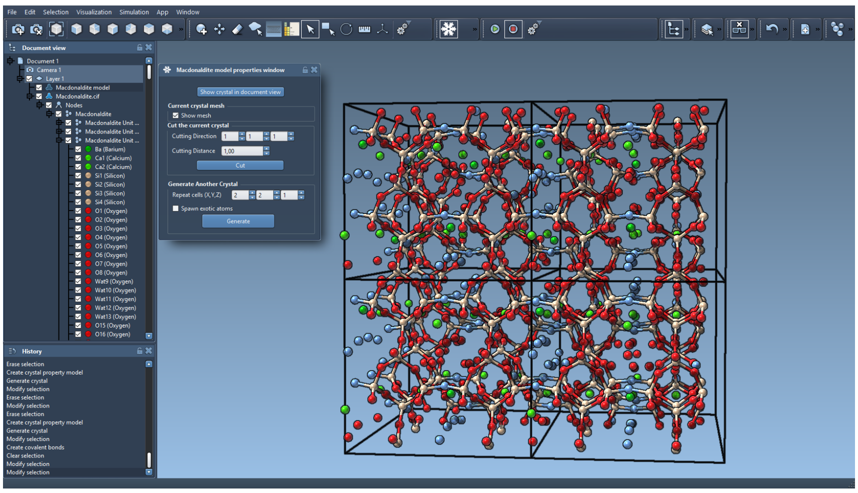

Figure 5. A Macdonaldite crystal generated in SAMSON

6.5. Software development process improvements

Participants: Jocelyn Gate, Stephane Redon.

We set up a Jenkins server on a virtual machine at Inria. The server is accessible to the team and is able to build and generate everything related to SAMSON. This Jenkins server is linked to diferents slaves, located in our offices:

- Window 7 / Windows 10
- Fedora 21 / Fedora 25 / Ubuntu 16.04
- MacOs 10.10.5

Slave machines are used by the Jenkins server to build the specified version of SAMSON, generate the associated SDK, build all SAMSON elements that are specified on Jenkins and upload everything to our private version of SAMSON Connect. Thanks to this, the team has access each day to the latest developments.

In order to efficiently upload everything from slaves nodes, Jenkins uses a private helpers that is able to communicate with SAMSON-Connect, and that knows every SAMSON files format.

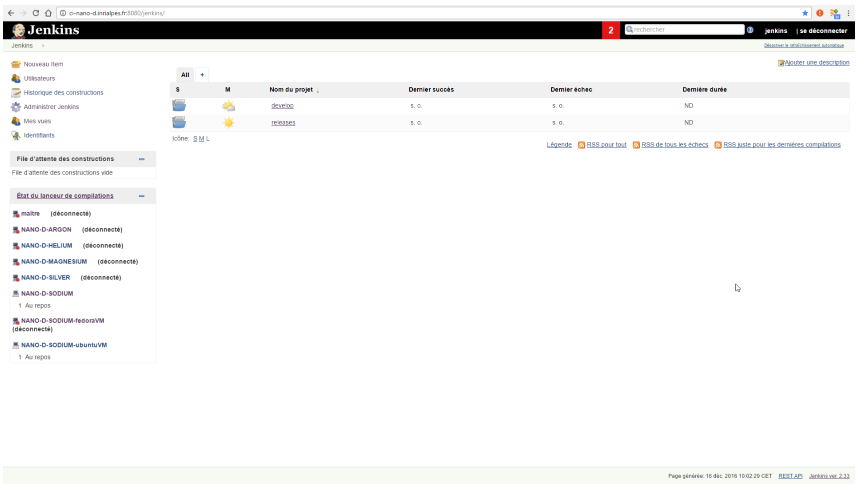

Figure 6. The jenkins interface

We developed a private, command line SAMSON helper that is able to do everything concerning the packing and the uploading of new versions of SAMSON, the SAMSON SDK and the installer to SAMSON Connect. It can:

- Upload the SAMSON or SAMSON-SDK packaged file to SAMSON-Connect (adding a new version of SAMSON/SAMSON-SDK).
- Upload the SAMSON or SAMSON-SDK Setup executable to SAMSON-Connect.
- Package the SAMSON elements of a developer to .element files.
- Upload .element files to SAMSON Connect.

6.6. Updates to SAMSON and SAMSON Connect

Participants: Jocelyn Gate, Stephane Redon.

To be able to know if SAMSON works well on users computers, we added some logging features inside SAMSON, SAMSON installers and SAMSON Helpers. Thanks to this functionality, users may accept to send logs when bugs are found. For example, if SAMSON crashes on a user computer, a log is generated, anonymized, and automatically sent to the SAMSON Connect web service. If SAMSON crashes because of a SAMSON Element, an email is sent to the author of the SAMSON Element. If a new user tries to install SAMSON or the SAMSON SDK, a log is sent to the SAMSON Connect web service.

We also added the possibility for users to configure proxy access to SAMSON Connect.

These functionalities will be part of the upcoming 0.6.0 release of SAMSON.

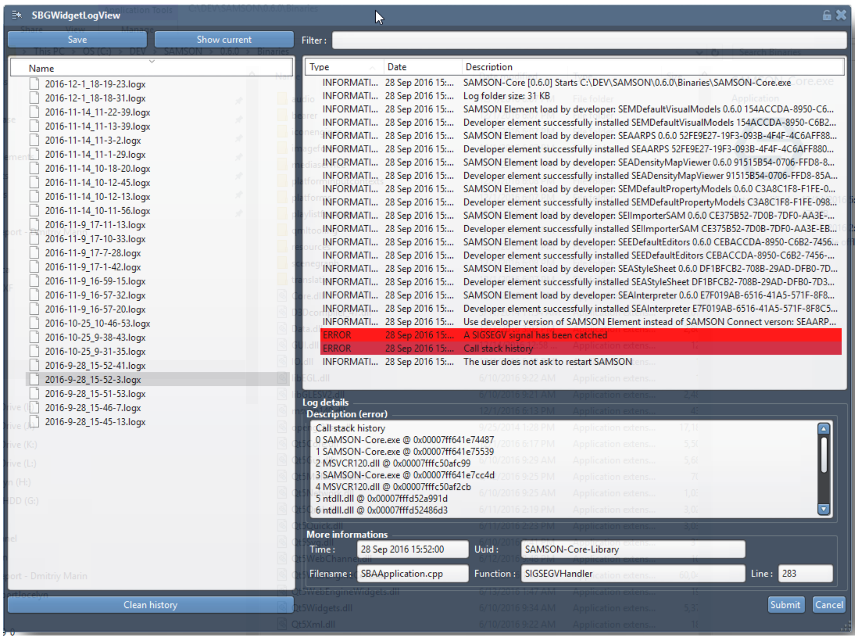

Figure 7. The SAMSON log interface

6.7. As-Rigid-As-Possible molecular interpolation paths

Participants: Minh Khoa Nguyen, Leonard Jaillet, Stephane Redon.

We submitted a paper describing a new method to generate interpolation paths between two given molecular conformations. It applies the As-Rigid-As-Possible (ARAP) from the field of computer graphics to manipulate complex meshes while preserving their essential structural characteristics. The adaptation of ARAP interpolation approach to the case of molecular systems was presented. Experiments were conducted on a large set of benchmarks and the performance was compared between ARAP interpolation and linear interpolation. They show that ARAP interpolation generates more relevant paths, that preserve bond lengths and bond angles better.

6.8. As-Rigid-As-Possible molecular interpolation paths

Participants: Krishna Kant Singh, Stephane Redon.

We have continued our work on the development of parallel adaptively restrained particle simulations. We proposed new algorithms to compute forces involving active particles faster. These algorithms involved construction of the Active Neighbor List (ANL) and incremental force computations. These algorithms have

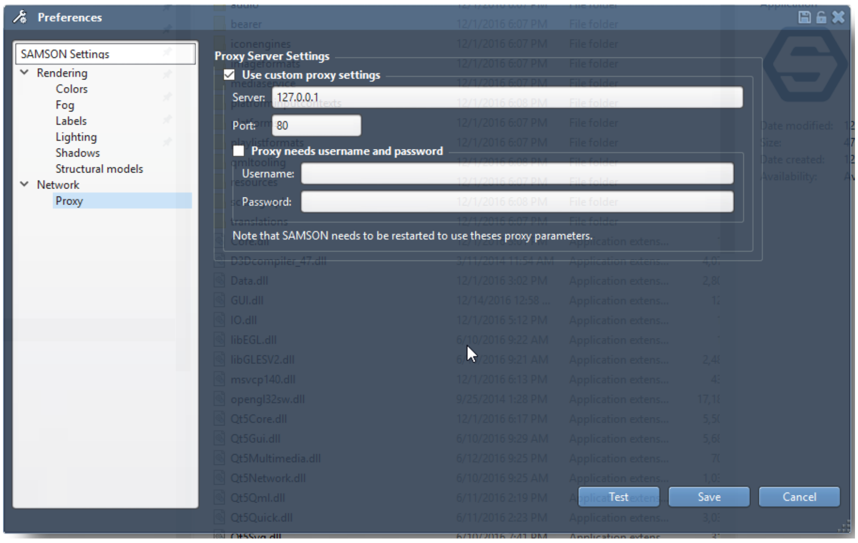

Figure 8. The proxy setting interface

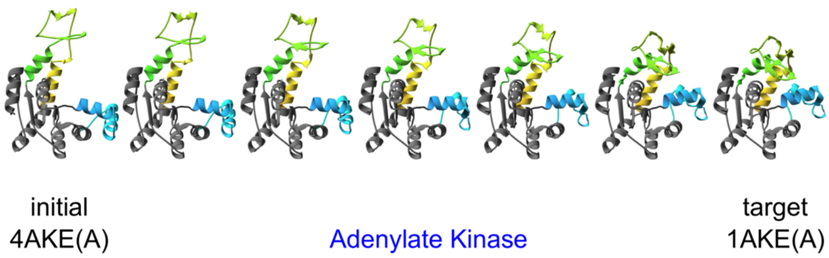

Figure 9. The morphing path for Adenylate Kinase from 4AKE (chain A) to 1AKE (chain A) by ARAP interpolation:

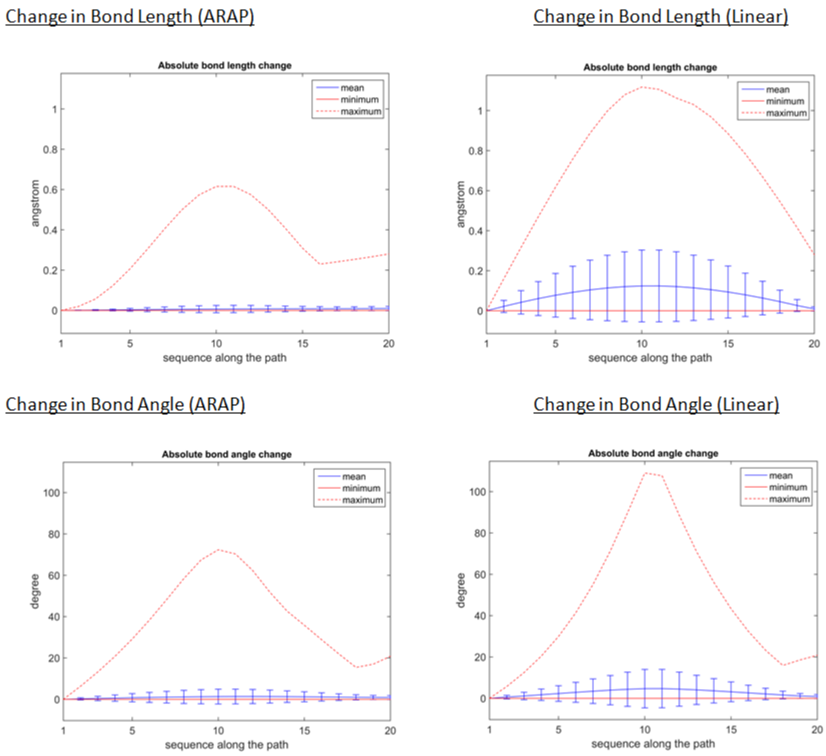

Figure 10. Comparison of ARAP and linear interpolation for preserving structural characteristics of adenylate kinase

advantages over the state-of-the-art methods for simulating a system using Adaptively Restrained Molecular Dynamics (ARMD). Previously proposed algorithms required at-least 60% restrained particles in order to achieve speed up. In new algorithms, we overcome this limitation and speed up can be achieve with 10% retrained particles. We implemented our algorithm in the popular molecular dynamics package LAMMPS and submitted our results in the *Computer Physics Communications* Journal [0]. Figure 11 show that speed-up can be achieved for more than 10% of the particles are restrained. We also achieved significant speed up in constructing the ANL (figure 12).

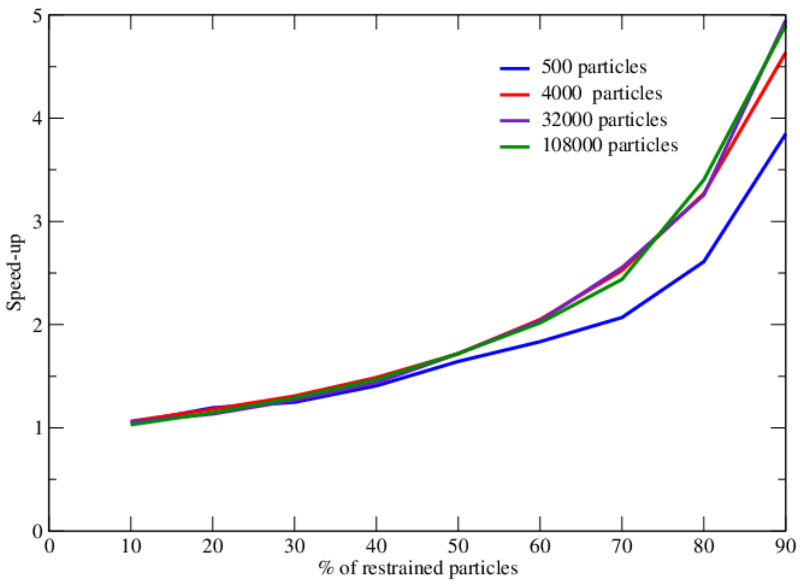

Figure 11. speed up using ARMD on different benchmark

6.9. Refining the energy landscape sampling of protein-protein associations

Participants: Dmytro Kozakov, Leonard Jaillet.

PIPER is a FFT-based protein docking program with pairwise potentials. It combines a systematic sampling procedure with an original pairwise potential that provides an energy landscape representation through a set of samples [48].

In [49], an experimental validation of the complexes obtained with PIPER, has been made possible thanks to the PRE method [31]. PRE (NMR paramagnetic relaxation enhancement) is an experimental technique used to characterize the states present for a given system. Hence, it characterizes the accessible region of the energy landscape corresponding to a given protein. For this, it introduces paramagnetic labels (tags) one at a time at few sites on one protein. The method then relies on measures of the transverse paramagnetic relaxation enhancement rates of the backbone amide protons (HN) of the partner protein. These value correspond to the weighted averages of the values for the various states present. One advantage of PRE is that it is nicely sensitive to lowly populated states.

In [49] the values measured obtained from a set of PIPER output have been compared to those obtained when using only the native state. It appears that using all the PIPER states give a better correlation respect to experimental results than when using only the native state.

[0]K.K. Singh, S. Redon, Adaptively Restrained Molecular Dynamics in LAMMPS, Submitted to *Computer Physics Communications*.

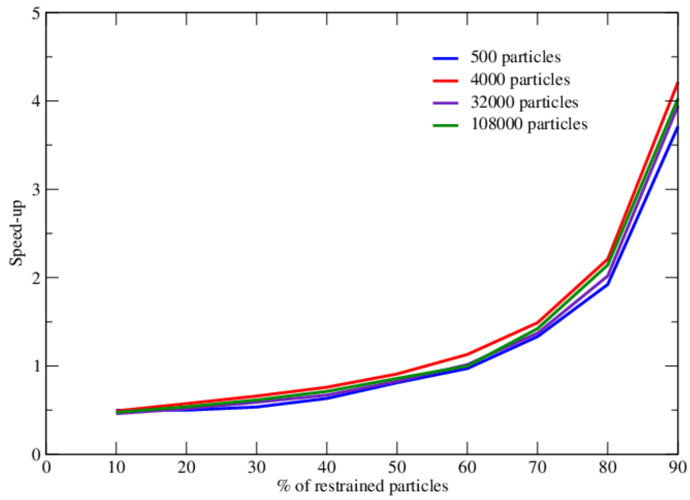

Figure 12. Obtained speed up in constructing the ANL.

In this context, our objective is to refine the energy landscape description by filtering some of the PIPER output complexes in order to improve even further the correlation with experimental measures. The method is developed as a module of the SAMSON software package (http://www.samson-connect.net/).

We have proposed a refinement from process of PIPER complexes based on two criterions: a RMSD-based filtering and an energy-based filtering.

The RMSD-filtering first creates a graph of connected component by connecting a pair of complexes if their distance is lower than a given RMSD threshold. Such a process forms clusters. Then, only the complexes that are in the cluster where belongs the native state are conserved. Since only rigid transforms are applied, RMSD are computed thanks to the fast RMSD computation method previously proposed in the team [56].

The energy-based filtering compares the energy of the complexes to the native state energy. The states for which the difference of energy is higher than a given threshold are discarded.

We have evaluated the results obtained when using our filtering scheme, for a distance threshold ranging form 3 to 9 and for an energy threshold ranging from 70 to $240kJ.mol^{-1}$. Some setting of the filtering are able to improve the correlation (see figure 13), but the gain around 0.3% remains limited (e.g. the correlation rising from 0.770 to 0.773). We are currently working on a more sophisticated state selection process to filter more precisely the PIPER states and hence to further improve the correlation.

6.10. CREST: Chemical Reactivity Exploration with Stochastic Trees

Participants: Leonard Jaillet, Stephane Redon.

We have proposed the CREST method (Chemical Reactivity Exploration with Stochastic Trees), a new simulation tool to assess the chemical reaction paths of molecular systems. First, it builds stochastic trees based on motion planning principles to search for relevant pathways inside a system's state space. This generates low energy paths transforming a reactant to a given product. Then, a nudged elastic band optimization step locally improves the quality of the initial solutions. The consistency of our approach has been evaluated through tests in various scenarios. It shows that CREST allows to appropriately describe conformational changes as well as covalent bond breaking and formations present in chemical reactions (see figure 14).

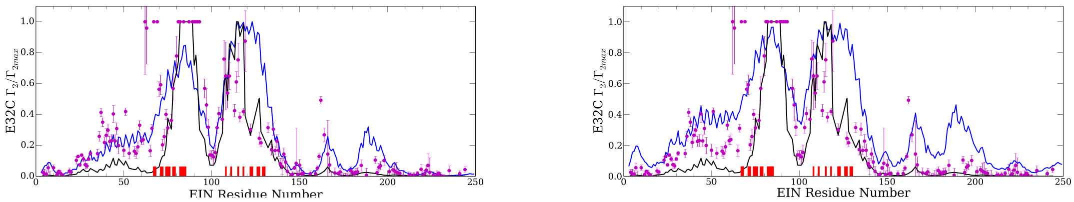

Figure 13. The experimental PRE rates ($\Gamma 2$) are displayed as filled-in magenta circles. Theoretical intermolecular PREs, calculated only from the coordinates of the specific EIN/HPr complex, are shown as black lines. Calculated PRE values from PIPER output are shown as blue lines. The calculated PRE value obtained from the filtered complexes (left) gives a higher correlation with experimental ($c = 0.773$) than the correlation obtained from all the complexes generated with PIPER (right) ($c = 0.770$).

This contribution appears in continuity of our previous work regarding the development of a geenric Motion planning architecture for nanosystems. Important features have been added to specifically treat the case of chemical reaction, such as structure alignment, exploration based on multiple trees, automatic resizing of the sampling volume, etc.

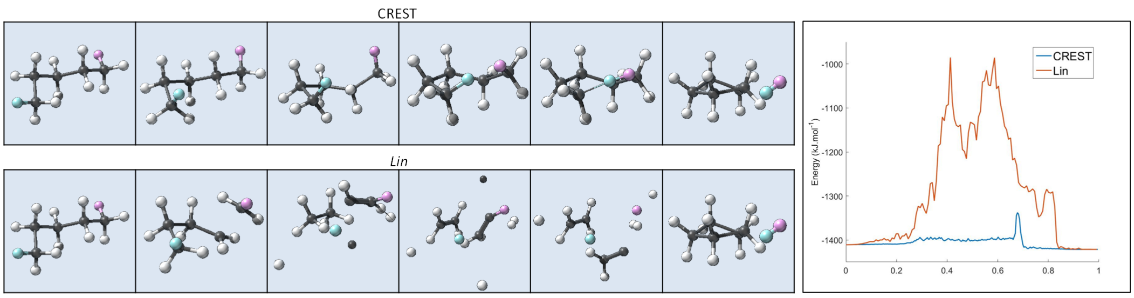

Figure 14. Fictive chemical reaction transforming a pentane into a cyclopentane with a H2 molecule. Hydrogen atoms leading to the H2 molecule are colored. The path obtained with CREST (top) is able to capture the CH3 internal rotations that approaches the two H2 Hydrogens and thus, lead to a low energy barrier. By comparison, a method based on linear interpolation (Lin) gives intermediate broken structures after local path optimization (down). The plot on the right shows the respective energies along the paths. This represents Scenario 3 described in our Results section.

6.11. IM-UFF: extending the Universal Force Field for interactive molecular modeling

Participants: Leonard Jaillet, Svetlana Artemova, Stephane Redon.

We have completed the development of IM-UFF (Interactive Modeling - UFF), an extension of UFF that combines the possibility to significantly modify molecular structures (as with reactive force fields) with a broad diversity of supported systems thanks to the universality of UFF. Such an extension lets the user easily build and edit molecular systems interactively while being guided by physically-based inter-atomic forces.

This approach introduces weighted atom types and weighted bonds, used to update topologies and atom parameterizations at every time step of a simulation. IM-UFF has been evaluated on a large set of benchmarks and is proposed as a self-contained implementation integrated in a new module for the SAMSON software platform for computational nanoscience.

This contribution has been submitted to the Journal of Molecular Modeling.

6.12. Incremental methods for long range interactions

Participants: Semeho Edorh, Stephane Redon.

Adaptively Restrained Particles Simulations (**ARPS**) were recently proposed with the purpose of speeding up molecular simulations. The main idea is to modify the Hamiltonian such that the kinetic energy is set to zero for low velocities, which allows to save computational time since particles do not move and forces need not be updated.

We continued our work on developing an extension of **ARPS** to electrostatic simulations.

We have decided to compute the electrostatic contribution by using Multigrid method. This choice have been made because of its $\mathcal{O}(N)$ behavior and its good scalability. In systems containing point charges, Multigrid can't be applied directly because of the discontinuous distribution created by these charges. To overcome this problem, one can replace this distribution by a smooth charge distribution. This charge distribution will be the source term of a Poisson equation which will be solved by Multigrid method. By doing so we retrieve an approximative electrostatic contribution which can be corrected by a near field correction. Concretely each charge will be smeared by a smooth density function.This function is chosen with a compact support. The accuracy of the method is related to the degree of smoothness and the size of the support r_{cut} of the chosen function Fig(15). The bottleneck of this method is often the time spent building the smooth charge distribution. To overcome this issue, We've introduced an interpolation scheme in the near field correction. This leads to a significant reduction of the support required to achieve a specified accuracy. The time spent building the smooth charge distribution is also reduced. Conversely the near correction is slowed down. Nevertheless, the introduction of the interpolation scheme speeds up the method in most of cases Fig(16).

Finally we modified our algorithm to take advantage of ARPS dynamics. This leads to a speed up related to the amount of restrained particles. According to our benchmarks our method can challenge Particle Particle Particle Mesh(**PPPM**), the traditional fast method to compute electrostatics Fig(17). Our algorithm is implemented in LAMMPS.

6.13. Error Analysis of Modified Langevin Dynamics

Participants: Zofia Trstanova, Gabriel Stoltz, Stephane Redon.

We performed a mathematical analysis of modified Langevin dynamics. The aim of this work was first to prove the ergodicity of the modified Langevin dynamics (which fails to be hypoelliptic), and next to analyze how the asymptotic variance on ergodic averages depends on the parameters of the modified kinetic energy. Numerical results illustrated the approach, both for low-dimensional systems where we resorted to a Galerkin approximation of the generator, and for more realistic systems using Monte Carlo simulations.

6.14. Estimating the speed-up of Adaptively Restrained Langevin Dynamics

Participants: Zofia Trstanova, Stephane Redon.

We performed a computational analysis of Adaptively Restrained Langevin dynamics, in which the kinetic energy function vanishes for small velocities. Properly parameterized, this dynamics makes it possible to reduce the computational complexity of updating inter-particle forces, and to accelerate the computation of ergodic averages of molecular simulations. We analyzed the influence of the method parameters on the total achievable speed-up. In particular, we estimated both the algorithmic speed-up, resulting from incremental force updates, and the influence of the change of the dynamics on the asymptotic variance. This allowed us to propose a practical strategy for the parametrization of the method. We validated these theoretical results by representative numerical experiments on the system of a dimer surrounded by a solvent.

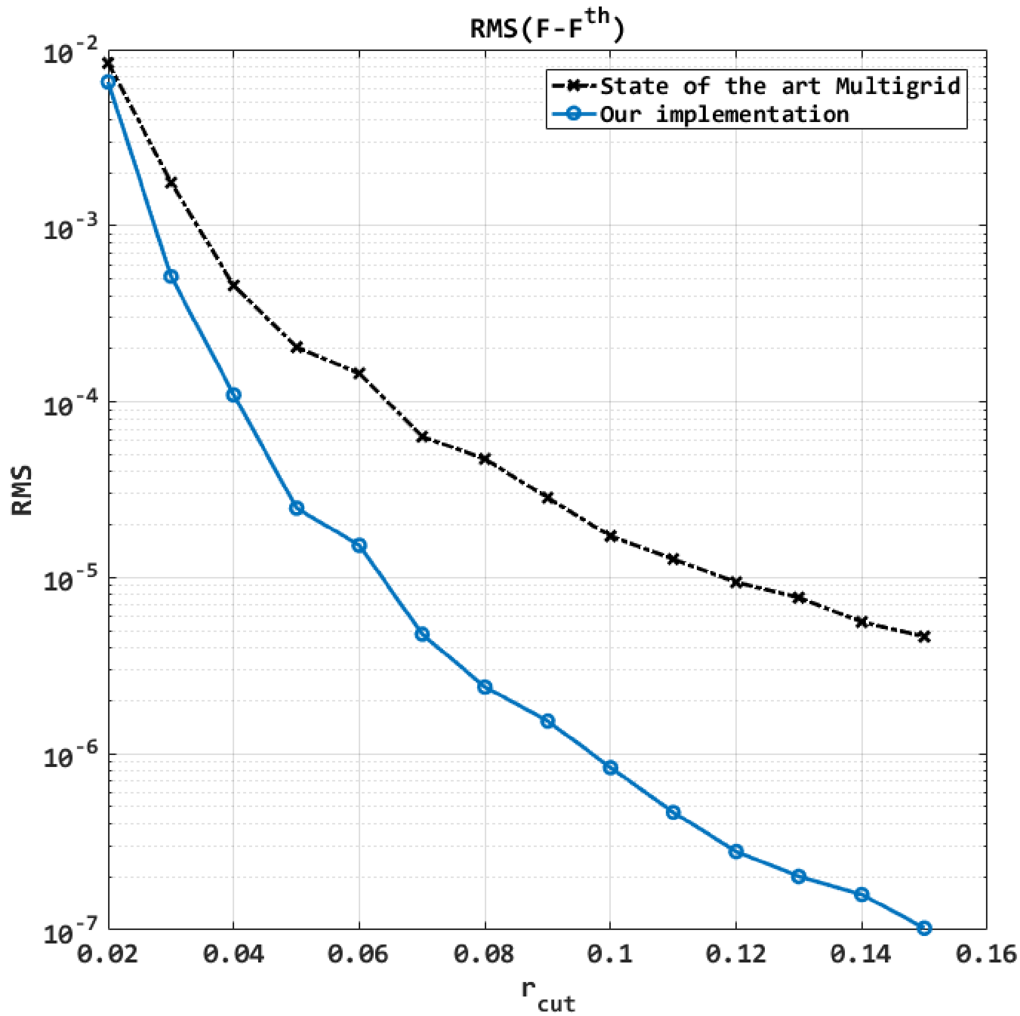

Figure 15. Accuracy in forces for the state of the art multigrid and our implementation : 125000 charged particles randomly distributed in a cubic box. r_{cut} represents the width of the chosen function.

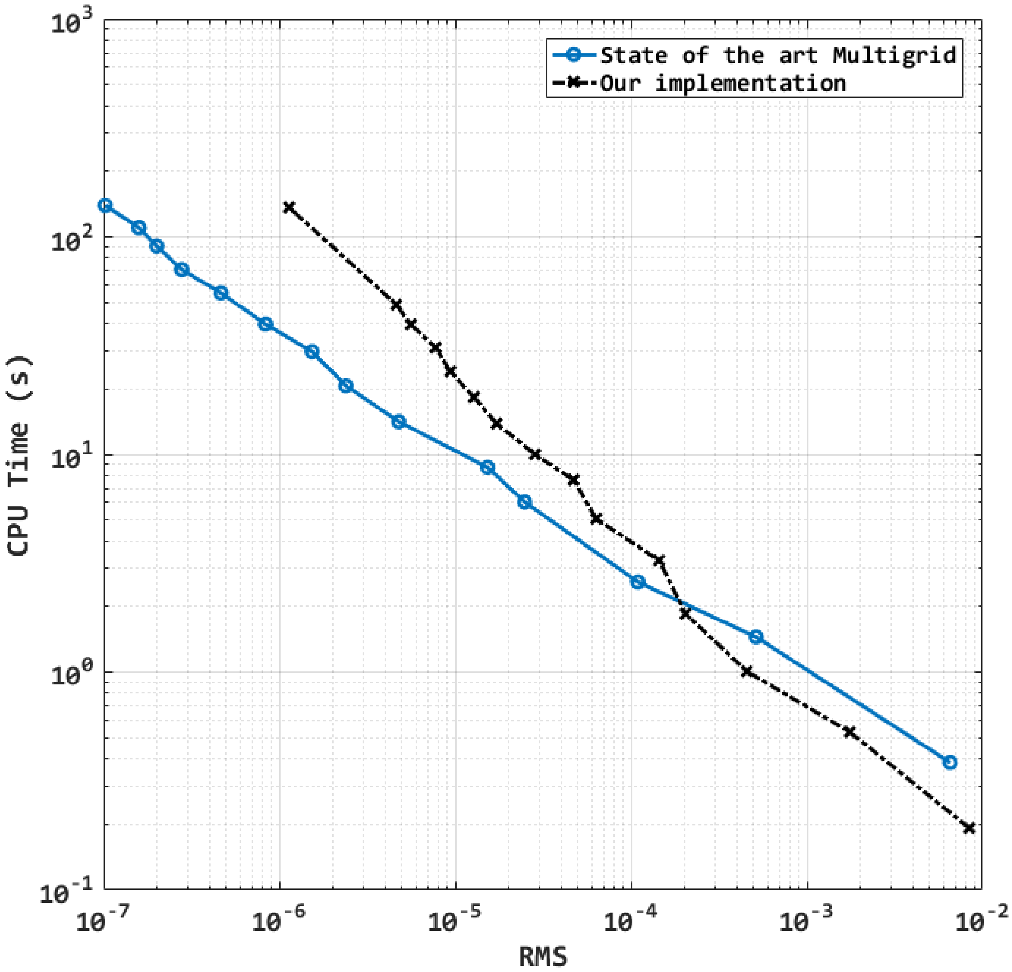

Figure 16. Comparison in terms of CPU time between the state of the art multigrid and our implementation : 125000 charged particles randomly distributed in a cubic box. r_{cut} represents the width of the chosen function.

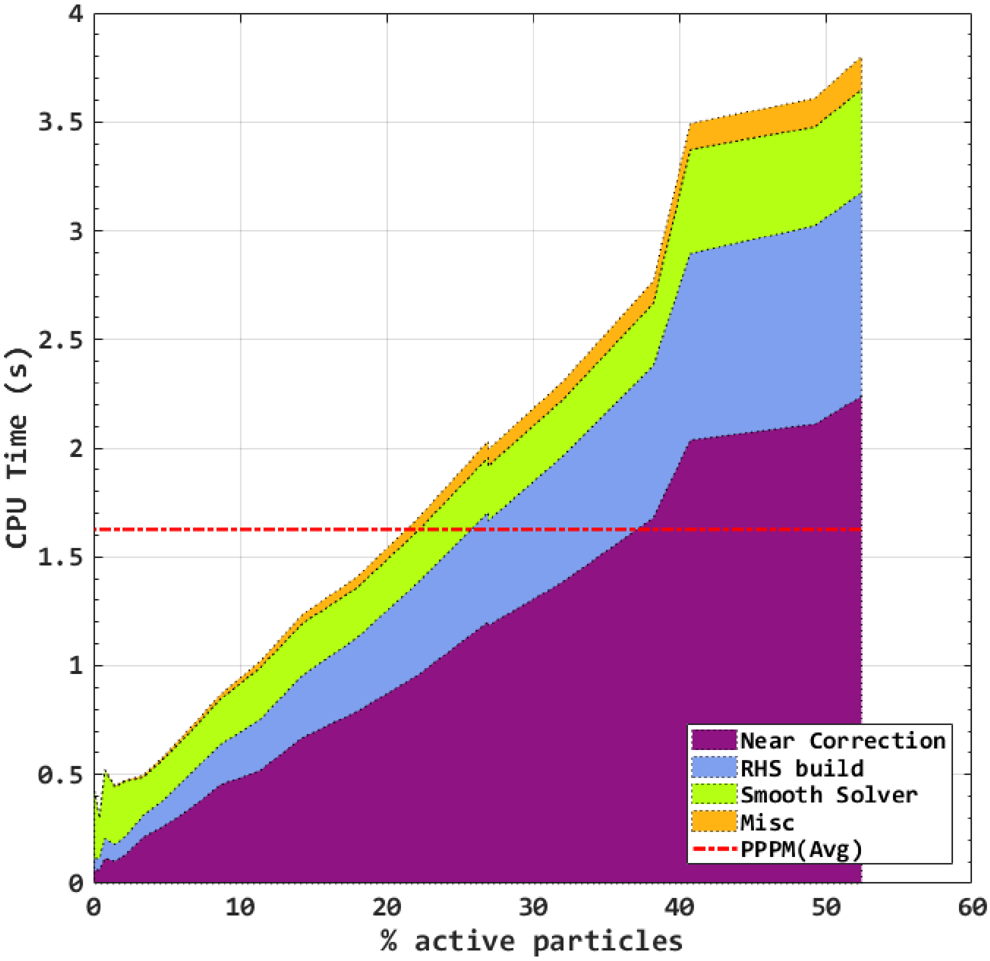

Figure 17. Comparison in terms of CPU time between PPPM and our implementation for a fixed accuracy : 64000 charged particles randomly distributed in a cubic box. Some particles are in restrained dynamics. Colored areas show the associated contribution of each part of our multigrid algorithm. Red dash-dot line represents CPU Time of Particle Particle Particle Mesh needed for this system.

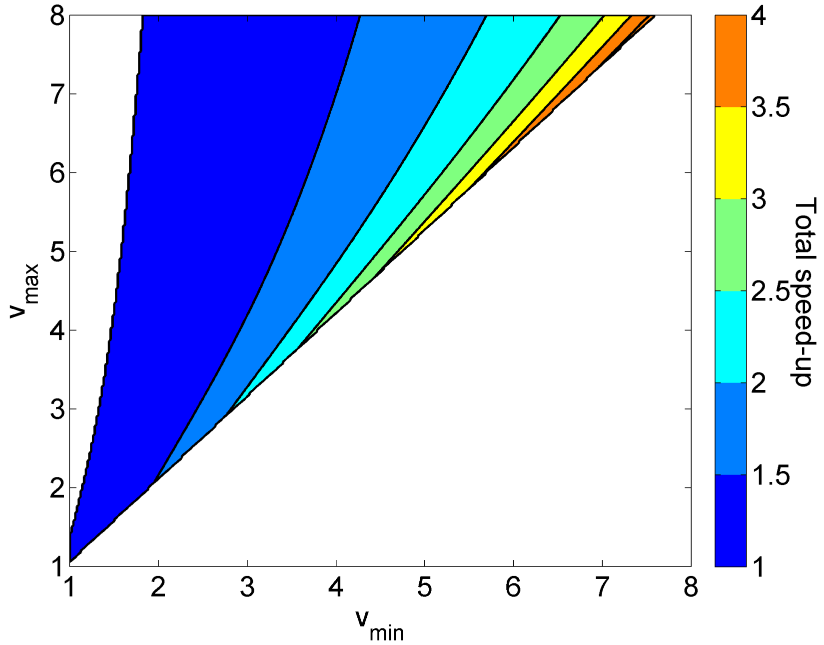

Figure 18. Analytical estimation of the total speed-up of the 3D simulation of the dimer in solvent. Only the solvent particles are restrained by the AR-method. We estimated the expected total speed-up S_{total} for the observable dimer distance A_D with respect to the restraining parameters $v_{\min}$ and $v_{\max}$ ($v_{\max} \leq 0.95 v_{\max}$). The variance was estimated from three points as a linear function of $v_{\min}$ and $v_{\max}$ and we used the analytical estimation of the algorithmic speed-up S_{a}. Only $S_{\mathrm{total}} > 1$ is plotted.

6.15. Stable and accurate schemes for Langevin dynamics with general kinetic energies

Participants: Zofia Trstanova, Gabriel Stoltz.

We studied integration schemes for Langevin dynamics with a kinetic energy different from the standard, quadratic one in order to accelerate the sampling of the Boltzmann–Gibbs distribution. We considered two cases: kinetic energies which are local perturbations of the standard kinetic energy around the origin, where they vanish (this corresponds to the so-called adaptively restrained Langevin dynamics); and more general non-globally Lipschitz energies. We developed numerical schemes which are stable and of weak order two, by considering splitting strategies where the discretizations of the fluctuation/dissipation are corrected by a Metropolis procedure. We used the newly developed schemes for two applications: optimizing the shape of the kinetic energy for the adaptively restrained Langevin dynamics, and reducing the metastability of some toy models with non-globally Lipschitz kinetic energies.

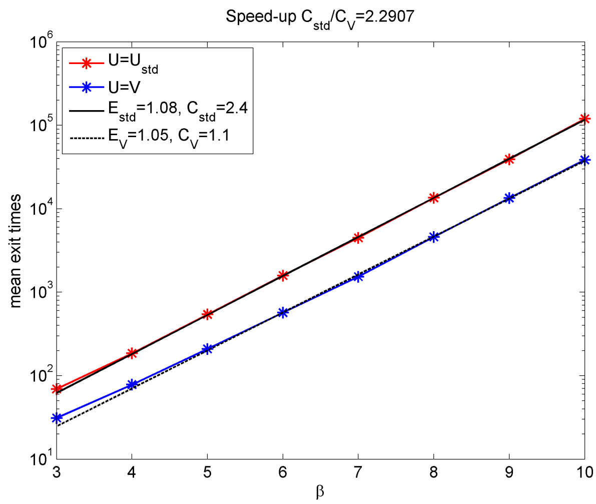

Figure 19. Comparison of the mean exit times for 2D double-well potential with the standard and the modified kinetic energy function (2000 realizations) as a function of the inverse temperature $\beta \in \{3, 4, 5, 6, 7, 8, 9, 10\}$. Thanks to the modified kinetic energy, the transition between two metastable states occurs on average three times faster.

6.16. Quadratic Programming Approach to Fit Protein Complexes into Electron Density Maps

Participants: Alexander Katrutsa, Sergei Grudinin.

We investigated the problem of simultaneous fitting protein complexes into electron density maps of their assemblies. These are represented by high-resolution cryo-EM density maps converted into overlapping matrices and partly show a structure of a complex. The general purpose is to define positions of all proteins inside it. This problem is known to be NP-hard, since it lays in the field of combinatorial optimization over a set of discrete states of the complex. We introduced quadratic programming approaches to the problem. To find an approximate solution, we converted a density map into an overlapping matrix, which is generally indefinite. Since the matrix is indefinite, the optimization problem for the corresponding quadratic form is non-convex.

To treat non-convexity of the optimization problem, we use different convex relaxations to find which set of proteins minimizes the quadratic form best.

6.17. Inverse Protein Folding Problem via Quadratic Programming

Participants: Mikhail Karasikov, Sergei Grudinin.

We presented a method of reconstruction a primary structure of a protein that folds into a given geometrical shape. This method predicts the primary structure of a protein and restores its linear sequence of amino acids in the polypeptide chain using the tertiary structure of a molecule. Unknown amino acids are determined according to the principle of energy minimization. This study represents inverse folding problem as a quadratic optimization problem and uses different relaxation techniques to reduce it to the problem of convex optimizations. Computational experiment compares the quality of these approaches on real protein structures.

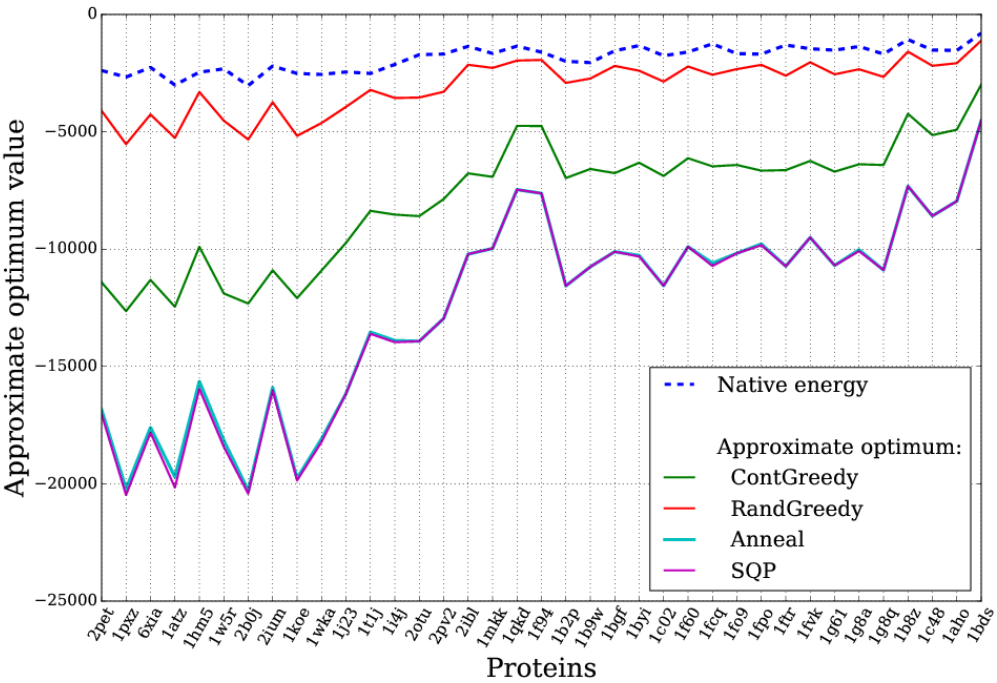

Figure 20. Approximate energy optimum for different relaxations computed on the test set

6.18. Coarse-Grained Protein Scoring Based on Geometrical Features

Participants: Mikhail Karasikov, Sergei Grudinin.

We learnt a scoring function to score protein structures with application to highly important problems in structural biology, namely, protein design, side-chain prediction, and selection of mutations increasing protein stability. For each native structure P_0 a set of ordered decoy structures $\mathcal{D}$ is given:

$$\mathcal{D} = \{P_1, \cdots, P_m\} \subset \mathcal{P},$$

$$(i_1, \cdots, i_m): \; P_{i_m} \preceq \cdots \preceq P_{i_1} \prec P_0.$$

The problem is to train protein scoring function

$$S: \; \mathcal{P} \to \mathbb{R},$$

such that

$$S(P_0) < S(P_{i_1}) \le \cdots \le S(P_{i_m}).$$

We proposed a residue-based scoring function, which uses not the positions of protein's atoms separately, but configurations of the entire residues. The proposed method requires artificially generated decoy structures for the training process and provides high quality scoring functions, which are efficient to compute. Several types of scoring functions are considered according to restrictions imposed by the specific application. For the prediction problems where the whole domain should be searched for the best prediction, we use functions that allow the reduction of emerging optimization problem

$$\sum_{k=1}^{m} \sum_{l=1}^{m} E_{kl}(a_k, a_l) \to \min_{(a_1, \cdots, a_m) \in \mathcal{A}^m} \tag{7}$$

to quadratic binary constrained optimization

$$\begin{aligned} \underset{\vec{x} \in \{0,1\}^n}{\text{minimize}} \quad & \vec{x}^{\mathsf{T}} \mathbf{Q} \vec{x} \\ \text{subject to} \quad & \mathbf{A} \vec{x} = \vec{1}_m. \end{aligned} \tag{8}$$

6.19. Development of a Normal Modes Analysis element for SAMSON platform

Participants: Yassine Naimi, Alexandre Hoffmann, Sergei Grudinin, Stephane Redon.

We are currently developing an element for the SAMSON platform for the calculation of normal modes based on the Normal Modes Analysis method. This element will be based on the program developed by Alexandre Hoffmann and Sergei Grudinin on Linux and Mac operating systems. First, we have ported the initial program from Linux and Mac operating systems to Windows and linked the program to the libraries needed for the calculations. These libraries consist in: an optimized version of BLAS (Basic Linear Algebra Subprograms) library called OpenBLAS for basic vector and matrix operations; LAPACK (Linear Algebra PACKage) library for solving systems of simultaneous linear equations, least-squares solutions of linear systems of equations, eigenvalue problems, and singular value problems; ARPACK library for solving large scale eigenvalue problems and ARMADILLO library which is a linear algebra library for the C++ language. We will also compare the performances of our program using these libraries to the Intel MKL (Math Kernel Library) libraries. The ultimate goal is to develop the interface for the SAMSON platform using the SAMSON SDK and Qt software.

6.20. Pairwise distance potential for protein folding

Participants: Maria Kadukova, Guillaume Pages, Alisa Patotskaya, Sergei Grudinin.

We have developed a new knowledge-based pairwise distance-dependent potential using convex optimization. This method uses histogram of distances repartition between each different pair of atom types as feature to feed an SVM-like algorithm. We then obtained a potential for each pair of atom types that can be used to score protein conformations. This method have been extensively used during the CASP12 blind assesement.

6.21. Knowledge-based scoring function for protein-ligand interactions

Participants: Maria Kadukova, Sergei Grudinin.

We have developed a knowledge-based pairwise distance-dependent scoring function based on the similar physical principles, as the protein folding potentials. It was trained on a set of protein-ligand complexes taken from the PDBBindCN database and validated on the CASF 2013 benchmark [50]. The corresponding paper submitted to Journal of Chemical Information and Modeling is currently under revision. We used this scoring function while participating in the 2015-2016 D3R Challenge.

6.22. Updates for the atomic typization software

Participants: Maria Kadukova, Sergei Grudinin.

We have additionally validated Knodle – our atomic typization software – on an extensive set of more than 300,000 small molecules based on the LigandExpo database. Knodle workflow involves machine-learning based "models" for different atoms, this year we retrained several of them on the updated version of PDBBindCN database. These results were published in Journal of Chemical Information and Modeling [45]. We also added functions that add missing hydrogen atoms to the molecules. Knodle was used to classify ligand atoms into different types in our protein-ligand interactions scoring function.

6.23. FFT-accelerated methods for fitting molecular structures into Cryo-EM maps

Participants: Alexandre Hoffmann, Sergei Grudinin.

We have developed a set of new methods for fitting molecular structures into Cryo-EM maps. The problem can be formally written as follows, We are given two proteins $\mathcal{P}_1$ and $\mathcal{P}_2$, and we also have $d_1 : \mathbb{R}^3 \to \mathbb{R}$, the electron density of $\mathcal{P}_1$ and $(Y_k)_{k=0 \cdots N_{atoms}-1}$, the starting positions of the atoms of $\mathcal{P}_2$. Assuming we can generate an artificial electron density $d_2 : \mathbb{R}^3 \to \mathbb{R}$ from $(Y_k)_{k=0 \cdots N_{atoms}-1}$, our problem is to find a transformation of the atoms $T : \mathbb{R}^3 \to \mathbb{R}^3$ that minimize the L^2 distance between d_1 and d_2.

In image processing this problem is usually solved using the optimal transport theory, but this method assumes that both of the densities have the same L^2 norm which is not necessarily the case for the fitting problem. To solve this problem, one instead starts by splitting T into a rigid transformation T_{rigid} (which is a combination of translation and rotation) and a flexible transformation $T_{flexible}$. Two classes of methods have been developed to find T_{rigid} :

- the first one uses optimization techniques such as gradient descent, and
- the second one uses Fast Fourier Transform (FFT) to compute the Cross Correlation Function (CCF) of d_1 and d_2.

The NANO-D team has already developed some algorithms based on the FFT to find T_{rigid} and we have been developing an efficient extension of these to find $T_{flexible}$.

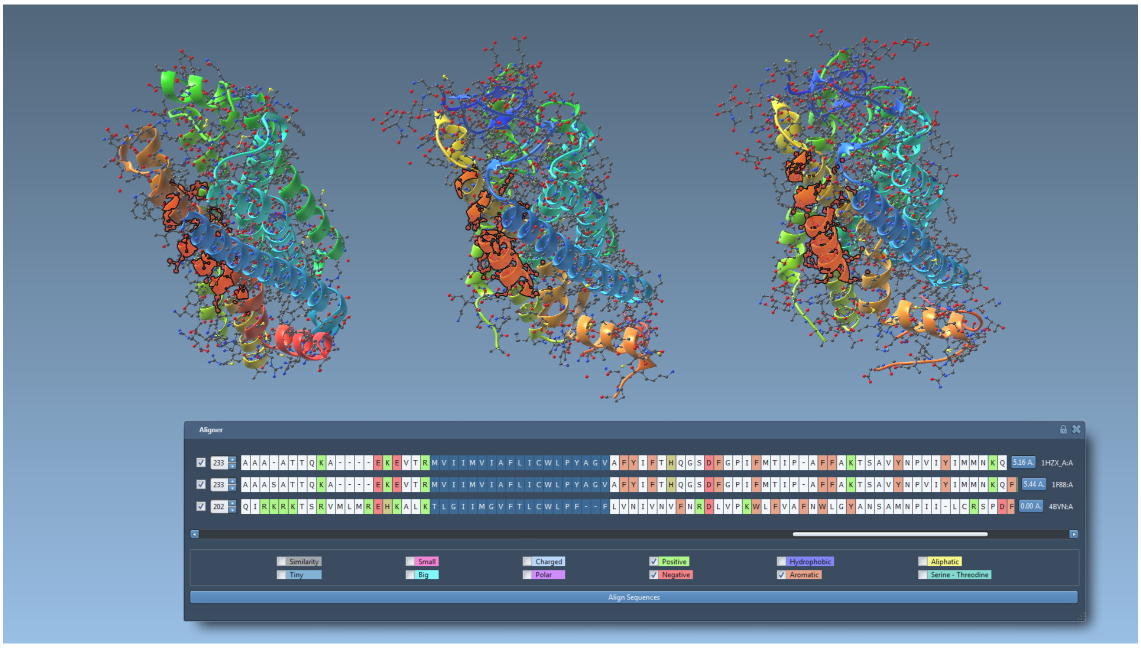

Figure 21. The protein aligner element

6.24. Protein sequence and structure aligner for SAMSON

Participants: Guillaume Pages, Sergei Grudinin.

Aligning sequences and structures of proteins is important to understand both the homologies and differences between them. We developed a SAMSON element for this purpose, that can perform both sequence and structure alignment. The sequence alignment is done thanks to the software MUSCLE [36]. The structural alignment is done by finding the transformation that minimize the RMSD between corresponding backbones atoms in both structures. We used the algorithm presented by Kearsley [47].

6.25. Implementation of an Interactive Ramachandran Plot Element for SAMSON

Participants: Guillaume Pages, Sergei Grudinin.

Each residue of a protein have two degrees of conformational freedom, described by the two dihedral angles of the backbone ϕ and ψ. Those two angles are crucial to visualize since they determine most of the protein backbone's overall conformation. A very useful way to represent them has been proposed by Ramachandran, Sasisekharan, and Ramakrishnan in 1963 [63].

We have developed a SAMSON element for displaying and editing the Ramachandran Plot of a protein. The favoured regions of the plot have been determined by analysing a database of high quality solved protein structure, provided on Richardson Lab's website (http://kinemage.biochem.duke.edu/databases/top8000.php).

7. Partnerships and Cooperations

7.1. Regional Initiatives

We have an ARC grant from the Rhone-Alpes region.

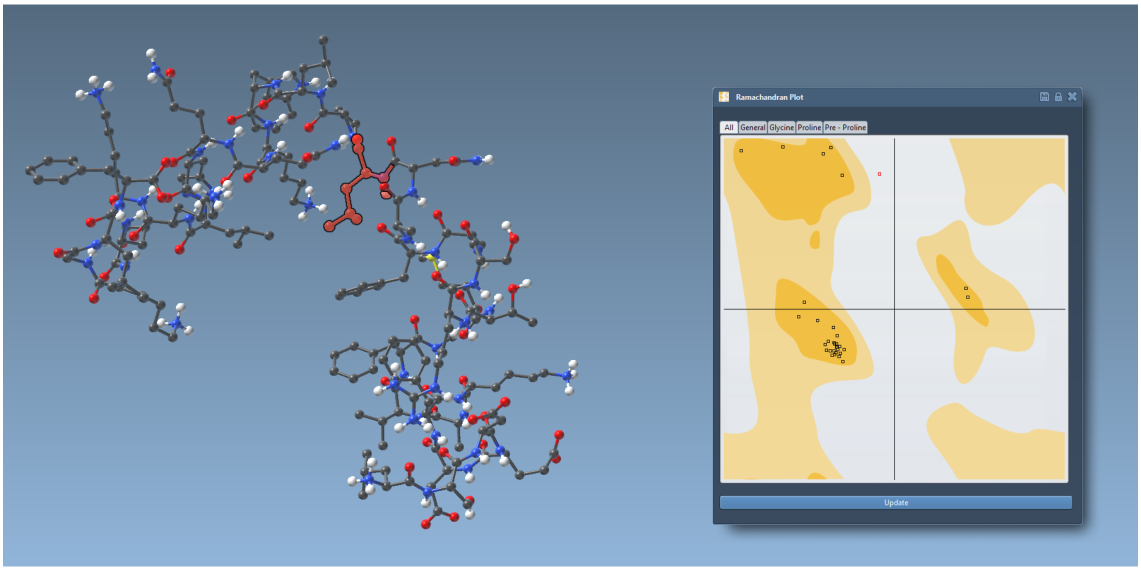

Figure 22. The Ramachandran plot element

7.2. National Initiatives

7.2.1. ANR

In 2015, NANO-D had funding from one ANR program:

- **ANR Modeles Numeriques (MN)**: 180,000 Euros over four years (2011-2015). This project, coordinated by NANO-D (S. Grudinin), gathers biologists and computer scientists from three research groups: Dave Ritchie at LORIA, Valentin Gordeliy at IBS (total grant: 360,000 Euros).

7.3. European Initiatives

7.3.1. FP7 & H2020 Projects

7.3.1.1. ADAPT

Title: Theory and Algorithms for Adaptive Particle Simulation

Programm: FP7

Duration: September 2012 - August 2017

Coordinator: Inria

Inria contact: Stephane Redon

'During the twentieth century, the development of macroscopic engineering has been largely stimulated by progress in digital prototyping: cars, planes, boats, etc. are nowadays designed and tested on computers. Digital prototypes have progressively replaced actual ones, and effective computer-aided engineering tools have helped cut costs and reduce production cycles of these macroscopic systems. The twenty-first century is most likely to see a similar development at the atomic scale. Indeed, the recent years have seen tremendous progress in nanotechnology - in particular in the ability to control matter at the atomic scale. Similar to what has happened with macroscopic engineering, powerful and generic computational tools will be needed to engineer complex nanosystems, through modeling and simulation. As a result, a major challenge is to develop efficient simulation methods and algorithms. NANO-D, the Inria research group I started in January 2008 in Grenoble, France, aims at developing efficient computational methods for modeling and simulating complex nanosystems, both natural and artificial. In particular, NANO-D develops SAMSON, a software application which gathers all algorithms designed by the group and its collaborators (SAMSON: Software for Adaptive Modeling and Simulation Of Nanosystems). In this project, I propose to develop a unified theory, and associated algorithms, for adaptive particle simulation. The proposed theory will avoid problems that plague current popular multi-scale or hybrid simulation approaches by simulating a single potential throughout the system, while allowing users to finely trade precision for computational speed. I believe the full development of the adaptive particle simulation theory will have an important impact on current modeling and simulation practices, and will enable practical design of complex nanosystems on desktop computers, which should significantly boost the emergence of generic nano-engineering.'

7.4. International Initiatives

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

7.4.1.1. PPI-3D

Title: Structure Meets Genomics

International Partner (Institution - Laboratory - Researcher):

Boston University (United States) - ___DEPARTMENT???___ - Dima Kozakov

Start year: 2015

See also: https://team.inria.fr/nano-d/research/ppi-3d-structure-meets-genomics/

Protein–protein interactions are integral to many mechanisms of cellular control, and therefore their characterization has become an important task for both experimental and computational approaches in systems biology. Genome-wide proteomics studies provide a growing list of putative protein-protein interactions, and demonstrate that most if not all proteins have interacting partners in the cell. A fraction of these interaction has been reliably established, however, one can only identify whether two proteins interact and, in the best cases, which are the individual domains mediating the interaction. A full comprehension of how proteins bind and form complexes can only come from high-resolution three-dimensional structures. While the most complete structural characterization of a complex is provided by X-ray crystallography, protein-protein hetero-complexes constitute less than 6%Â§ of protein structures in the Protein Data Bank. Thus, it is important to develop computational methods that, starting from the structures of component proteins, can determine the structure of their complexes.

The basic problem of predictive protein docking is to start with the structures (or sequences) of unbound component proteins A and B, and to obtain computationally a model of the bound complex AB, as detailed structural knowledge of the interactions facilitates understanding of protein function and mechanism. Our current docking approaches performs ab initio docking of the two structures without the use of any additional information. The goal of this proposal is to speed up docking approaches to tackle genome-scale problems, and utilize additional information on interactions, sequences, and structures that is available for virtually any protein.

This project includes several methodological and application research directions: 1) Developing fast sampling approaches; 2) Development of new scoring functions; 3) Integrative approaches for structure determination.

Overall, during the course of the project we will (i) jointly develop new methodology and algorithms in the field of genomic-scale protein complex prediction; (ii) provide server-based applications built upon services of the Boston team; (iii) and finally develop modular applications coded inside the SAMSON software platform created by the Inria team.

7.4.2. Inria International Partners

7.4.2.1. BIOTOOLS

Title: Novel Computational Tools for Structural Bioinformatics

International Partner (Institution - Laboratory - Researcher):

MIPT (Russia (Russian Federation)) - Vadim Strijov

Duration: 2016 - 2020

7.5. International Research Visitors

7.5.1. Visits of International Scientists

7.5.1.1. Internships

Sergey Kravchenko

Supervisor: Sergey Grudinin

7.5.2. Visits to International Teams

7.5.2.1. Research Stays Abroad

Leonard Jaillet, Alexandre Hoffmann and Sergei Grudinin visited the lab of Dima Kozakov.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Selection

8.1.1.1. Reviewer

- Leonard Jaillet was a reviewer for the ICRA (International Conference on Robotics and Automation) and IROS (International Conference on Intelligent Robots and Systems) conferences, the WAFR (International Workshop on the Algorithmic Foundations of Robotics) workshop and the T-RO (Transactions on Robotics) journal.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

- Stephane Redon is teaching INF585 (Introduction to C++) at Ecole polytechnique
- Stephane Redon is part of the teaching team of INF442 (Big data and high-performance computing) at Ecole polytechnique

8.2.2. Supervision

- Leonard Jaillet is advising the PhD of Minh Khoa Nguyen
- Sergei Grudinin is advising the PhD of Alexandre Hoffmann
- Sergei Grudinin is advising the PhD of Guillaume Pages
- Stephane Redon is co-advising the PhD of Krishna Kant Singh in collaboration with Jean-Francois Mehaut
- Stephane Redon is advising the PhD of Francois Rousse
- Stephane Redon is advising the PhD of Semeho Edorh
- Stephane Redon is co-advising the PhD of Zofia Trstanova in collaboration with Gabriel Stoltz (defended in november 2016)

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Project-Team NECS

Networked Controlled Systems

IN COLLABORATION WITH: Grenoble Image Parole Signal Automatique (GIPSA)

IN PARTNERSHIP WITH:
CNRS

Institut polytechnique de Grenoble

Université Grenoble Alpes

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Optimization and control of dynamic systems

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Project-Team NECS

Creation of the Project-Team: 2007 January 01

Keywords:

Computer Science and Digital Science:

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Other Research Topics and Application Domains:

7. - Transport and logistics
7.1. - Traffic management
7.2. - Smart travel

1. Members

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Others

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Jakob Zietsch [Inria, Master Student, from Mar 2016 until Jul 2016]

2. Overall Objectives

2.1. Context and overall goal of the project

NECS is a joint INRIA/GIPSA-LAB team, bi-located at the INRIA-Rhône-Alpes Center in Montbonnot and at GIPSA-LAB (http://www.gipsa-lab.grenoble-inp.fr) in the Saint-Martin-d'Hères campus, both locations being in the Grenoble area. NECS team's research is focused on Networked Controlled Systems.
The research field of Networked Controlled Systems deals with feedback systems controlled over networks, but also concerns systems that naturally exhibit a network structure (e.g., traffic, electrical networks, etc.).

The first system category results from the arrival of new control problems posed by the consideration of several factors, such as: new technological components (e.g., wireless, RF, communications, local networks, etc.), increase of systems complexity (e.g., increase in vehicle components), the distributed location of sensor and actuator, and computation constraints imposed by their embedded nature. In this class of systems, the way that the information is transferred and processed (information constraints), and the manner in which the computation resources are used (resources management), have a substantial impact in the resulting stability and performance properties of the feedback controlled systems. One main challenge here is the co-design of control together with one or more other components of different nature. The NECS team has tackled co-design problems concerning:

- Control under communications and network constraints;
- Control under resources constraints.

The second category of systems is motivated by the natural network structure in which the original systems are built. Examples are biologic networks, traffic networks, and electrical networks. The complex nature of such systems makes the classical centralized view of the control design obsolete. New distributed and/or collaborative control and estimation algorithms need to be devised as a response to this complexity. Even if the dynamic behavior of each individual system is still important, the aggregated behavior (at some macroscopic level), and its interconnection graph properties become of dominant importance. To build up this research domain, the team has put a strong focus on traffic (vehicular) networks, and in some associated research topics capturing problems that are specific to these complex network systems (distributed estimation, graph-discovering, etc).

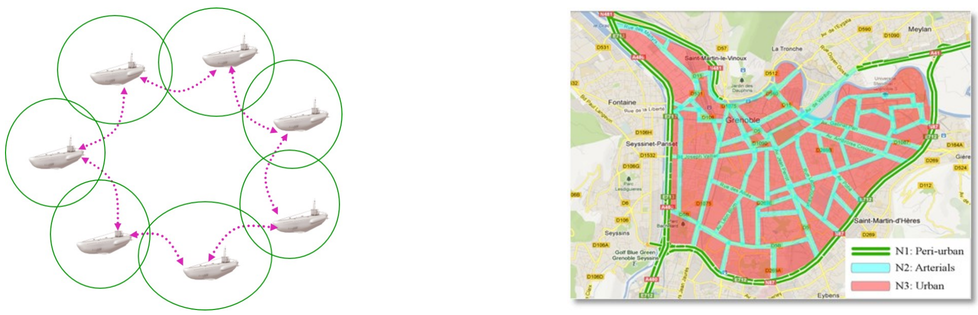

Figure 1. Left: a system of autonomous agents, where the network structure is created by the feedback, used to coordinate agents towards a common goal. Right: a system naturally having a network structure.

3. Research Program

3.1. Introduction

NECS team deals with Networked Control Systems. Since its foundation in 2007, the team has been addressing issues of control under imperfections and constraints deriving from the network (limited computation resources of the embedded systems, delays and errors due to communication, limited energy resources), proposing co-design strategies. The team has recently moved its focus towards general problems on *control of network systems*, which involve the analysis and control of dynamical systems with a network structure or whose operation is supported by networks. This is a research domain with substantial growth and is now recognized as a priority sector by the IEEE Control Systems Society: IEEE has started a new journal, IEEE Transactions on Control of Network Systems, whose first issue appeared in 2014.

More in detail, the research program of NECS team is along lines described in the following sections.

3.2. Distributed estimation and data fusion in network systems

This research topic concerns distributed data combination from multiple sources (sensors) and related information fusion, to achieve more specific inference than could be achieved by using a single source (sensor). It plays an essential role in many networked applications, such as communication, networked control, monitoring, and surveillance. Distributed estimation has already been considered in the team. We wish to capitalize and strengthen these activities by focusing on integration of heterogeneous, multidimensional, and large data sets:

- Heterogeneity and large data sets. This issue constitutes a clearly identified challenge for the future. Indeed, heterogeneity comes from the fact that data are given in many forms, refer to different scales, and carry different information. Therefore, data fusion and integration will be achieved by developing new multi-perception mathematical models that can allow tracking continuous (macroscopic) and discrete (microscopic) dynamics under a unified framework while making different scales interact with each other. More precisely, many scales are considered at the same time, and they evolve following a unique fully-integrated dynamics generated by the interactions of the scales. The new multi-perception models will be integrated to forecast, estimate and broadcast useful system states in a distributed way. Targeted applications include traffic networks and navigation, and concern recent grant proposals that team has elaborated, among which the SPEEDD EU FP7 project, which has started in February 2014.

- Multidimensionality. This issue concerns the analysis and the processing of multidimensional data, organized in multiway array, in a distributed way. Robustness of previously-developed algorithms will be studied. In particular, the issue of missing data will be taken into account. In addition, since the considered multidimensional data are generated by dynamic systems, dynamic analysis of multiway array (or tensors) will be considered. The targeted applications concern distributed detection in complex networks and distributed signal processing for collaborative networks. This topic is developed in strong collaboration with UFC (Brazil).

3.3. Network systems and graph analysis

This is a research topic at the boundaries between graph theory and dynamical systems theory.

A first main line of research will be to study complex systems whose interactions are modeled with graphs, and to unveil the effect of the graph topology on system-theoretic properties such as observability or controllability. In particular, on-going work concerns observability of graph-based systems: after preliminary results concerning consensus systems over distance-regular graphs, the aim is to extend results to more general networks. A special focus will be on the notion of ‘generic properties’, namely properties which depend only on the underlying graph describing the sparsity pattern, and hold true almost surely with a random choice of the non-zero coefficients. Further work will be to explore situations in which there is the need for new notions different from the classical observability or controllability. For example, in opinion-forming in social networks or in formation of birds flocks, the potential leader might have a goal different from classical controllability. On the one hand, his goal might be much less ambitious than the classical one of driving the system to any possible state (e.g., he might want to drive everybody near its own opinion, only, and not to any combination of different individual opinions), and on the other hand he might have much weaker tools to construct his control input (e.g., he might not know the whole system’s dynamics, but only some local partial information). Another example is the question of detectability of an unknown input under the assumption that such an input has a sparsity constraint, a question arising from the fact that a cyber-physical attack might be modeled as an input aiming at controlling the system’s state, and that limitations in the capabilities of the attacker might be modeled as a sparsity constraint on the input.

A second line of research will concern graph discovery, namely algorithms aiming at reconstructing some properties of the graph (such as the number of vertices, the diameter, the degree distribution, or spectral properties such as the eigenvalues of the graph Laplacian), using some measurements of quantities related to a dynamical system associated with the graph. It will be particularly challenging to consider directed graphs, and to impose that the algorithm is anonymous, i.e., that it does not makes use of labels identifying the different agents associated with vertices.

3.4. Collaborative and distributed network control

This research line deals with the problem of designing controllers with a limited use of the network information (i.e. with restricted feedback), and with the aim to reach a pre-specified global behavior. This is in contrast to centralized controllers that use the whole system information and compute the control law at some central node. Collaborative control has already been explored in the team in connection with the underwater robot fleet, and to some extent with the source seeking problem. It remains however a certain number of challenging problems that the team wishes to address:

- Design of control with limited information, able to lead to desired global behaviors. Here the graph structure is imposed by the problem, and we aim to design the “best” possible control under such a graph constraint [0]. The team would like to explore further this research line, targeting a better understanding of possible metrics to be used as a target for optimal control design. In particular, and in connection with the traffic application, the long-standing open problem of ramp metering control under minimum information will be addressed.

[0] Such a problem has been previously addressed in some specific applications, particularly robot fleets, and only few recent theoretical works have initiated a more systematic system-theoretic study of sparsity-constrained system realization theory and of sparsity-constrained feedback control.

- Clustering control for large networks. For large and complex systems composed of several sub-networks, feedback design is usually treated at the sub-network level, and most of the times without taking into account natural interconnections between sub-networks. The team is exploring new control strategies, exploiting the emergent behaviors resulting from new interconnections between the network components. This requires first to build network models operating in aggregated clusters, and then to re-formulate problems where the control can be designed using the cluster boundaries rather than individual control loops inside of each network. Examples can be found in the transportation application domain, where a significant challenge will be to obtain dynamic partitioning and clustering of heterogeneous networks in homogeneous sub-networks, and then to control the perimeter flows of the clusters to optimize the network operation. This topic is at the core of the Advanced ERC project Scale-FreeBack.

3.5. Transportation networks

This is currently the main application domain of the NECS team. Several interesting problems in this area capture many of the generic networks problems described above. For example, distributed collaborative algorithms can be devised for ramp-metering control and traffic-density balancing can be achieved using consensus concepts. The team is already strongly involved in this field, both this theoretical works on traffic modeling, prediction and control, and with the Grenoble Traffic Lab platform. These activities will be continued and strengthened, also thanks to the contributions from the new staff member M.L. Delle Monache.

4. Application Domains

4.1. A large variety of application domains

Sensor and actuator networks are ubiquitous in modern world, thanks to the advent of cheap small devices endowed with communication and computation capabilities. Potential application domains for research in networked control and in distributed estimation are extremely various, and include the following examples.

- Intelligent buildings, where sensor information on CO_2 concentration, temperature, room occupancy, etc. can be used to control the heating, ventilation and air conditioning (HVAC) system under multi-objective considerations of comfort, air quality, and energy consumption.
- Smart grids: the operation of electrical networks is changing from a centralized optimization framework towards more distributed and adaptive protocols, due to the high number of small local energy producers (e.g., solar panels on house roofs) that now interact with the classic large power-plants.
- Disaster relief operations, where data collected by sensor networks can be used to guide the actions of human operators and/or to operate automated rescue equipment.
- Surveillance using swarms of Unmanned Aerial Vehicles (UAVs), where sensor information (from sensors on the ground and/or on-board) can be used to guide the UAVs to accomplish their mission.
- Environmental monitoring and exploration using self-organized fleets of Autonomous Underwater Vehicles (AUVs), collaborating in order to reach a goal such as finding a pollutant source or tracing a seabed map.
- Infrastructure security and protection using smart camera networks, where the images collected are shared among the cameras and used to control the cameras themselves (pan-tilt-zoom) and ensure tracking of potential threats.

In particular, NECS team is currently focusing in the areas described in detail below.

4.2. Intelligent transportation systems

Throughout the world, roadways are notorious for their congestion, from dense urban network to large freeway systems. This situation tends to get worse over time due to the continuous increase of transportation demand whereas public investments are decreasing and space is lacking to build new infrastructures. The most obvious impact of traffic congestion for citizens is the increase of travel times and fuel consumption. Another critical effect is that infrastructures are not operated at their capacity during congestion, implying that fewer vehicles are served than the amount they were designed for. Using macroscopic fluid-like models, the NECS team has initiated new researches to develop innovative traffic management policies able to improve the infrastructure operations. The research activity is on two main challenges: (1) modeling and forecasting, so as to provide accurate information to users, e.g., travel times; and (2) control, via ramp-metering and/or variable speed limits. The Grenoble Traffic Lab (see http://necs.inrialpes.fr/pages/grenoble-traffic-lab.php) is an experimental platform, collecting traffic infrastructure information in real time from Grenoble South Ring, together with innovative software e.g. for travel-time prediciton, and a show-case where to graphically illustrate results to the end-user. This activity is done in close collaboration with local traffic authorities (DIR-CE, CG38, La Metro), and with the start-up company Karrus (http://www.karrus-its.com/)

4.3. Inertial navigation

Since 2014, the team is exploring techniques for pedestrian navigation and algorithms for attitude estimation, in collaboration with the Tyrex team (Inria-Rhône-Alpes). The goal is to use such algorithms in augmented reality with smartphones. Inertial navigation is a research area related to the determination of 3D attitude and position of a rigid body. Attitude estimation is usually based on data fusion from accelerometers, magnetometers and gyroscopes, sensors that we find usually in smartphones. These algorithms can be used also to provide guidance to pedestrians, e.g., to first responders after a disaster, or to blind people walking in unfamiliar environments. This tasks is particularly challenging for indoor navigation, where no GPS is available.

4.4. Multi-robot collaborative coordination

Due to the cost or the risks of using human operators, many tasks of exploration, or of after-disaster intervention are performed by un-manned drones. When communication becomes difficult, e.g., under water, or in spatial exploration, such robots must be autonomous. Complex tasks, such as exploration, or patrolling, or rescue, cannot be achieved by a single robot, and require a self-coordinated fleet of autonomous devices. NECS team has studied the marine research application, where a fleet of Autonomous Underwater Vehicles (AUVs) self-organize in a formation, adapting to the environment, and reaching a source, e.g., of a pollutant. This has been done in collaboration with IFREMER, within the national project ANR CONNECT and the European FP7 project FeedNetBack [1]. On-going research in the team concerns source localization, with a fleet of mobile robots, including wheeled land vehicles.

4.5. Control design of hydroelectric powerplants

We have started a collaboration with ALSTOM HYDRO, on collaborative and reconfigurable resilient control design of hydroelectric power plants. This work is within the framework of the joint laboratory Inria/ALSTOM (see http://www.inria.fr/innovation/actualites/laboratoire-commun-inria-alstom). A first concrete collaboration has been established with the CIFRE thesis of Simon Gerwig, who has studied how to improve performance of a hydro-electric power-plant outside its design operation conditions, by adaptive cancellation of oscillations that occur in such operation range.

5. Highlights of the Year

5.1. Highlights of the Year

- C. Canudas de Wit has been elevated to the grade of Fellow of the IEEE.
- C. Canudas de Wit has been named a Fellow of the IFAC (International Federation of Automatic Control).
- C. Canudas de Wit has received an ERC Advanced Grant for the project “Scale-FreeBack”.
- The GTL platform and website went public in November.
- G. De Nunzio received the “Prix de thèse 2016 de la COMUE Université Grenoble Alpes” for his doctoral work, co-advised by C. Canudas de Wit and P. Moulin.
- A. Kibangou defended his HDR (Habilitation à diriger les recherches).
- P. Frasca and M.L. Delle Monache have joined the team as permanent researchers.
- H. Fourati has edited the book “Recent Advances on Multisensor Attitude and Heading Estimation: Fundamental Concepts and Applications”, by Taylor & Francis Group LLC.

6. New Software and Platforms

6.1. GTL

Grenoble Traffic Lab

FUNCTIONAL DESCRIPTION

The Grenoble Traffic Lab (GTL) initiative, led by the NeCS team, is a real-time traffic data Center (platform) that collects traffic road infrastructure information in real-time with minimum latency and fast sampling periods. The main elements of the GTL are: a real-time data-base, a show room, and a calibrated micro-simulator of the Grenoble South Ring. Sensed information comes from a dense wireless sensor network deployed on Grenoble South Ring, providing macroscopic traffic signals such as flows, velocities, densities, and magnetic signatures. This sensor network was set in place in collaboration with Inria spin-off Karrus-ITS, local traffic authorities (DIR-CE, CG38, La Metro), and specialized traffic research centers. In addition to real data, the project also uses simulated data, in order to validate models and to test the ramp-metering, the micro-simulator is a commercial software (developed by TSS AIMSUN ©). More details at http://necs.inrialpes.fr/pages/grenoble-traffic-lab.php.

- Participants: Carlos Canudas De Wit, Iker Bellicot, Pascal Bellemain, Dominik Pisarski, Alain Kibangou, Hassen Fourati, Fabio Morbidi, Federica Garin, Andres Alberto Ladino Lopez, Pietro Grandinetti, Enrico Lovisari, Rohit Singhal, Anton Andreev, Remi Piotaix, Vadim Bertrand, Maria Laura Delle Monache and Paolo Frasca
- Contact: Carlos Canudas De Wit
- URL: http://necs.inrialpes.fr/pages/grenoble-traffic-lab.php

6.2. Senslogs – Sensors recorder for Android application

Participants: T. Michel [contact person], H. Fourati, P. Geneves, N. Layaida.

This Android application records direct and computed measurements from internal sensors (Accelerometer, Gyroscope, Magnetometer, Calibrated Gyroscope, Calibrated Magnetic Field, Game Rotation Vector, Geomagnetic, Rotation Vector, Gravity, Linear Acceleration, Significant Motion, Step Counter, Step Detector, Ambient Temperature, Light, Pressure, Relative Humidity, Heart Rate, Proximity, GPS Location, Cell and Wifi Location, Passive Location, NMEA data, Wifi signals, Bluetooth signals (not yet), NFC (not yet), and others available...). Data are stored in files using space-separated values. This application has been designed for post-processing projects. It will be used in pedestrian navigation and augmented reality applications. This application is available online: https://play.google.com/store/apps/details?id=fr.inria.tyrex.senslogs&hl=fr_BE

6.3. Wifi Scan Interval for Android application

Participants: T. Michel [contact person], H. Fourati, P. Geneves, N. Layaida.

This app records the wifi scan sampling rate on your phone. This application is available online: https://play.google.com/store/apps/details?id=fr.inria.tyrex.wifiscaninterval To contribute to a database: http://thibaud-michel.com/mobile/wifi-scan-interval.txt More information: https://github.com/ThibaudM/WifiScanIntervalhttp://stackoverflow.com/questions/37193175

7. New Results

7.1. Networked and multi-agent systems: modeling, analysis, and estimation

7.1.1. Modeling of animal groups

Participants: P. Frasca [Contact person], A. Aydogdu [Rutgers University at Camden], C. d'Apice [Univ. Salerno], R. Manzo [Univ. Salerno], W. Saidel [Rutgers University at Camden], B. Piccoli [Rutgers University at Camden].

The paper [13] introduces a mathematical model to study the group dynamics of birds resting on wires. The model is agent-based and postulates attraction-repulsion forces between the interacting birds: the interactions are "topological", in the sense that they involve a given number of neighbors irrespective of their distance. The main properties of the model are investigated by combining rigorous mathematical analysis and simulations. This analysis gives indications about the total length of a group and the inter-animal spacings within it: in particular, the model predicts birds to be more widely spaced near the borders of each group. We compare these insights from the model with new experimental data, derived from the analysis of pictures of pigeons and starlings taken by the team in New Jersey. We have used two different image elaboration protocols to derive the data for the statistical analysis, which allowed us to establish a good agreement with the model and to quantify its main parameters. Our data also seem to indicate potential handedness of the birds: we investigated this issue by analyzing the group organization features and the group dynamics at the arrival of new birds. However, data are still insufficient to draw a definite conclusion on this matter. Finally, arrivals and departures of birds from the group are included in a refined version of the model, by means of suitable stochastic processes.

7.1.2. Cyber-Physical Systems: a control-theoretic approach to privacy and security

Participants: A. Kibangou [Contact person], F. Garin, S. Gracy, H. Nouasse.

Cyber-physical systems are composed of many simple components (agents) with interconnections giving rise to a global complex behaviour. Interesting recent research has been exploring how the graph describing interactions affects control-theoretic properties such as controllability or observability, namely answering the question whether a small group of agents would be able to drive the whole system to a desired state, or to retrieve the state of all agents from the observed local states only. A related problem is observability in the presence of an unknown input, where the input can represent a failure or a malicious attack, aiming at disrupting the normal system functioning while staying undetected. In our work [24], we study linear network systems affected by a single unknown input. The main result is a characterization of input and state observability, namely the conditions under which both the whole network state and the unknown input can be reconstructed from some measured local states. This characterization is in terms of observability of a suitably-defined subsystem, which allows the use of known graphical characterizations of observability of cyber-physical systems, leading to structural results (true for almost all interaction weights) or strong structural results (true for all non-zero interaction weights). Observability is also related to privacy issues. In the ProCyPhyS project, started recently (October 2016), we are studying privacy-preserving properties of cyber-physical systems, by analyzing observability properties of such systems, in order to derive privacy-preserving policies for applications related to smart mobility.

7.1.3. Sensor networks: Multisensor data fusion for attitude estimation

Participants: H. Fourati [Contact person], A. Kibangou, A. Makni, T. Michel, P. Geneves [Tyrex, Inria], N. Layaida [Tyrex, Inria], J. Wu [University of Electronic Science and Technology of China, Chengdu], Z. Zhou [University of Electronic Science and Technology of China, Chengdu], D. Belkhiat [University Ferhat Abbas, Setif, Algeria].

Attitude estimation consists in the determination of rigid body orientation in 3D space (principally in terms of Euler angles, rotation matrix, or quaternion). This research area is a multilevel, multifaceted process involving the automatic association, correlation, estimation, and combination of data and information from several sources. Another interest consists in the fact that redundant and complementary sensor data can be fused and integrated using multisensor fusion techniques to enhance system capability and reliability. Data fusion for attitude estimation is therefore a research area that borrows ideas from diverse fields, such as signal processing, sensor fusion, and estimation theory, where enhancements are involved in point-of-view data authenticity or availability. Data fusion for attitude estimation is motivated by several issues and problems, such as data imperfection, data multimodality, data dimensionality, and processing framework. As a majority of these problems have been identified and heavily investigated, no single data fusion algorithm is capable of addressing all the aforementioned challenges. Consequently, a variety of methods in the literature focuses on a subset of these issues. These concepts and ideas are treated in the book [28], as a response to the great interest and strong activities in the field of multisensor attitude estimation during the last few years, both in theoretical and practical aspects. In the team, we have carried out works related to attitude estimation evaluation for pedestrian navigation purpose. In [18], we focused on two main challenges. The first one concerns the attitude estimation during dynamic cases, in which external acceleration occurs. In order to compensate for such external acceleration, we design a quaternion-based adaptive Kalman filter q-AKF. Precisely, a smart detector is designed to decide whether the body is in static or dynamic case. Then, the covariance matrix of the external acceleration is estimated to tune the filter gain. The second challenge is related to the energy consumption issue of gyroscope. In order to ensure a longer battery life for the Inertial Measurement Units, we study the way to reduce the gyro measurements acquisition by switching on/off the sensor while maintaining an acceptable attitude estimation. The switching policy is based on the designed detector. The efficiency of the proposed scheme is evaluated by means of numerical simulations and experimental tests. In [31], we investigate the precision of attitude estimation algorithms in the particular context of pedestrian navigation with commodity smartphones and their inertial/magnetic sensors. We report on an extensive comparison and experimental analysis of existing algorithms. We focus on typical motions of smartphones when carried by pedestrians. We use a precise ground truth obtained from a motion capture system. We test state-of-the-art attitude estimation techniques with several smartphones, in the presence of magnetic perturbations typically found in buildings. We discuss the obtained results, analyze advantages and limits of current technologies for attitude estimation in this context. Furthermore, we propose a new technique for limiting the impact of magnetic perturbations with any attitude estimation algorithm used in this context. We show how our technique compares and improves over previous works. A novel quaternion-based attitude estimator with magnetic, angular rate, and gravity (MARG) sensor arrays is proposed in [20] within the framework of collaboration with Prof. Zhou from University of Electronic Science and Technology of China, Chengdu. A new structure of a fixed-gain complementary filter is designed fusing related sensors. To avoid using iterative algorithms, the accelerometer-based attitude determination is transformed into a linear system. Stable solution to this system is obtained via control theory. With only one matrix multiplication, the solution can be computed. Using the increment of the solution, we design a complementary filter that fuses gyroscope and accelerometer together. The proposed filter is fast, since it is free of iteration. We name the proposed filter the fast complementary filter (FCF). To decrease significant effects of unknown magnetic distortion imposing on the magnetometer, a stepwise filtering architecture is designed. The magnetic output is fused with the estimated gravity from gyroscope and accelerometer using a second complementary filter when there is no significant magnetic distortion. Several experiments are carried out on real hardware to show the performance and some comparisons. Results show that the proposed FCF can reach the accuracy of Kalman filter. It successfully finds a balance between estimation accuracy and time consumption. Compared with iterative methods, the proposed FCF has much less convergence speed. Besides, it is shown that the magnetic distortion would not affect the estimated Euler angles.

7.2. Control design and networked systems

7.2.1. Control design for hydro-electric power-plants

Participants: C. Canudas de Wit [Contact person], S. Gerwig [Feb 2014–Mar 2016], F. Garin, B. Sari [Alstom].

This is the study of collaborative and resilient control of hydro-electric power-plants, in collaboration with Alstom. The goal is to improve performance of a hydro-electric power-plant outside its design operation conditions, by cancellation of oscillations that occur in such an operation range. Indeed, current operation of power-plants requires to operate on a variety of conditions, often different from the ones initially considered when designing the plant. At off-design operation pressure, the hydraulic turbine exhibits a vortex rope below the runner. This vortex generates pressure fluctuations after the turbine and can excite the hydraulic pipes. Indeed the water is compressible and the pipe walls elastic, so the system can oscillate. The goal is to damp these pressure oscillations as they create vibrations in the system and can lead to damages. Our first contribution [23] has been to model the effect of the vortex rope on the hydraulic system as an external perturbation source acting on pipes. The pipes themselves are described with equations taking into account water compressibility and pipe-wall elasticity. The resulting model is nonlinear with hyperbolic functions in the equations (analogous to high-frequency transmission lines), from which we obtain a suitably linearized model. This model can then be used for control design.

7.2.2. Collaborative source seeking

Participants: F. Garin [Contact person], C. Canudas de Wit, R. Fabbiano.

The problem of source localization consists in finding the point or the spatial region from which a quantity of interest is being emitted. We consider collaborative source seeking, where various moving devices, each equipped with a sensor, share information to coordinate their motion towards the source. We focus on the case where information can only be shared locally (with neighbor agents) and where the the agents have no global position information, and only limited relative information (bearing angle of neighbor agents). This setup is relevant when GPS navigation is not available, as in underwater navigation or in cave exploration, and when relative position of neighbors is vision-based, making it easier to measure angles than distances. In [16] we propose and analize a control law, which is able to bring and keep the agents on a circular equispaced formation, and to steer the circular formation towards the source via a gradient-ascent technique; the circular equispaced formation is beneficial to a good approximation of the gradient from local pointwise measurements. This algorithm is different from the ones present in the literature, because it can cope with our above-described restrictive assumptions on the available position information.

7.2.3. Distributed control and game theory: self-optimizing systems

Participants: F. Garin [Contact person], B. Gaujal [POLARIS], S. Durand.

The design of distributed algorithms for a networked control system composed of multiple interacting agents, in order to drive the global system towards a desired optimal functioning, can benefit from tools and algorithms from game theory. This is the motivation of the Ph.D. thesis of Stéphane Durand, a collaboration between POLARIS and NECS teams. The first results of this thesis concern the complexity of a classical algorithm in game theory, the Best Response Algorithm, an iterative algorithm to find a Nash Equilibrium. For potential games, Best Response Algorithm converges in finite time to a pure Nash Equilibrium. The worse-case convergence time is known to be exponential in the number of players, but surprisingly it turns out that on average (over the possible values of the potentials) the complexity is much smaller, only linearly growing, see [27], [26], [22].

7.3. Transportation networks and vehicular systems

7.3.1. Travel time prediction

Participants: A. Kibangou [Contact person], C. Canudas de Wit, H. Fourati, A. Ladino.

One of the regular performance metrics for qualifying the level of congestion in traffic networks is the travel time. Precision in the estimation or measurement of this variable is one of the most desired features for traffic management. The computation of the travel time is regularly performed based on instantaneous information so called instantaneous travel time (ITT), but regularly traffic changes on time and spaces and the computation depends dynamically on the speeds of the system and the notion of dynamic travel time (DTT) is required. Here the computation requires future information of speed so a short term forecast is required. First in [25] we have presented a framework for instantaneous travel time predictions for multiple origins and destinations in a highway. Secondly in [32], a detailed real time application to compute predictions of dynamic travel time (DTT) is presented. Speed measurements describing a spatio-temporal distribution are captured, from there the DTT is constructed. Definitions, computational details and properties in the construction of DTT are provided. DTT is dynamically clustered using a K-means algorithm and then information on the level and the trend of the centroid of the clusters is used to devise predictors computationally simple to be implemented. To take into account lack of information of cluster assignment of the data to be predicted, a fusion strategy based on the best linear unbiased estimator principle is proposed to combine the predictions of each model. The algorithm is deployed in a real time application and the performance is evaluated using real traffic data from the South Ring of the Grenoble city in France.

7.3.2. Urban traffic control

Participants: C. Canudas de Wit [Contact person], F. Garin, P. Grandinetti.

This work deals with optimal or near-optimal operation of traffic lights in an urban area, e.g., a town or a neighborhood. The goal is on-line optimization of traffic lights schedule in real time, so as to take into account variable traffic demands, with the objective of obtaining a better use of the road infrastructure. More precisely, we aim at maximizing total travel distance within the network, while also ensuring good servicing of demands of incoming cars in the network from other areas. The complexity of optimization over a large area is addressed both in the formulation of the optimization problem, with a suitable choice of the traffic model, and in a distributed solution, which not only parallelizes computations, but also respects the geometry of the town, i.e., it is suitable for an implementation in a smart infrastructure where each intersection can compute its optimal traffic lights by local computations combined with exchanges of information with neighbor intersections.

7.3.3. Optimal control of freeway access

Participants: C. Canudas de Wit [Contact person], D. Pisarski.

The work [19] contains Dominik Pisarski's major results which he obtained during the realization of his Ph.D. thesis at Inria-Rhone Alpes. In concerns the problem of optimal control for balancing traffic density in freeway traffic. The control is realized by ramp metering. The balancing of traffic was proposed as a new objective to improve the vehicular flow on freeways and ring-roads. It was demonstrated that the balancing may result in significantly shortened travel delays and reduced pollution. It may also be beneficial for safety and comfort during a travel. For the controller, a novel modular decentralized structure was proposed where each of the modules computes its optimal decision by using local traffic state and supplementary information arriving from the neighboring controllers. For such a structure, the optimal control problem was formulated as a Nash game, where each player (controller's module) optimizes its local subsystem with respect to decisions of the other players. In comparison to the existing solutions, this new approach significantly reduces the computational burden needed for optimal traffic control, allowing for on-line implementation over long freeway segments. In the paper, the proposed control method was tested via numerical examples with the use of Cell Transmission Model. Later, the performance of the designed method was validated by employing a micro-simulator and real traffic data collected from the south ring of Grenoble. The designed distributed controller resulted in 5% reduction of total time spent on the ring road, 18% reduction of total time spent in the on-ramp queues, 2reduction of the average fuel consumption, and 4% reduction of the traffic density.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. ALSTOM

Contract with ALSTOM in the framework of Inria/ALSTOM joint laboratory, and CIFRE PhD grant of Simon Gerwig. This thesis explores collaborative and reconfigurable resilient control design of hydroelectric power plants; current work is on improving performance of a hydro-electric power-plant outside its design operation conditions, by cancellation of oscillations that occur in such operation range.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. ProCyPhyS

ProCyPhyS is a one year project funded by University Grenoble Alps, MSTIC department, with the aim to study privacy in cyberphysical system. A post-doc (H. Nouasse) has been hired to perform analysis of privacy protection through system-theoretic measures. We are interested with cyber-physical systems that can be viewed as systems of interconnected entities which are locally governed by difference equations of partial differential equations, namely intelligent transportation systems and indoor navigation. A first approach to analyze privacy preservation is to study observability of the overall system, see [8] where a large family of non-observable networks have been characterized for homogeneous systems of consensus type. In this approach, the network structure immunizes the overall system. A second approach, consists in adding information (noise) to the sensitive one: that is the differential privacy concept that leads to differential filtering where the aim is to develop an estimator that is robust enough according to the added noise [33]. In ProCyPhyS the main goal is to make the system partially nonobservable. The idea is to compress the state space while adding noise to the sensitive information in a smarter way.

9.1.2. Collaboration with IFSTTAR, Lyon, and LICIT team

The group has begun a collaboration with IFSTTAR in Lyon and namely with the LICIT team. We held two informal workshops: the first one in Grenoble, where we presented the team, and the second one in Lyon, which was focused on traffic modeling. During this workshop, the NeCS team proposed the following talks:

- C. Canudas de Wit, A variable-length cell transmission model for road traffic system;
- M. L. Delle Monache, Coupled PDE-ODE models for traffic flow.

A third workshop is planned next March and we expect a sustained collaboration during the coming year.

9.2. European Initiatives

9.2.1. FP7 & H2020 Projects

9.2.1.1. SPEEDD (Scalable ProactivE Event-Driven Decision making)

Type: STREP

Objective: ICT-2013.4.2a – Scalable data analytics – Scalable Algorithms, software frameworks and viualisation

Duration: Feb. 2014 to Jan. 2017.

Coordinator: National Centre of Scientific Research ‘Demokritos’ (Greece)

Partners: IBM Israel, ETH Zurich (CH), Technion (Israel), Univ. of Birmingham (UK), NECS CNRS (France), FeedZai (Portugal)

Inria contact: C. Canudas de Wit

Abstract: SPEEDD is developing a prototype for robust forecasting and proactive event-driven decision-making, with on-the-fly processing of Big Data, and resilient to the inherent data uncertainties. NECS leads the intelligent traffic-management use and show case.

See also: http://speedd-project.eu

9.2.1.2. Scale-FreeBack

Type: ERC Advanced Grant

Duration: Sep. 2016 to Aug. 2021

Coordinator: C. Canudas de Wit

Inria contact: C. Canudas de Wit

Abstract: The overall aim of Scale-FreeBack is to develop holistic scale-free control methods of controlling complex network systems in the widest sense, and to set the foundations for a new control theory dealing with complex physical networks with an arbitrary size. Scale-FreeBack envisions devising a complete, coherent design approach ensuring the scalability of the whole chain (modelling, observation, and control). It is also expected to find specific breakthrough solutions to the problems involved in managing and monitoring large-scale road traffic networks. Field tests and other realistic simulations to validate the theory will be performed using the equipment available at the Grenoble Traffic Lab center (see GTL), and a microscopic traffic simulator replicating the full complexity of the Grenoble urban network.

See also: http://scale-freeback.eu

9.3. International Initiatives

9.3.1. Inria International Labs

Inria@SiliconValley

Associate Team involved in the International Lab:

9.3.1.1. COMFORT

Title: COntrol and FOrecasting in Transportation networks

International Partner (Institution - Laboratory - Researcher):

University of California Berkeley (United States) - Mechanical Engineering - Roberto Horowitz

Start year: 2014

See also: http://necs.inrialpes.fr/v2/pages/comfort/EA_homepage_COMFORT.html

COMFORT addresses open issues for Intelligent Transportation Systems (ITS). The goal of these systems is to use information technologies (sensing, signal processing, machine learning, communications, and control) to improve traffic flow, as well as enhance the safety and comfort of drivers. It has been established over the past several decades, through field studies and many scholarly publications, that the tools of ITS can significantly improve the flow of traffic on congested freeways and streets. Traffic operators can manage the system in a top-down fashion, for example, by changing the speed limit on a freeway, or by controlling the flow on the onramps (ramp metering). Individual drivers can also affect traffic conditions from the bottom up, by making decisions based on reliable predictions. These predictions must be provided by a centralized system that can evaluate the decisions based on global information and sophisticate modeling techniques. It is now crucial to develop efficient algorithms for control and prediction that are well adapted to current and emerging sensing and communication technologies. The areas of traffic modeling and calibration, state estimation, and traffic control remain central to this effort. Specifically, COMFORT addresses issues related to model validation and development of new traffic forecasting and distributed control algorithms. The efficiency of the derived methods will be assessed using large networks simulators and real data obtained from the Californian and the Grenoble's testbed.

This year is the final one of the current project: however, the positive results from the project have lead to the request of its extension, which is pending approval.

9.3.2. Participation in Other International Programs

9.3.2.1. TICO-MED

TicoMed (Traitement du signal Traitement numérique multidimensionnel de l'Information avec applications aux Télécommunications et au génie Biomédical) is a French-Brazilian project funded by CAPES-COFECUB. It started in February 2015 with University of Nice Sophia Antipolis (I3S Laboratory), CNAM, SUPELEC, University of Grenoble Alpes (Gipsa-Lab), Universidade Federal do Ceara, Universidade Federal do Rio de Janeiro, and Universidade Federal do Santa Catarina as partners.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

Prof. Andre L.F. de Almeida from (Universidade Federal do Ceara, Fortaleza, Brazil) visited the team in June 2015 within the framework of the French-Brazilian CAPES-COFECUB project TICO-MED.

Dr. Thibault Liard (University Pierre et Marie Curie, Paris VI) visited the team in November. He gave a seminar to the team with the title "A Kalman rank condition for the indirect controllability of coupled systems of linear operator groups" and discussed with M. L. Delle Monache on traffic flow modeling and control using conservation laws.

9.4.2. Visits to International Teams

9.4.2.1. Research Stays Abroad

Maria Laura Delle Monache and Giacomo Casadei visited UC Berkeley in December. They had research meeting with faculty and students at ITS and PATH and in particular with Prof. M. Arcak.

A. Kibangou visited the Nelson Mandela Metropolitan University (Port Elizabeth) and the University of Johanesburg (UJ) in May 2016. During his stay, he gave a lecture to students of Department of Town and Regional Planning of UJ on Mobility and traffic management.

A. Kibangou visited Universidade Federal do Ceara (UFC) in Fortaleza (Brazil) in November 2016 within the framework of the Tico-Med bilateral project. During his stay, he worked with Prof. Andre L.F. de Almeida on tensor models for graph filters and gave a course on Graph Signal Processing to researchers and doctoral students of UFC.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

C. Canudas de Wit has been appointed General Chair of the 58th IEEE Conference on Decision and Control, 2019.

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

P. Frasca has been Associate Editor-at-Large in the International Program Committee of the 55th IEEE Conference on Decision and Control, 2016.

P. Frasca and F. Garin are Associate Editors in the IEEE Control System Society Conference Editorial Board. This year, they served for the 2016 American Control Conference, the 2017 American Control Conference, and the 55th IEEE Conference on Decision and Control, 2016.

P. Frasca is Associate Editor in the European Control Association (EUCA) Conference Editorial Board. This year, he served for the 2016 European Control Conference.

P. Frasca has been appointed as Associate Editor in the IEEE Robotics and Automation Society CASE Conference Editorial Board: he shall serve for 13th IEEE International Conference on Automation Science and Engineering, 2017.

Hassen Fourati was a member of the International and Scientific Program Committees of the International Conference on Control, Automation and Diagnosis (ICCAD'17), 2017, and the International Conference on Sciences and Techniques of Automatic Control and Computer Engineering STA2016, 2016.

10.1.2.2. Reviewer

Team members, and in particular faculty, have been reviewers for several conferences (including the most prestigious ones in their research area): IEEE Conference on Decision and Control CDC, European Control Conference ECC, American Control Conference ACC, European Signal Processing Conference, IEEE International Conference on Robotics and Automation ICRA, IEEE/RSJ International Conference on Intelligent Robots and Systems IROS, IFAC Workshop on Distributed Estimation and Control in Networked Systems (NecSys), Indian Control Conference.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

Carlos Canudas de Wit is Associate Editor of IEEE Transactions on Control of Networks Systems IEEE-TCNS (since June 2013), Associate Editor of IEEE Transactions on Control System Technology IEEE-TCST (since January 2013), and Editor of the Asian Journal of Control AJC (since 2010).

Paolo Frasca is Subject Editor of the International Journal of Robust and Nonlinear Control (Wiley) (since February 2014) and has been appointed as starting Associate Editor of IEEE Control System Letters (from February 2017).

Hassen Fourati is Associate Editor of the Asian Journal of Control AJC (since January 2016).

10.1.3.2. Reviewer - Reviewing Activities

Team members, and in particular faculty, have been reviewers for several journals (including the most prestigious ones in their research area): IEEE Trans. on Automatic Control, IEEE Trans. on Control of Network Systems, IEEE Trans. on Signal Processing, Automatica, IEEE Signal Processing Letters, Systems and Control Letters, IEEE Transactions on Information Theory, Elsevier Signal Processing, Int. Journal of Robust and Nonlinear Control, IET Communications, IET Wireless Sensor Networks. IEEE/ASME Trans. on Mechatronics, IEEE Trans. on Instrumentations and Measurements, IEEE Sensors journal, IEEE Trans. on Robotics, Networks and Heterogeneous Network (NHM), Mathematical Methods in the Applied Sciences (MMAS), Journal of Mathematical Analysis and Applications (JMMA), AMS Mathematical Reviews, Journal of Intelligent Transportation Systems.

10.1.4. Invited Talks

- C. Canudas de Wit, "Optimal Traffic Control: Eco-driving, Green-waves, Adaptive traffic lights" (plenary talk), Latin American Conference on Automatic Control 2016, Medellin, Colombia, October 2016.
- M. L. Delle Monache, "Some control strategies for conservation laws with applications to traffic flow", Séminaire de théorie du contrôle de Toulon, University of Toulon, November 2016.
- P. Frasca, "Non-smooth and hybrid systems in opinion dynamics", IEEE CDC satellite workshop on Dynamics and Control in Social Networks, Las Vegas, Nevada, December 2016.
- P. Frasca, "Non-smooth and hybrid systems in opinion dynamics", ANR Workshop "Control subject to computational and communication constraints" (CO4), Toulouse, France, October 2016.

10.1.5. Leadership within the Scientific Community

C. Canudas de Wit has been president of the European Control Association (EUCA) until June 2015, and is now (until 2017) Past-president and member of the EUCA Council.

10.1.6. Scientific Expertise

Team members participate to the following technical committees of IEEE Control Systems Society and of the International Federation of Automatic Control:
CSS Technical Committee “Networks and Communications Systems” (P. Frasca and F. Garin);
IFAC Technical Committee 1.5 on Networked Systems (P. Frasca and C. Canudas de Wit);
IFAC Technical Committee 2.5 on Robust Control (P. Frasca);
IFAC-TC7.1 Automotive Control (C. Canudas de Wit);
IFAC-TC7.4 Transportation systems (C. Canudas de Wit).

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master: F. Garin, Distributed Algorithms and Network Systems, 13.5h, M2, Univ. Grenoble Alpes, France.

Licence: H. Fourati, Informatique Industrielle, 105h, L1, IUT 1 (GEII), Univ. Grenoble Alpes, France;

Licence: H. Fourati, Réseaux locaux industriels, 50h, L1 et L2, IUT1 (GEII), Univ. Grenoble Alpes, France.

Licence: H. Fourati, Automatique, 61,5h, L3, UFR physique, Univ. Grenoble Alpes, France.

Licence: H. Fourati, Automatique échantillonnée, 15h, L2, IUT 1 (GEII), Univ. Grenoble Alpes, France.

Licence: A. Kibangou, Automatique, 52h, L2, IUT1(GEII1), Univ. Grenoble Alpes, France.

Licence: A. Kibangou, Mathématiques, 33h, L2, IUT1 (GEII1), Univ. Grenoble Alpes, France.

Licence: A. Kibangou, Mathématiques, 44h, L1, IUT1 (GEII1), Univ. Grenoble Alpes, France.

Licence: A.Kibangou, Automatique, 16h, L3, IUT1 (GEII1), Univ. Grenoble Alpes, France.

Doctorat: C. Canudas de Wit has organized the 37th International Summer School of Automatic Control Grenoble, France September, 12-16, 2016 on the topic “Advanced algorithms for traffic prediction and control”.

10.2.2. Supervision

PhD: Aida Makni, Inertial and magnetic data fusion for attitude estimation under energetic constraint for accelerated rigid body, Univ. Grenoble Alpes, March 2016, co-advised by H. Fourati, A. Kibangou and C. Canudas de Wit.

PhD in progress: Simon Gerwig, Collaborative, reconfigurable and resilient control for hydro-electric power-plants, from Feb. 2014 until Mar. 2017, co-advised by C. Canudas de Wit, F. Garin and B. Sari (Alstom).

PhD in progress: Pietro Grandinetti, Control of large-scale traffic networks, from Apr. 2014, co-advised by C. Canudas de Wit and F. Garin.

PhD in progress: Andrés Alberto Ladino Lopez, Robust estimation and prediction in large scale traffic networks, from Oct. 2014, co-advised by C. Canudas de Wit, A. Kibangou and H. Fourati.

PhD in progress: Thibaud Michel, Mobile Augmented Reality Applications for Smart Cities, from Nov. 2014, co-advised by N. Layaïda, H. Fourati and P. Geneves.

PhD in progress: Sebing Gracy, Cyber-physical systems: a control-theoretic approach to privacy and security, from Oct. 2015, co-advised by A. Kibangou and F. Garin.

PhD in progress: Stéphane Durand, Coupling distributed control and game theory: application to self-optimizing systems, from Oct. 2015, co-advised by B. Gaujal and F. Garin.

PhD in progress: Stéphane Mollier, Aggregated Scale-Free Models for 2-D Large-scale Traffic Systems, from Oct. 2016, co-advised by C. Canudas de Wit, M. L. Delle Monache and B. Seibold.

PhD in progress: Nicolas Martin, On-line partitioning algorithms for evolutionary scale-free networks, from Dec. 2016, co-advised by C. Canudas de Wit and P. Frasca.

10.2.3. Juries

- C. Canudas de Wit was committee member of the PhD defence of Kuo-Yun Liang, KTH Stockholm. Ph.D. advisor: K.H. Johansson, June 10, 2016.
- H. Fourati was committee member of the PhD defense of Christophe Combettes, Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR), Spécialité : Automatique et Informatique appliquée, October 17, 2016.
- P. Frasca was committee member of the PhD defence of Laura Dal Col, *On distributed control analysis and design for multi-agent systems subject to limited information*, Institut National des Sciences Appliquées, Toulouse, France. Ph.D. advisors: Luca Zaccarian and Sophie Tarbouriech, October 25, 2016.
- H. Fourati was committe member of "Qualification Maître de Conferences 2016" during January 2016, Autrans, France.

10.3. Popularization

The GTL webpage (http://gtl.inrialpes.fr/status) went public in November: more generally the traffic activities have been popularized via the following public talks.

- M. L. Delle Monache. DEMO on the GTL at the "Journées des nouveaux arrivants", Inria, Paris, Dec. 2016
- M. L. Delle Monache, Traffic flow modeling, GIPSA-Lab days, Grenoble, Nov. 2016

11. Bibliography

Major publications by the team in recent years

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[32] A. LADINO, A. Y. KIBANGOU, H. FOURATI, C. CANUDAS DE WIT.*A real time forecasting tool for dynamic travel time from clustered time series*, August 2016, Submitted to Transportation Research Part C. Emerging Technologies.

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Project-Team NUMED

Numerical Medicine

IN COLLABORATION WITH: Unité de Mathématiques Pures et Appliquées

IN PARTNERSHIP WITH:
CNRS

Ecole normale supérieure de Lyon

Université Claude Bernard (Lyon 1)

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Modeling and Control for Life Sciences

Table of contents

Project-Team NUMED

Creation of the Project-Team: 2009 January 01

Keywords:

Computer Science and Digital Science:

6. - Modeling, simulation and control
6.1. - Mathematical Modeling
6.2. - Scientific Computing, Numerical Analysis & Optimization
6.3. - Computation-data interaction

Other Research Topics and Application Domains:

1. - Life sciences
1.1. - Biology
1.2. - Ecology
1.4. - Pathologies
2. - Health
2.2. - Physiology and diseases
2.2.2. - Nervous system and endocrinology
2.2.3. - Cancer
2.2.4. - Infectious diseases, Virology
2.4.1. - Pharmaco kinetics and dynamics
2.4.2. - Drug resistance
2.6.1. - Brain imaging

1. Members

Research Scientist

Vincent Calvez [CNRS, Researcher, HDR]

Faculty Members

Emmanuel Grenier [Team leader, ENS Lyon, Professor, HDR]
Marie Aimee Dronne [Univ. Lyon I, Associate Professor]
Paul Vigneaux [ENS Lyon, Associate Professor]

PhD Students

Mathilde Giacalone [Univ. Lyon]
Arthur Marly [ENS Lyon]
Alvaro Mateos Gonzalez [ENS Lyon]
Edouard Ollier [ENS Lyon]
Aziz Ouerdani [Inria, until May 2016]

Post-Doctoral Fellows

Thibault Bourgeron [ENS Lyon]
Christopher Henderson [Univ. Lyon, until Aug 2016]

Administrative Assistant

Sylvie Boyer [Inria]

2. Overall Objectives

2.1. Overall Objectives

The purpose of Numed is to develop new numerical methods and tools to simulate and parametrize complex systems arising in biology and medicine. Numed focuses on two axes:

- Thema 1: Modeling using complex models: how to deal with multiple spatial or temporal scales (theoretical study, numerical simulations)?

  This covers several aims: design of models of propagation taking into account the microscopic phenomena and starting from small scale description, importance of mechanics in the growth of tissues, peculiarities of tumor tissues, nonlinear rheology, evolutionary perspectives.

  Thema 1 may be split in three objectives.

  - Multiscale propagation phenomena in biology
  - Growth of biological tissues
  - Multiscale models in oncology
- Thema 2: Parametrization of complex models: how to find parameters for complex models, with particular emphasis on population approaches and on computationally expensive models.

and two main axes of applications

- Thema 3: Stroke

  Stroke is one of the major diseases in developed countries. Its modeling is very challenging and rich, involving imagery, cell death modeling, apoptosis, energy issues, inflammation, free radicals, anatomy, ...
- Thema 4: Cancer

  The aim is to develop models of cancer growth in close link with clinical data.

3. Research Program

3.1. Multiscale propagation phenomena in biology

3.1.1. Project team positioning

The originality of our work is the quantitative description of propagation phenomena accounting for several time and spatial scales. Here, propagation has to be understood in a broad sense. This includes propagation of invasive species, chemotactic waves of bacteira, evoluation of age structures populations ... Our main objectives are the quantitative calculation of macroscopic quantities as the rate of propagation, and microscopic distributions at the edge and the back of the front. These are essential features of propagation which are intimately linked in the long time dynamics.

Multiscale modeling of propagation phenomena raises a lot of interest in several fields of application. This ranges from shock waves in kinetic equations (Boltzmann, BGK, etc...), bacterial chemotactic waves, selection-mutation models with spatial heterogeneities, evolution in age-structured population or subdiffusive processes.

Earlier works generally focused on numerical simulations, hydrodynamic limits to average over the microscopic variable, or specific models with only local features, not suitable for most of the relevant biological situations. Our contribution enables to derive the relevant features of propagation analytically, and far from the hydrodynamic regime for a wide range of models including nonlocal interaction terms.

Our recent understanding is closely related to the analysis of large deviations in multiscale dispersion equations (e.g. PDMP), for which we gave important contributions too in collaboration with E. Bouin (CEREMADE Dauphine), E. Grenier (Inria NUMED) and G. Nadin (Univ. Paris 6).

These advances are linked to the work of other Inria teams (MAMBA, DRACULA, BEAGLE), and collaborators in mathematics, physics and theoretical biology in France, Austria and UK.

3.1.2. Recent results

Vincent Calvez has focused on the modelling and analysis of propagation phenomena in structured populations. This includes chemotactic concentration waves, transport-reaction equations, coupling between ecological processes (reaction-diffusion) and evolutionary processes (selection of the fittest trait, adaptation), evolution of age structured poulations, and anomalous diffusion. As a main result, he could establish the existence of concentration waves of chemotactic bacteria E. coli in a fully coupled kinetic/reaction-diffusion system previously validated on experimental data.

In collaboration with a group of theoretical biologists at ISEM Montpellier (O. Ronce and O. Cotto), and J. Garnier (Univ. Savoie), Th. Lepoutre (Inria DRACULA), Th. Bourgeron (Inria NUMED) he has investigated quantitatively the maladaptation of an age-structured population in a changing environment. He has unravelled a striking phenomenon of severe maladaptation specific to age structure. This was observed on numerical simulations by biologists, but it has now a systematic mathematical comprehension.

He has also continued his work on the optimal control of monotone linear dynamical systems, using the Hamilton-Jacobi framework, and the weak KAM theory, in collaboration with P. Gabriel (UVSQ) and S. Gaubert (Inria MAXPLUS).

Alvaro Mateos Gonzalez has started his PhD on September 2014 under the supervision of Vincent Calvez, and Hugues Berry (BEAGLE), . He has already collaborated fruitfully with Thomas Lepoutre (DRACULA) and Hugues Berry to investigate the long-time asymptotics of a degenerate renewal equation. This is a first step towards the mathematical analysis of anomalous diffusion processes. In collaboration with P. Gabriel (UVSQ) and V. Calvez (Inria NUMED) he has investigated large deviations of heterogenous continuous time random walks.

3.1.3. Collaborations

- Mathematical description of bacterial chemotactic waves:
  - **N. Bournaveas** (Univ. Edinburgh), **V. Calvez** (ENS de Lyon, Inria NUMED) **B. Perthame** (Univ. Paris 6, Inria BANG), **Ch. Schmeiser** (Univ. Vienna), **N. Vauchelet**: design of the model, analysis of traveling waves, analysis of optimal strategies for bacterial foraging.
  - **J. Saragosti**, **V. Calvez** (ENS de Lyon, Inria NUMED), **A. Buguin**, **P. Silberzan** (Institut Curie, Paris): experiments, design of the model, identification of parameters.
- Transport-reaction waves and large deviations:
  - **E. Bouin**, **V. Calvez** (ENS de Lyon, Inria NUMED), **E. Grenier** (ENS de Lyon, Inria NUMED), **G. Nadin** (Univ. Paris 6)
- Selection-mutation models of invasive species:
  - **E. Bouin** (ENS de Lyon, Inria NUMED), **V. Calvez** (ENS de Lyon, Inria NUMED), **S. Mirrahimi** (Inst. Math. Toulouse): construction of traveling waves, asymptotic propagation of fronts,
  - **E. Bouin** (ENS de Lyon, Inria NUMED), **V. Calvez** (ENS de Lyon, Inria NUMED), **N. Meunier**, (Univ. Paris 5), **B. Perthame** (Univ. Paris 6, Inria Bang), **G. Raoul** (CEFE, Montpellier), **R. Voituriez** (Univ. Paris 6): formal analysis, derivation of various asymptotic regimes.
- Age-structured equations for anomalous diffusion processes, and evolution

– **H. Berry** (Inria BEAGLE), **V. Calvez** (ENS de Lyon, Inria NUMED), **Th. Lepoutre** (Inria DRACULA), **P. Gabriel** (Univ. UVSQ), O. Ronce (ISEM Montpellier), O. Cotto (ISEM Montpellier), J. Garnier (Univ. Savoie).

3.2. Growth of biological tissues

3.2.1. Project-team positioning

The originality of our work is the derivation, analysis and numerical simulations of mathematical model for growing cells and tissues. This includes mechanical effects (growth induces a modification of the mechanical stresses) and biological effects (growth is potentially influenced by the mechanical forces).

This leads to innovative models, adapted to specific biological problems (*e.g.* suture formation, cell polarisation), but which share similar features. We perform linear stability analysis, and look for pattern formation issues (at least instability of the homogeneous state).

The biophysical literature of such models is large. We refer to the groups of Ben Amar (ENS Paris), Boudaoud (ENS de Lyon), Mahadevan (Harvard), etc.

Our team combines strong expertise in reaction-diffusion equations (V. Calvez) and mechanical models (P. Vigneaux). We develop linear stability analysis on evolving domains (due to growth) for coupled biomechanical systems.

Another direction of work is the mathematical analysis of classical tumor growth models. These continuous mechanics models are very close to classical equations like Euler or Navier Stokes equations in fluid mechanics. However they bring there own difficulties: Darcy law, multispecies equations, non newtonian dynamics (Bingham flows). Part of our work consist in deriving existence results and designing acute numerical schemes for these equations.

3.2.2. Recent results

We have worked on several biological issues. Cell polarisation is the main one. We first analyzed a nonlinear model proposed by theoretical physicists and biologists to describe spontaneous polarisation of the budding yeast *S. cerevisae*. The model assumes a dynamical transport of molecules in the cytoplasm. It is analogous to the Keller-Segel model for cell chemotaxis, except for the source of the transport flux. We developped nonlinear analysis and entropy methods to investigate pattern formation (Calvez et al 2012). We are currently validating the model on experimental data. The analysis of polarization of a single cell is a preliminary step before the study of mating in a population of yeast cells. In the mating phase, secretion of pheromones induces a dialogue between cells of opposite types.

We also derive realistic models for the growth of the fission yeast *S. pombe*. We proposed two models which couple growth and geometry of the cell. We aim to tackle the issue of pattern formation, and more specifically the instability of the spherical shape, leading to a rod shape. The mechanical coupling involves the distribution of microtubules in the cytoplasm, which bring material to the cell wall.

Over the evaluation period, Paul Vigneaux developped expertise in modelling and design of new numerical schemes for complex fluid models of the viscoplastic type. Associated materials are involved in a broad range of applications ranging from chemical industry to geophysical and biological materials. In the context of NUMED, this expertise is linked to the development of complex constitutive laws for cancer cell tissue. During the period, NUMED used mixed compressible/incompressible fluid model for tumor growth and viscoelastic fluid model. Viscoplastic is one of the other types of complex fluid model which is usable in the field. Mathematically, it involves variational inequalities and the need for specific numerical methods.

3.2.3. Collaborations

- **V. Calvez** (ENS de Lyon, Inria NUMED), **Th. Lepoutre** (Inria DRACULA), **N. Meunier**, (Univ. Paris 5), **N. Muller** (Univ. Paris 5), **P. Vigneaux** (ENS de Lyon, Inria NUMED): mathematical analysis of cell polarisation, numerical simulations

- **V. Calvez** (ENS de Lyon, Inria NUMED), **N. Meunier**, (Univ. Paris 5), **M. Piel**, (Institut Curie, Paris), **R. Voituriez** (Univ. Paris 6): biomechanical modeling of the growth of *S. pombe*
- **D. Bresch** (Univ. Chambéry), **V. Calvez** (ENS de Lyon, Inria NUMED), **R.H. Khonsari** (King's College London, CHU Nantes), **J. Olivier** (Univ. Aix-Marseille), **P. Vigneaux** (ENS de Lyon, Inria NUMED): modeling, analysis and simulations of suture formation.
- **Didier Bresch** (Univ Chambéry), **Benoit Desjardins**(Moma group): petrology.

ANR JCJC project "MODPOL", *Mathematical models for cell polarization*, led by Vincent Calvez (ENS de Lyon, CNRS, Inria NUMED).

3.3. Multiscale models in oncology

3.3.1. Project-team positioning

Since 15 years, the development of mathematical models in oncology has become a significant field of research throughout the world. Several groups of researchers in biomathematics have developed complex and multiscale continuous and discrete models to describe the pathological processes as well as the action of anticancer anti-cancer drugs. Many groups in US (e.g. Alexander Anderson's lab, Kristin Swansson's lab) and in Canada (e.g. Thomas Hillen, Gerda de Vries), quickly developed and published interesting modeling frameworks. The setup of European networks such as the Marie Curie research and training networks managed by Nicolas Bellomo and Luigi Preziosi constituted a solid and fertile ground for the development of new oncology models by teams of biomathematicians and in particular Zvia Agur (Israel), Philip Maini (UK), Helen Byrne (UK), Andreas Deutsch (Germany), or Miguel Herrero (Spain).

3.3.2. Results

We have worked on the development of a multiscale system for modeling the complexity of the cancer disease and generate new hypothesis on the use of anti-cancer drugs. This model relies on a multiscale formalism integrating a subcellular level integrating molecular interactions, a cell level (integrating the regulation of the cell cycle at the levels of individual cells) and a macroscopic level for describing the spatio-temporal dynamics of different types of tumor tissues (proliferating, hypoxic and necrotic). The model is thus composed by a set of partial differential equations (PDEs) integrating molecular network up to tissue dynamics using lax from fluid dynamic. This formalism is useful to investigate theoretically different cancer processes such as the angiogenesis and invasion. We have published several examples and case studies of the use of this model in particular, the action of phase-specific chemotherapies (Ribba, You et al. 2009), the use of anti-angiogenic drugs (Billy, Ribba et al. 2009) and their use in combination with chemotherapies (Lignet, Benzekry et al. 2013). This last work also integrates a model of the VEGF molecular pathway for proliferation and migration of endothelial cells in the context of cancer angiogenesis (Lignet, Calvez et al. 2013).

If these types of models present interesting framework to theoretically investigate biological hypothesis, they however present limitation due to their large number of parameters. In consequence, we decided to stop the development of the multiscale platform until exploration of alternative modeling strategies to deal with real data. We focus our interest on the use of mixed-effect modeling techniques as classically used in the field of pharmacokinetic and pharmacodynamics modeling. The general principal of this approach lies in the integration of several levels of variability in the model thus allowing for the simultaneous analysis of data in several individuals. Nowadays, complex algorithms allow for dealing with this problem when the model is composed by few ordinary differential equations (ODEs). However, no similar parameter estimation method is available for models defined as PDEs. In consequence, we decided: 1. To develop more simple models, based on systems of ODEs, assuming simplistic hypothesis of tumor growth and response to treatment but with a real focus on model ability to predict real data. 2. To work alone the development of parameter estimation methods for PDE models in oncology.

3.4. Parametrization of complex systems

3.4.1. Project-team positioning

We focus on a specific problem: the "population" parametrization of a complex system. More precisely, instead of trying to look for parameters in order to fit the available data for one patient, in many cases it is more pertinent to look for the distribution of the parameters (assuming that it is gaussian or log gaussian) in a population of patients, and to maximize the likelihood of the observations of all patients. It is a very useful strategy when few data per patients are available, but when we have a lot of patients. The number of parameters to find is multiplied by two (average and standard deviation for each parameter) but the number of data is greatly increased.

This strategy, that we will call "population" parametrization has been initiated in the eighties by software like Nonmem. Recently Marc Lavielle (Popix team) made a series of breakthroughs and designed a new powerfull algorithm, leading to Monolix software.

However population parametrization is very costly. It requires several hundred of thousands of model evaluations, which may be very long.

3.4.2. Results

We address the problem of computation time when the complex model is long to evaluate. In simple cases like reaction diffusion equations in one space dimension, the evaluation of the model may take a few seconds of even a few minutes. In more realistic geometries, the computation time would be even larger and can reach the hour or day. It is therefore impossible to run a SAEM algorith on such models, since it would be much too long. Moreover the underlying algorithm can not be parallelized.

We propose a new iterative approach combining a SAEM algorithm together with a kriging. This strategy appears to be very efficient, since we were able to parametrize a PDE model as fast as a simple ODE model.

We are currently developing the corresponding software.

3.5. Models for the analysis of efficacy data in oncology

3.5.1. Project-team positioning

The development of new drugs for oncology patients faces significant issues with a global attrition rate of 95 percents and only 40 percents of drug approval in phase III after successful phase II. As for meteorology, the analysis through modeling and simulation (MS), of time-course data related to anticancer drugs efficacy and/or toxicity constitutes a rational method for predicting drugs efficacy in patients. This approach, now supported by regulatory agencies such as the FDA, is expected to improve the drug development process and in consequence the treatment of cancer patients. A private company, Pharsight, has nowadays the leader team in the development of such modeling frameworks. In 2009, this team published a model describing tumor size time-course in more than one thousand colorectal cancer patients. This model was used in an MS framework to predict the outcome of a phase III clinical trials based on the analysis of phase II data. From 2009 to 2013, 12 published articles address similar analysis of different therapeutic indications such as lung, prostate, thyroid and renal cancer. A similar modeling activity is also proposed for the analysis of data in preclinical experiments, and in particular, experiments in mice. Animal experiments represent critical stages to decide if a drug molecule should be tested in humans. MS methods are considered as tools to better investigate the mechanisms of drug action and to potentially facilitate the transition towards the clinical phases of the drug development process. Our team has worked in the development of two modeling frameworks with application in both preclinical and clinical oncology. For the preclinical context, we have worked on the development of models focusing on the process of tumor angiogenesis, i.e. the formation of intra-tumoral blood vessels. At the clinical level, we have developed a model to predict tumor size dynamics in patients with low-grade glioma.

At Inria, several project-teams have developed similar efforts. The project-team BANG has a solid experience in the development of age-structured models of the cell cycle and tissue regulation of tumors with clinical applications for chronotherapy. BANG is also currently applying these types of partial differential equation (PDE) models to the study of leukemia through collaboration with the project-team DRACULA. Project-team MC2 has recently shown that the analysis, through a simplified PDE model of tumor growth and treatment response, of 3D imaging, could lead to correct prediction of tumor volume evolution in patients with pulmonary metastasis from thyroid cancer. Regarding specifically the modeling of brain tumors, project-team ASCLEPIOS has brought an important contribution towards personalized medicine in analyzing 3D data information from MRI with a multiscale model that describes the evolution of high grade gliomas in the brain. Their framework relies on the cancer physiopathological model that was mainly developed by Kristin Swanson and her group at the university of Washington.

Outside from Inria, we wish to mention here the work of the group of Florence Hubert in Marseille in the development of models with an interesting compromise between mathematical complexity and data availability. A national ANR project led by the team is expected to support the development of an MS methodology for the analysis of tumor size data in patients with metastases.

3.5.2. Results

Regarding our contribution in preclinical modeling, we have developed a model to analyze the dynamics of tumor progression in nude mice xenografted with HT29 or HCT116 colorectal cancer cells. This model, based on a system of ordinary differential equations (ODEs), integrated the different types of tumor tissues, and in particular, the proliferating, hypoxic and necrotic tissues. Practically, in our experiment, tumor size was periodically measured, and percentages of hypoxic and necrotic tissue were assessed using immunohistochemistry techniques on tumor samples after euthanasia. In the proposed model, the peripheral non-hypoxic tissue proliferates according to a generalized-logistic equation where the maximal tumor size is represented by a variable called "carrying capacity". The ratio of the whole tumor size to the carrying capacity was used to define the hypoxic stress. As this stress increases, non-hypoxic tissue turns hypoxic. Hypoxic tissue does not stop proliferating, but hypoxia constitutes a transient stage before the tissue becomes necrotic. As the tumor grows, the carrying capacity increases owing to the process of angiogenesis (Ribba, Watkin et al. 2011). The model is shown to correctly predict tumor growth dynamics as well as percentages of necrotic and hypoxic tissues within the tumor.

Regarding our contribution in clinical oncology, we developed an ODE model based on the analysis of mean tumor diameter (MTD) time-course in low-grade glioma patients (Ribba, Kaloshi et al. 2012).

In this model, the tumor is composed of proliferative (P) and non-proliferative quiescent tissue (Q) expressed in millimeters. The proportion of proliferative tissue transitioning into quiescence is constant. The treatment directly eliminates proliferative cells by inducing lethal DNA damage while these cells progress through the cell cycle. The quiescent cells are also affected by the treatment and become damaged quiescent cells (k_{PQ}). Damaged quiescent cells, when re-entering the cell cycle, can repair their DNA and become proliferative once again (transition from Q_P to P) or can die due to unrepaired damages. We modeled the pharmacokinetics of the PCV chemotherapy using a kinetic-pharmacodynamic (K-PD) approach, in which drug concentration is assumed to decay according to an exponential function. In this model, we did not consider the three drugs separately. Rather, we assumed the treatment to be represented as a whole by a unique variable (C), which represents the concentration of a virtual drug encompassing the three chemotherapeutic components of the PCV regimen. We modeled the exact number of treatment cycles administered by setting the value of C to 1 (arbitrary unit) at the initiation of each cycle(T_{Treat}): $C(T = T_{Treat}) = 1$.

The resulting model is as follows:

$$
\begin{aligned}
\frac{dC}{dt} &= -KDE \times C \\
\frac{dP}{dt} &= \lambda_P P \left(1 - \frac{P^{\star}}{K}\right) + k_{Q_pP} Q_p - k_{PQ} P - \gamma \times C \times KDE \times P \\
\frac{dQ}{dt} &= k_{PQ} P - \gamma \times C \times KDE \times Q \\
\frac{dQ_p}{dt} &= \gamma \times C \times KDE \times Q - k_{Q_pP} Q_p - \delta_{Q_p} Q_p
\end{aligned}
\tag{9}
$$

We challenged this model with additional patient data. In particular, MTD time-course information from 24 patients treated with TMZ (subset of the 120 patients from SH) and 25 patients treated with radiotherapy (SH). Note that exactly the same K-PD approach was used to model treatment pharmacokinetic (including for radiotherapy). This choice, though not really realistic was adopted for simplicity reasons: the same model can be indifferently applied to the three different treatment modalities of LGG patients.

3.5.3. Collaborations

François Ducray and Jérôme Honnorat (Pierre Wertheimer Hospital in Lyon)

External support: grant INSERM PhysiCancer 2012 and Inria IPL MONICA

3.6. Stroke

3.6.1. Project team positioning

Stroke is a major public health problem since it represents the second leading cause of death worldwide and the first cause of acquired disability in adults.

Numed is currently starting completely new issues with D. Rousseau (INSA) and his team. We have now at hand a large data base of clinical images. Our aim is to develop model which are able to predict the final size of the dead brain area as a function of the first two clinical data.

4. Highlights of the Year

4.1. Highlights of the Year

In the context of a long standing collaboration with Sanofi group, E. Grenier develops a software for the study of the stability of vaccines. This software has been used in a formal presentation of a new vaccine to the FDA (Food and Drug Administration).

4.1.1. Awards

Vincent Calvez has been award the prize of the European Mathematical Society (2016).

5. New Software and Platforms

5.1. Bingham flows

FUNCTIONAL DESCRIPTION

A 1D and 2D code with a new method for the computation of viscoplatic flows with free-surface. It essentially couples Optimization methods and Well-Balanced Finite-Volumes schemes for viscous shallow-water equations (induced by the viscoplastic nature of the fluid). Currently applied to avalanches of dense snow, it is a private code currently actively developed (in C++). One of the key feature is that its well-balanced property allows to obtained the stationary states which are linked to the stopping of the snow avalanche for this highly non-linear type of fluid.

- Contact: Paul Vigneaux

5.2. OptimChemo

FUNCTIONAL DESCRIPTION

OptimChemo is a userfriendly software designed to study numerically the effect of multiple chemotherapies on simple models of tumour growth and to optimize chemotherapy schedules.

- Participants: Emmanuel Grenier, Violaine Louvet, Paul Vigneaux and Ehouarn Maguet
- Contact: Emmanuel Grenier

5.3. SETIS

KEYWORDS: Health - DICOM - Medical imaging - Drug development
FUNCTIONAL DESCRIPTION

SETIS software is a GUI allowing to treat DICOM medical images to extract pathological data. These data can then be exported and used in a SAEM software (including Monolix (Inria et Lixoft)) for the parameters' estimation of models in the context of population approaches. As an example SETIS can be used to segment and compute the tumor size of a patients from MRI scans taken at different times. The software is sufficiently general to be used in various situations by clinicians (already done by colleagues in Lyon Hospital).

- Participants: Paul Vigneaux and Ehouarn Maguet
- Partner: ENS Lyon
- Contact: Paul Vigneaux

5.4. VAXSIMSTAB

KEYWORDS: Bioinformatics - Health - Drug development
FUNCTIONAL DESCRIPTION

VAXSIMSTAB is a modeler stability prediction of vaccine software.

- Participants: Benjamin Ribba, Emmanuel Grenier and Vincent Calvez
- Contact: Emmanuel Grenier

6. Bilateral Contracts and Grants with Industry

6.1. Bilateral Contracts with Industry

- Long standing contract with Sanofi company, on the stability of vaccines. This contract leads to the design and coding of a complete software devoted to the study of the degradation of vaccines. This software has been used in presentations of new vaccines to the FDA.
- Modeling of the quality of glass for a small French company.

7. Partnerships and Cooperations

7.1. European Initiatives

Vincent Calvez is the main investigator of an ERC.

7.1.1. FP7 & H2020 Projects

7.1.1.1. DDMoRE

Programm: FP7

Duration: February 2011 - January 2016

Coordinator: Pfizer

Inria contact: Marc Lavielle

7.2. International Research Visitors

7.2.1. Visits of International Scientists

Toan Nguyen (Penn State University) has visited Numed in june 2016.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Expertise

Emmanuel Grenier has been expert for an INSERM cancer call.

8.1.2. Research Administration

Emmanuel Grenier is member of the board of the LABEX Archimede (Marseille).

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Paul Vigneaux, Vincent Calvez and Emmanuel Grenier teach in L3, M1 and M2 at ENSL, including lectures on partial differential equations, modeling, analysis.

8.2.2. Supervision

Edouard Ollier and Mathilde Giacalone is supervised by Emmanuel Grenier, Arthur Marly by Paul Vigneaux and Alvaro Mateos Gonzalez by Vincent Calvez.

9. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journal

[1] H. BERRY, T. LEPOUTRE, Á. MATEOS GONZÁLEZ.*Quantitative convergence towards a self similar profile in an age-structured renewal equation for subdiffusion*, in "Acta Applicandae Mathematicae", 2016, n^{o} 145, p. 15-45, in press, https://hal.inria.fr/hal-01136667.

[2] S. EUGENE, T. BOURGERON, Z. XU.*Effects of initial telomere length distribution on senescence onset and heterogeneity*, in "Journal of Theoretical Biology", January 2017, vol. 413, 8, https://hal.inria.fr/hal-01378596.

[3] E. GRENIER, C. HELBERT, V. LOUVET, A. SAMSON, P. VIGNEAUX.*Population parametrization of costly black box models using iterations between SAEM algorithm and kriging*, in "Computational and Applied Mathematics", April 2016, Accepted March, 24, 2016 [*DOI :* 10.1007/S40314-016-0337-5], https://hal.archives-ouvertes.fr/hal-01224004.

[4] M. S. LEGUÈBE, M. G. NOTARANGELO, M. TWAROGOWSKA, R. NATALINI, C. POIGNARD.*Mathematical model for transport of DNA plasmids from the external medium up to the nucleus by electroporation*, in "Mathematical Biosciences", November 2016 [*DOI :* 10.1016/J.MBS.2016.11.015], https://hal.inria.fr/hal-01412380.

Invited Conferences

[5] P. VIGNEAUX.*Numerical schemes for viscoplastic avalanches. A shallow - Bingham flow model*, in "SIMAI 2016", Milano, Italy, SIMAI, Politecnico di Milano, September 2016, https://hal.archives-ouvertes.fr/hal-01376649.

[6] P. VIGNEAUX.*SAEM methods for statistical PDE parameters estimation and application to biology*, in "CIMPA School "Mathematical models in biology and medicine"", Moka, Mauritius, December 2016, https://hal.archives-ouvertes.fr/hal-01419082.

Other Publications

[7] E. BOUIN, V. CALVEZ, E. GRENIER, G. NADIN.*Large deviations for velocity-jump processes and non-local Hamilton-Jacobi equations*, July 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01344939.

[8] E. BOUIN, C. HENDERSON.*Super-linear spreading in local bistable cane toads equations*, March 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01293988.

[9] V. CALVEZ.*Chemotactic waves of bacteria at the mesoscale*, July 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01340375.

[10] V. CALVEZ, P. GABRIEL, Á. MATEOS GONZÁLEZ.*Limiting Hamilton-Jacobi equation for the large scale asymptotics of a subdiffusion jump-renewal equation*, September 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01372949.

[11] V. CALVEZ, T. O. GALLOUËT.*Blow-up phenomena for gradient flows of discrete homogeneous functionals*, 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01286518.

[12] E. GRENIER, F. HAMEL.*Large time monotonicity of solutions of reaction-diffusion equations in R^N*, June 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01324533.

[13] H. HIVERT.*Numerical schemes for kinetic equation with diffusion limit and anomalous time scale*, October 2016, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01389100.

Project-Team PERCEPTION

Interpretation and Modeling of Images and Sounds

IN COLLABORATION WITH: Laboratoire Jean Kuntzmann (LJK)

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Vision, perception and multimedia interpretation

Table of contents

Project-Team PERCEPTION

Creation of the Team: 2006 September 01, updated into Project-Team: 2008 January 01

Keywords:

Computer Science and Digital Science:

3.4. - Machine learning and statistics
5.1. - Human-Computer Interaction
5.3. - Image processing and analysis
5.4. - Computer vision
5.7. - Audio modeling and processing
5.10.2. - Perception
5.10.5. - Robot interaction (with the environment, humans, other robots)
8.2. - Machine learning
8.5. - Robotics

Other Research Topics and Application Domains:

5.6. - Robotic systems

1. Members

Research Scientists

Radu Horaud [Team leader, Inria, Senior Researcher, HDR]
Xavier Alameda-Pineda [Inria, Researcher, from Dec 2016]
Georgios Evangelidis [Inria, Starting Research Position, until Jun 2016, granted by ERC VHIA]
Sileye Ba [Inria, Starting Research Position, until Jun 2016, granted by ERC VHIA]
Xiaofei Li [Inria, Starting Research Position, granted by ERC VHIA]
Pablo Mesejo Santiago [Inria, Starting Research Position, from Sep 2016, granted by ERC VHIA]

Faculty Member

Laurent Girin [Grenoble INP, Professor, HDR]

Technical Staff

Bastien Mourgue [Inria, from Dec 2016, granted by ERC VHIA]
Quentin Pelorson [Inria, until May 2016, granted by FP7 EARS]
Guillaume Sarrazin [Inria, from Jun 2016, granted by ERC VHIA]
Fabien Badeig [Inria, until Oct 2016, granted by ERC VHIA]

PhD Students

Yutong Ban [Inria, granted by ERC VHIA]
Israel Dejene Gebru [Inria, granted by Inria]
Vincent Drouard [Inria, granted by ERC VHIA]
Dionyssos Kounades [Inria, granted by FP7 EARS]
Stephane Lathuiliere [Inria, granted by ERC VHIA]
Benoit Masse [Inria, granted by ERC VHIA]

Visiting Scientists

Yuval Dorfan [Inria, from Jun 2016 until Jul 2016]
Sharon Gannot [Inria, until Oct 2016]
Rafael Munoz Salinas [Inria, from Jun 2016 until Aug 2016]

Administrative Assistant

Nathalie Gillot [Inria]

Others

Remi Juge [Inria, Intern, from Jul 2016]
Richard Thomas Marriott [Inria, Intern, from Feb until Sep 2016]
Alexander Pashevich [Inria, Intern, from Feb 2016 until Jun 2016]

2. Overall Objectives

2.1. Overall Objectives

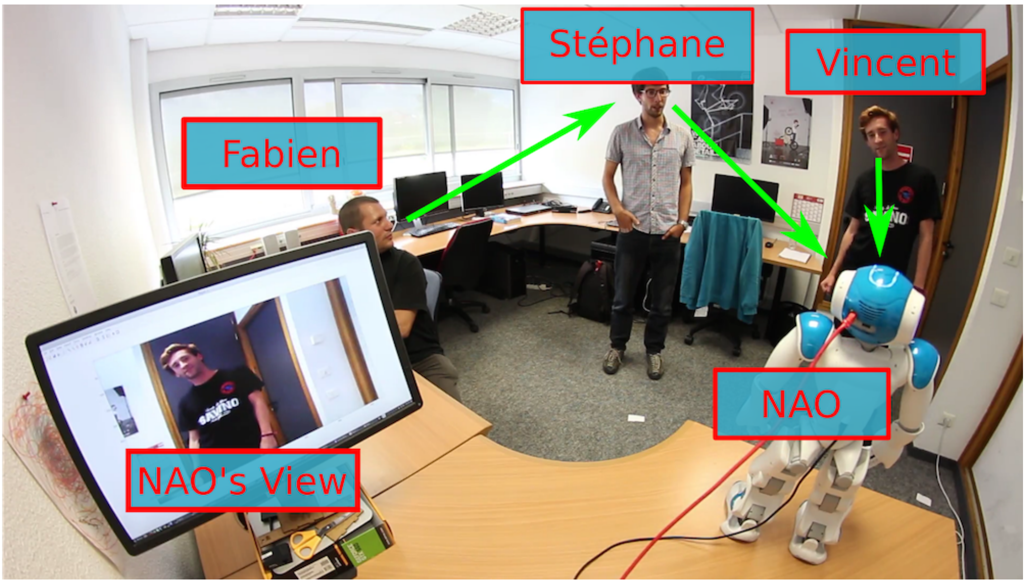

Figure 1. This figure illustrates the audio-visual multi-party human-robot interaction paradigm that the PERCEPTION team has developed in the recent past [18], [2], [25]. There are inter-person as well as person-robot interactions that must be properly detected and analyzed over time. This includes multiple-person tracking [24], person detection and head-pose estimation [42], sound-source separation and localization [5], [1], [28], [29], [44], and speaker diarization [26]. These developments are supported by the European Union via the FP7 STREP project "Embodied Audition for Robots" (EARS) and the ERC advanced grant "Vision and Hearing in Action" (VHIA).

Auditory and visual perception play a complementary role in human interaction. Perception enables people to communicate based on verbal (speech and language) and non-verbal (facial expressions, visual gaze, head movements, hand and body gesturing) communication. These communication modalities have a large degree of overlap, in particular in social contexts. Moreover, the modalities disambiguate each other whenever one of the modalities is weak, ambiguous, or corrupted by various perturbations. Human-computer interaction (HCI) has attempted to address these issues, e.g., using smart & portable devices. In HCI the user is in the loop for decision taking: images and sounds are recorded purposively in order to optimize their quality with respect to the task at hand.

However, the robustness of HCI based on speech recognition degrades significantly as the microphones are located a few meters away from the user. Similarly, face detection and recognition work well under limited lighting conditions and if the cameras are properly oriented towards a person. Altogether, the HCI paradigm cannot be easily extended to less constrained interaction scenarios which involve several users and whenever is important to consider the *social context*.

The PERCEPTION team investigates the fundamental role played by audio and visual perception in human-robot interaction (HRI). The main difference between HCI and HRI is that, while the former is user-controlled, the latter is robot-controlled, namely *it is implemented with intelligent robots that take decisions and act autonomously*. The mid term objective of PERCEPTION is to develop computational models, methods, and applications for enabling non-verbal and verbal interactions between people, analyze their intentions and their dialogue, extract information and synthesize appropriate behaviors, e.g., the robot waves to a person, turns its head towards the dominant speaker, nods, gesticulates, asks questions, gives advices, waits for instructions, etc. The following topics are thoroughly addressed by the team members: audio-visual sound-source separation and localization in natural environments, for example to detect and track moving speakers, inference of temporal models of verbal and non-verbal activities (diarisation), continuous recognition of particular gestures and words, context recognition, and multimodal dialogue.

3. Research Program

3.1. Audio-Visual Scene Analysis

From 2006 to 2009, R. Horaud was the scientific coordinator of the collaborative European project POP (Perception on Purpose), an interdisciplinary effort to understand visual and auditory perception at the crossroads of several disciplines (computational and biological vision, computational auditory analysis, robotics, and psychophysics). This allowed the PERCEPTION team to launch an interdisciplinary research agenda that has been very active for the last five years. There are very few teams in the world that gather scientific competences spanning computer vision, audio signal processing, machine learning and human-robot interaction. The fusion of several sensorial modalities resides at the heart of the most recent biological theories of perception. Nevertheless, multi-sensor processing is still poorly understood from a computational point of view. In particular and so far, audio-visual fusion has been investigated in the framework of speech processing using close-distance cameras and microphones. The vast majority of these approaches attempt to model the temporal correlation between the auditory signals and the dynamics of lip and facial movements. Our original contribution has been to consider that audio-visual localization and recognition are equally important. We have proposed to take into account the fact that the audio-visual objects of interest live in a three-dimensional physical space and hence we contributed to the emergence of *audio-visual scene analysis* as a scientific topic in its own right. We proposed several novel statistical approaches based on supervised and unsupervised mixture models. The *conjugate mixture model* (CMM) is an unsupervised probabilistic model that allows to cluster observations from different modalities (e.g., vision and audio) living in different mathematical spaces [18], [2]. We thoroughly investigated CMM, provided practical resolution algorithms and studied their convergence properties. We developed several methods for sound localization using two or more microphones [1]. The *Gaussian locally-linear model* (GLLiM) is a partially supervised mixture model that allows to map high-dimensional observations (audio, visual, or concatenations of audio-visual vectors) onto low-dimensional manifolds with a partially known structure [6]. This model is particularly well suited for perception because it encodes both observable and unobservable phenomena. A variant of this model, namely *probabilistic piecewise affine mapping* has also been proposed and successfully applied to the problem of sound-source localization and separation [5]. The European projects HUMAVIPS (2010-2013) coordinated by R. Horaud and EARS (2014-2017), applied audio-visual scene analysis to human-robot interaction.

3.2. Stereoscopic Vision

Stereoscopy is one of the most studied topics in biological and computer vision. Nevertheless, classical approaches of addressing this problem fail to integrate eye/camera vergence. From a geometric point of view, the integration of vergence is difficult because one has to re-estimate the epipolar geometry at every new eye/camera rotation. From an algorithmic point of view, it is not clear how to combine depth maps obtained with different eyes/cameras relative orientations. Therefore, we addressed the more general problem of binocular vision that combines the low-level eye/camera geometry, sensor rotations, and practical algorithms based on global optimization [12], [20]. We studied the link between mathematical and computational approaches to stereo (global optimization and Markov random fields) and the brain plausibility of some of these approaches: indeed, we proposed an original mathematical model for the complex cells in visual-cortex areas V1 and V2 that is based on steering Gaussian filters and that admits simple solutions [13]. This addresses the fundamental issue of how local image structure is represented in the brain/computer and how this structure is used for estimating a dense disparity field. Therefore, the main originality of our work is to address both computational and biological issues within a unifying model of binocular vision. Another equally important problem that still remains to be solved is how to integrate binocular depth maps over time. Recently, we have addressed this problem and proposed a semi-global optimization framework that starts with sparse yet reliable matches and proceeds with propagating them over both space and time. The concept of seed-match propagation has then been extended to TOF-stereo fusion [8].

3.3. Audio Signal Processing

Audio-visual fusion algorithms necessitate that the two modalities are represented in the same mathematical space. Binaural audition allows to extract sound-source localization (SSL) information from the acoustic signals recorded with two microphones. We have developed several methods, that perform sound localization in the temporal and the spectral domains. If a direct path is assumed, one can exploit the *time difference of arrival* (TDOA) between two microphones to recover the position of the sound source with respect to the position of the two microphones. The solution is not unique in this case, the sound source lies onto a 2D manifold. However, if one further assumes that the sound source lies in a horizontal plane, it is then possible to extract the azimuth. We used this approach to predict possible sound locations in order to estimate the direction of a speaker [2]. We also developed a geometric formulation and we showed that with four non-coplanar microphones the azimuth and elevation of a single source can be estimated without ambiguity [1]. We also investigated SSL in the spectral domain. This exploits the filtering effects of the head related transfer function (HRTF): there is a different HRTF for the left and right microphones. The interaural spectral features, namely the ILD (interaural level difference) and IPD (interaural phase difference) can be extracted from the short-time Fourier transforms of the two signals. The sound direction is encoded in these interaural features but it is not clear how to make SSL explicit in this case. We proposed a supervised learning formulation that estimates a mapping from interaural spectral features (ILD and IPD) to source directions using two different setups: audio-motor learning [5] and audio-visual learning [7].

3.4. Visual Reconstruction With Multiple Color and Depth Cameras

For the last decade, one of the most active topics in computer vision has been the visual reconstruction of objects, people, and complex scenes using a multiple-camera setup. The PERCEPTION team has pioneered this field and by 2006 several team members published seminal papers in the field. Recent work has concentrated onto the robustness of the 3D reconstructed data using probabilistic outlier rejection techniques combined with algebraic geometry principles and linear algebra solvers [23]. Subsequently, we proposed to combine 3D representations of shape (meshes) with photometric data [21]. The originality of this work was to represent photometric information as a scalar function over a discrete Riemannian manifold, thus *generalizing image analysis to mesh and graph analysis*. Manifold equivalents of local-structure detectors and descriptors were developed [22]. The outcome of this pioneering work has been twofold: the formulation of a new research topic now addressed by several teams in the world, and allowed us to start a three year collaboration with Samsung Electronics. We developed the novel concept of *mixed camera systems* combining high-resolution color cameras with low-resolution depth cameras [14], [10],[9]. Together with our start-up company 4D Views Solutions and with Samsung, we developed the first practical depth-color multiple-camera multiple-PC system and the first algorithms to reconstruct high-quality 3D content [8].

3.5. Registration, Tracking and Recognition of People and Actions

The analysis of articulated shapes has challenged standard computer vision algorithms for a long time. There are two difficulties associated with this problem, namely how to represent articulated shapes and how to devise robust registration and tracking methods. We addressed both these difficulties and we proposed a novel kinematic representation that integrates concepts from robotics and from the geometry of vision. In 2008 we proposed a method that parameterizes the occluding contours of a shape with its intrinsic kinematic parameters, such that there is a direct mapping between observed image features and joint parameters [19]. This deterministic model has been motivated by the use of 3D data gathered with multiple cameras. However, this method was not robust to various data flaws and could not achieve state-of-the-art results on standard dataset. Subsequently, we addressed the problem using probabilistic generative models. We formulated the problem of articulated-pose estimation as a maximum-likelihood with missing data and we devised several tractable algorithms [17], [16]. We proposed several expectation-maximization procedures applied to various articulated shapes: human bodies, hands, etc. In parallel, we proposed to segment and register articulated shapes represented with graphs by embedding these graphs using the spectral properties of graph Laplacians [4]. This turned out to be a very original approach that has been followed by many other researchers in computer vision and computer graphics.

4. Highlights of the Year

4.1. Highlights of the Year

- **The three-year FP7 STREP project *Embodied Audition for Robots* successfully terminated in December 2016**. The project has addressed the problem of robot hearing, more precisely, the analysis of audio signals in complex environments: reverberant rooms, multiple users, and background noise. In collaboration with the project partners, PERCEPTION contributed to audio-source localization, audio-source separation, audio-visual alignment, and audio-visual disambiguation. The humanoid robot NAO has been used as a robotic platform and a new head (hardware and software) was developed: a stereoscopic camera pair, a spherical microphone array, and the associated synchronization, signal and image processing software modules.
- This year, PERCEPTION started a one year collaboration with the **Digital Media and Communications R&D Center, Samsung Electronics** (Seoul, Korea). The topic of this collaboration is *multi-modal speaker localization and tracking* (a central topic of the team) and is part of a strategic partnership between Inria and Samsung Electronics.

4.1.1. Awards

- **Antoine Deleforge** (former PhD student, PANAMA team), **Florence Forbes** (MISTIS team) and **Radu Horaud** received the **2016 Award for Outstanding Contributions in Neural Systems** for their paper: “Acoustic Space Learning for Sound-source Separation and Localization on Binaural Manifolds," International Journal of Neural Systems, volume 25, number 1, 2015. The Award for Outstanding Contributions in Neural Systems established by World Scientific Publishing Co. in 2010, is awarded annually to the most innovative paper published in the previous volume/year of the International Journal of Neural Systems.
- **Xavier Alameda-Pineda** and his co-authors from the University of Trento received the **Intel Best Scientific Paper Award** (Track: Image, Speech, Signal and Video Processing) for their paper “Multi-Paced Dictionary Learning for Cross-Domain Retrieval and Recognition" presented at the 23rd IEEE International Conference on Pattern Recognition, Cancun, Mexico, December 2016 .

BEST PAPERS AWARDS :

[41] **IEEE International Conference on Pattern Recognition**. D. XU, J. SONG, X. ALAMEDA-PINEDA, E. RICCI, N. SEBE.

5. New Software and Platforms

5.1. ECMPR

Expectation Conditional Maximization for the Joint Registration of Multiple Point Sets
FUNCTIONAL DESCRIPTION

Rigid registration of two or several point sets based on probabilistic matching between point pairs and a Gaussian mixture model

- Participants: Florence Forbes, Radu Horaud and Manuel Yguel
- Contact: Patrice Horaud
- URL: https://team.inria.fr/perception/research/jrmpc/

5.2. Mixcam

Reconstruction using a mixed camera system
KEYWORDS: Computer vision - 3D reconstruction
FUNCTIONAL DESCRIPTION

We developed a multiple camera platform composed of both high-definition color cameras and low-resolution depth cameras. This platform combines the advantages of the two camera types. On one side, depth (time-of-flight) cameras provide coarse low-resolution 3D scene information. On the other side, depth and color cameras can be combined such as to provide high-resolution 3D scene reconstruction and high-quality rendering of textured surfaces. The software package developed during the period 2011-2014 contains the calibration of TOF cameras, alignment between TOF and color cameras, TOF-stereo fusion, and image-based rendering. These software developments were performed in collaboration with the Samsung Advanced Institute of Technology, Seoul, Korea. The multi-camera platform and the basic software modules are products of 4D Views Solutions SAS, a start-up company issued from the PERCEPTION group.

- Participants: Patrice Horaud, Pierre Arquier, Quentin Pelorson, Michel Amat, Miles Hansard, Georgios Evangelidis, Soraya Arias, Radu Horaud, Richard Broadbridge and Clement Menier
- Contact: Patrice Horaud
- URL: https://team.inria.fr/perception/mixcam-project/

5.3. NaoLab

Distributed middleware architecture for interacting with NAO
FUNCTIONAL DESCRIPTION

This software provides a set of librairies and tools to simply the control of NAO robot from a remote machine. The main challenge is to make easy prototuping applications for NAO ising C++ and Matlab programming environments. Thus NaoLab provides a prototyping-friendly interface to retrieve sensor date (video and sound streams, odometric data...) and to control the robot actuators (head, arms, legs...) from a remote machine.This interface is available on Naoqi SDK, developed by Aldebarab company, Naoqi SDK is needed as it provides the tools to acess the embedded NAO services (low-level motor command, sensor data access...)

- Authors: Quentin Pelorson, Fabien Badeig and Patrice Horaud
- Contact: Patrice Horaud
- URL: https://team.inria.fr/perception/research/naolab/

5.4. Stereo matching and recognition library

KEYWORD: Computer vision
FUNCTIONAL DESCRIPTION

Library providing stereo matching components to rectify stereo images, to retrieve faces from left and right images, to track faces and method to recognise simple gestures

- Participants: Jordi Sanchez-Riera, Soraya Arias, Jan Cech and Radu Horaud
- Contact: Soraya Arias
- URL: https://code.humavips.eu/projects/stereomatch

5.5. Platforms

5.5.1. Audio-Visual Head Popeye+

In 2016 we upgraded our audio-visual platform, from Popeye to Popeye+. Popeye+ has two high-definitions cameras with a wide field of view. We also upgraded the software libraries that perform synchronized acquisition of audio signals and color images. Popeye+ has been used for several datasets.
Website:
https://team.inria.fr/perception/projects/popeye/
https://team.inria.fr/perception/projects/popeye-plus/
https://team.inria.fr/perception/avtrack1/.

5.5.2. NAO Robots

The PERCEPTION team selected the companion robot NAO for experimenting and demonstrating various audio-visual skills as well as for developing the concept of a social robot that is able to recognize human presence, to understand human gestures and voice, and to communicate by synthesizing appropriate behavior. The main challenge of our team is to enable human-robot interaction in the real world.

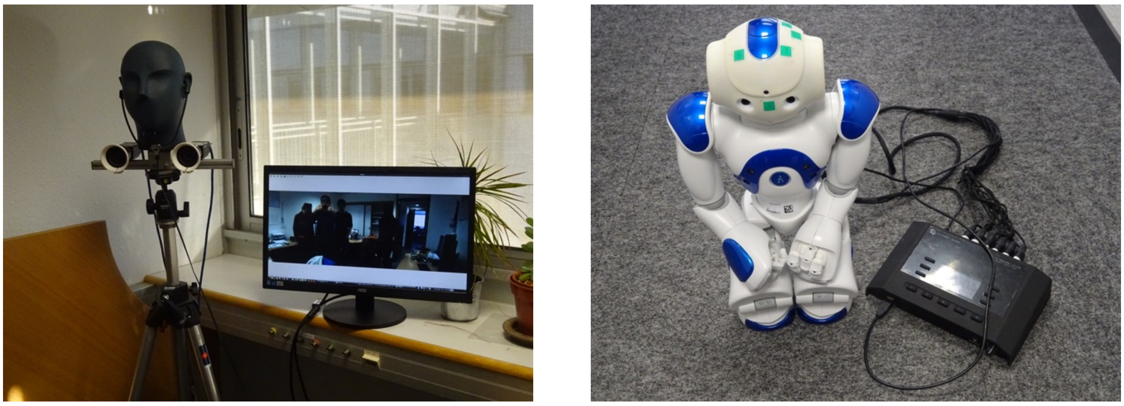

Figure 2. The Popeye+ audio-visual platform (left) delivers high-quality, high-resolution and wide-angle images at 30FPS. The NAO prototype used by PERCEPTION in the EARS STREP project has a twelve-channel spherical microphone array synchronized with a stereo camera pair.

The humanoid robot NAO is manufactured by Aldebaran Robotics, now SoftBank. Standing, the robot is roughly 60 cm tall, and 35cm when it is sitting. Approximately 30 cm large, NAO includes two CPUs. The first one, placed in the torso, together with the batteries, controls the motors and hence provides kinematic motions with 26 degrees of freedom. The other CPU is placed in the head and is in charge of managing the proprioceptive sensing, the communications, and the audio-visual sensors (two cameras and four microphones, in our case). NAO's on-board computing resources can be accessed either via wired or wireless communication protocols.

NAO's commercially available head is equipped with two cameras that are arranged along a vertical axis: these cameras are neither synchronized nor a significant common field of view. Hence, they cannot be used in combination with stereo vision. Within the EU project HUMAVIPS, Aldebaran Robotics developed a binocular camera system that is arranged horizontally. It is therefore possible to implement stereo vision algorithms on NAO. In particular, one can take advantage of both the robot's cameras and microphones. The cameras deliver VGA sequences of image pairs at 12 FPS, while the sound card delivers the audio signals arriving from all four microphones and sampled at 48 kHz. Subsequently, Aldebaran developed a second binocular camera system to go into the head of NAO v5.

In order to manage the information flow gathered by all these sensors, we implemented our software on top of the Robotics Services Bus (RSB). RSB is a platform-independent event-driven middleware specifically designed for the needs of distributed robotic applications. Several RSB tools are available, including real-time software execution, as well as tools to record the event/data flow and to replay it later, so that application development can be done off-line. RSB events are automatically equipped with several time stamps for introspection and synchronization purposes. RSB was chosen because it allows our software to be run on a remote PC platform, neither with performance nor deployment restrictions imposed by the robot's CPUs. Moreover, the software packages can be easily reused for other robots.

More recently (2015-2016) the PERCEPTION team started the development of NAOLab, a middleware for hosting robotic applications in C, C++, Python and Matlab, using the computing power available with NAO, augmented with a networked PC.

Websites:
https://team.inria.fr/perception/nao/
https://team.inria.fr/perception/research/naolab/

6. New Results

6.1. Audio-Source Localization

In previous years we have developed several *supervised* sound-source localization algorithms. The general principle of these algorithms was based on the learning of a mapping (regression) between binaural feature vectors and source locations [5], [7]. While fixed-length wide-spectrum sounds (white noise) are used for training to reliably estimate the model parameters, we show that the testing (localization) can be extended to variable-length sparse-spectrum sounds (such as speech), thus enabling a wide range of realistic applications. Indeed, we demonstrate that the method can be used for audio-visual fusion, namely to map speech signals onto images and hence to spatially align the audio and visual modalities, thus enabling to discriminate between speaking and non-speaking faces. We released a novel corpus of real-room recordings that allow quantitative evaluation of the co-localization method in the presence of one or two sound sources. Experiments demonstrate increased accuracy and speed relative to several state-of-the-art methods. During the period 2015-2016 we extended this method to an arbitrary number of microphones based on the *relative transfer function – RTF* (between any channel and a reference channel). Then we extended this work and developed a novel transfer function that contains the direct path between the source and the microphone array, namely the *direct-path relative transfer function* [29], [36].

Websites:

https://team.inria.fr/perception/research/acoustic-learning/
https://team.inria.fr/perception/research/binaural-ssl/
https://team.inria.fr/perception/research/ssl-rtf/

6.2. Audio-Source Separation

We address the problem of separating audio sources from time-varying convolutive mixtures. We proposed an unsupervised probabilistic framework based on the local complex-Gaussian model combined with non-negative matrix factorization [33], [28]. The time-varying mixing filters are modeled by a continuous temporal stochastic process. This model extends the case of static filters which corresponds to static audio sources. While static filters can be learnt in advance, e.g. [5], time-varying filters cannot and therefore the problem is more complex. We present a variational expectation-maximization (VEM) algorithm that employs a Kalman smoother to estimate the time-varying mixing matrix, and that jointly estimates the source parameters. The sound sources are then separated by Wiener filters constructed with the estimators provided by the VEM algorithm. Extensive experiments on simulated data show that the proposed method outperforms a block-wise version of a state-of-the-art baseline method. This work is part of the PhD topic of Dionyssos Kounades Bastian and is conducted in collaboration with Sharon Gannot (Bar Ilan University) and Xavier Alameda Pineda (University of Trento). Our journal paper [28] is an extended version of a paper presented at IEEE WASPAA in 2015 which received the best student paper award.

Website:
https://team.inria.fr/perception/research/vemove/
https://team.inria.fr/perception/research/nmfig/

6.3. Single-Channel Audio Processing

While most of our audio scene analysis work involves microphone arrays, it is important to develop single-channel (one microphone) signal processing methods as well. In particular, it is important to detect speech signal (or voice) in the presence of various types of noise (stationary or non-stationary). In this context, we developed the following methods [39], [37]:

- Statistical likelihood ratio test is a widely used voice activity detection (VAD) method, in which the likelihood ratio of the current temporal frame is compared with a threshold. A fixed threshold is always used, but this is not suitable for various types of noise. In this work, an adaptive threshold is proposed as a function of the local statistics of the likelihood ratio. This threshold represents the upper bound of the likelihood ratio for the non-speech frames, whereas it remains generally lower than the likelihood ratio for the speech frames. As a result, a high non-speech hit rate can be achieved, while maintaining speech hit rate as large as possible.
- Estimating the noise power spectral density (PSD) is essential for single channel speech enhancement algorithms. We propose a noise PSD estimation approach based on regional statistics which consist of four features representing the statistics of the past and present periodograms in a short-time period. We show that these features are efficient in characterizing the statistical difference between noise PSD and noisy-speech PSD. We therefore propose to use these features for estimating the speech presence probability (SPP). The noise PSD is recursively estimated by averaging past spectral power values with a time-varying smoothing parameter controlled by the SPP. The proposed method exhibits good tracking capability for non-stationary noise, even for abruptly increasing noise level.

Website:
https://team.inria.fr/perception/research/noise-psd/

6.4. Tracking Multiple Persons

Object tracking is an ubiquitous problem in computer vision with many applications in human-machine and human-robot interaction, augmented reality, driving assistance, surveillance, etc. Although thoroughly investigated, tracking multiple persons remains a challenging and an open problem. In this work, an online variational Bayesian model for multiple-person tracking is proposed. This yields a variational expectation-maximization (VEM) algorithm. The computational efficiency of the proposed method is made possible thanks to closed-form expressions for both the posterior distributions of the latent variables and for the estimation of the model parameters. A stochastic process that handles person birth and person death enables the tracker to handle a varying number of persons over long periods of time [24], [30].

Website:
https://team.inria.fr/perception/research/ovbt/

6.5. Audio-Visual Speaker Detection, Localization, and Diarization

Any multi-party conversation system benefits from speaker diarization, that is, the assignment of speech signals among the participants. More generally, in HRI and CHI scenarios it is important to recognize the speaker over time. We propose to address speaker detection, localization and diarization using both audio and visual data. We cast the diarization problem into a tracking formulation whereby the active speaker is detected and tracked over time. A probabilistic tracker exploits the spatial coincidence of visual and auditory observations and infers a single latent variable which represents the identity of the active speaker. Visual and auditory observations are fused using our recently developed weighted-data mixture model [25], while several options for the speaking turns dynamics are fulfilled by a multi-case transition model. The modules that translate raw audio and visual data into image observations are also described in detail. The performance of the proposed method are tested on challenging data-sets that are available from recent contributions which are used as baselines for comparison [26].

Websites:
https://team.inria.fr/perception/research/wdgmm/
https://team.inria.fr/perception/research/speakerloc/
https://team.inria.fr/perception/research/speechturndet/
https://team.inria.fr/perception/research/avdiarization/

6.6. Head Pose Estimation and Tracking

Head pose estimation is an important task, because it provides information about cognitive interactions that are likely to occur. Estimating the head pose is intimately linked to face detection. We addressed the problem of head pose estimation with three degrees of freedom (pitch, yaw, roll) from a single image and in the presence of face detection errors. Pose estimation is formulated as a high-dimensional to low-dimensional mixture of linear regression problem [6]. We propose a method that maps HOG-based descriptors, extracted from face bounding boxes, to corresponding head poses. To account for errors in the observed bounding-box position, we learn regression parameters such that a HOG descriptor is mapped onto the union of a head pose and an offset, such that the latter optimally shifts the bounding box towards the actual position of the face in the image. The performance of the proposed method is assessed on publicly available datasets. The experiments that we carried out show that a relatively small number of locally-linear regression functions is sufficient to deal with the non-linear mapping problem at hand. Comparisons with state-of-the-art methods show that our method outperforms several other techniques [42]. This work is part of the PhD of Vincent Drouard and it received the best student paper award (second place) at the IEEE ICIP'15. Currently we investigate a temporal extension of this model.

Website:
https://team.inria.fr/perception/research/head-pose/

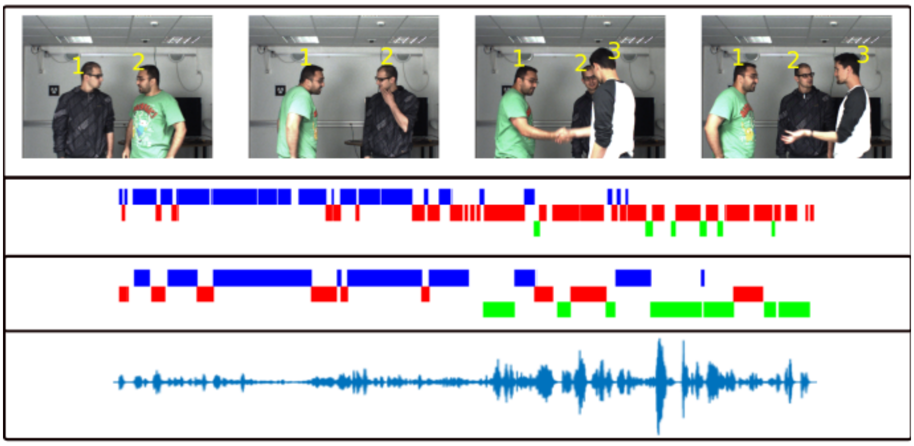

Figure 3. This figure illustrates the audiovisual tracking and diarization method that we have recently developed. First row: A number is associated with each tracked person. Second row: diarization result. Third row: the ground truth diarization. Fourth row: acoustic signal recorded by one of the two microphones.

6.7. Estimation of Eye Gaze and of Visual Focus of Attention

We address the problem of estimating the visual focus of attention (VFOA), e.g. who is looking at whom? This is of particular interest in human-robot interactive scenarios, e.g. when the task requires to identify targets of interest and to track them over time. We make the following contributions. We propose a Bayesian temporal model that links VFOA to eye-gaze direction and to head orientation. Model inference is cast into a switching Kalman filter formulation, which makes it tractable. The model parameters are estimated via training based on manual annotations. The method is tested and benchmarked using a publicly available dataset. We show that both eye-gaze and VFOA of several persons can be reliably and simultaneously estimated and tracked over time from observed head poses as well as from people and object locations [40].

Website:
https://team.inria.fr/perception/research/eye-gaze/.

6.8. High-Resolution Scene Reconstruction

We addressed the problem of range-stereo fusion for the construction of high-resolution depth maps. In particular, we combine time-of-flight (low resolution) depth [27] data with high-resolution stereo data, in a maximum a posteriori (MAP) formulation. Unlike existing schemes that build on MRF optimizers, we infer the disparity map from a series of local energy minimization problems that are solved hierarchically, by growing sparse initial disparities obtained from the depth data. The accuracy of the method is not compromised, owing to three properties of the data-term in the energy function. Firstly, it incorporates a new correlation function that is capable of providing refined correlations and disparities, via sub-pixel correction. Secondly, the correlation scores rely on an adaptive cost aggregation step, based on the depth data. Thirdly, the stereo and depth likelihoods are adaptively fused, based on the scene texture and camera geometry. These properties lead to a more selective growing process which, unlike previous seed-growing methods, avoids the tendency to propagate incorrect disparities. The proposed method gives rise to an intrinsically efficient algorithm, which runs at 3FPS on 2.0MP images on a standard desktop computer. The strong performance of the new method is established both by quantitative comparisons with state-of-the-art methods, and by qualitative comparisons using real depth-stereo data-sets [8]. This work is funded by the ANR project MIXCAM.

Website:
https://team.inria.fr/perception/research/dsfusion/

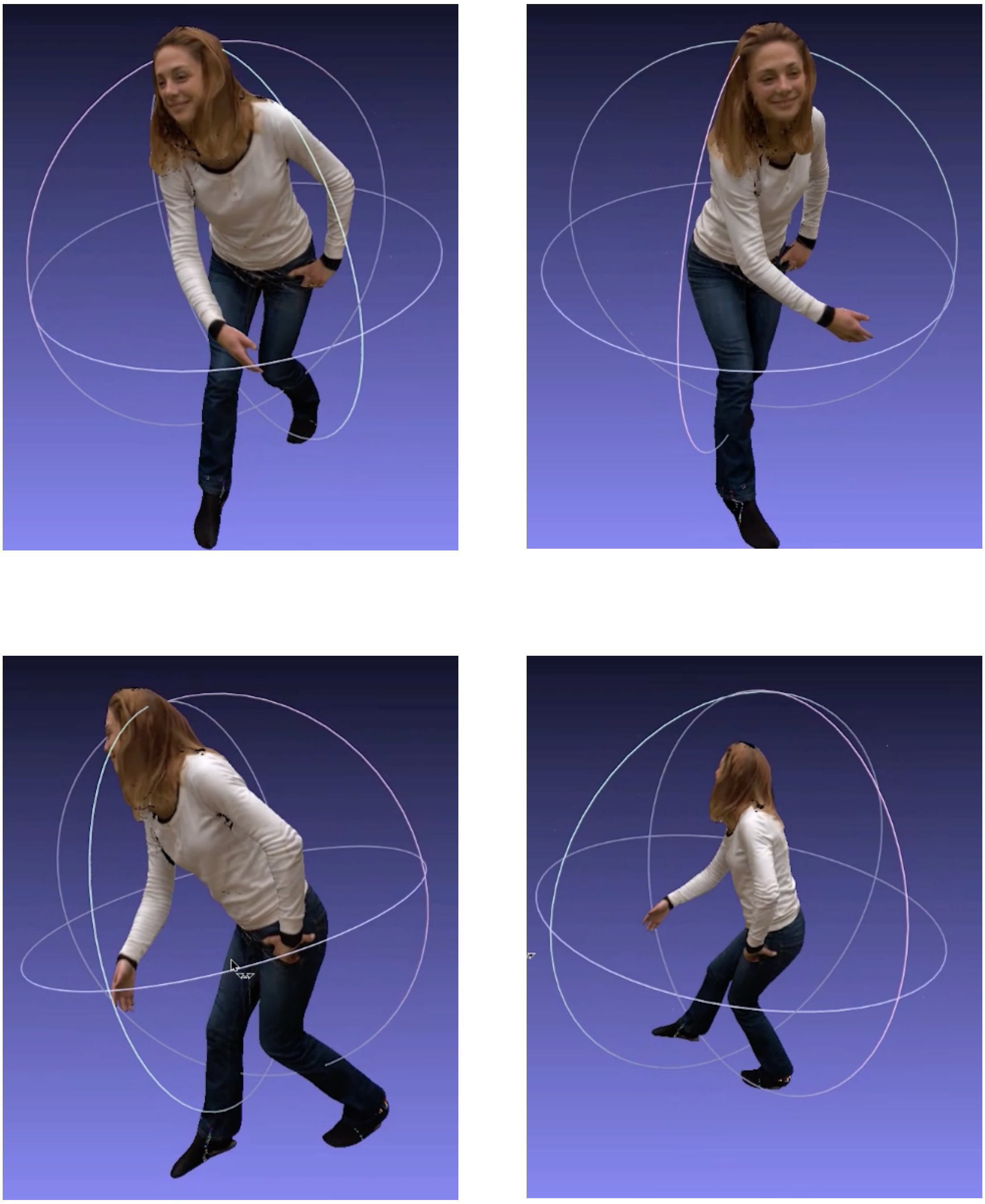

Figure 4. Four views of a 3D person reconstructed with our algorithm. In this example we used a large number of high-resolution cameras and the rendering was performed by the software of 4D View Solutions.

6.9. Registration of Multiple Point Sets

We have also addressed the rigid registration problem of multiple 3D point sets. While the vast majority of state-of-the-art techniques build on pairwise registration, we proposed a generative model that explains jointly registered multiple sets: back-transformed points are considered realizations of a single Gaussian mixture model (GMM) whose means play the role of the (unknown) scene points. Under this assumption, the joint registration problem is cast into a probabilistic clustering framework. We formally derive an expectation-maximization procedure that robustly estimates both the GMM parameters and the rigid transformations that map each individual cloud onto an under-construction reference set, that is, the GMM means. GMM variances carry rich information as well, thus leading to a noise- and outlier-free scene model as a by-product. A second version of the algorithm is also proposed whereby newly captured sets can be registered online. A thorough discussion and validation on challenging data-sets against several state-of-the-art methods confirm the potential of the proposed model for jointly registering real depth data [43].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- In December, PERCEPTION started a one year collaboration with the **Digital Media and Communications R&D Center, Samsung Electronics** (Seoul, Korea). The topic of this collaboration is *multi-modal speaker localization and tracking* (a central topic of the team) and is part of a strategic partnership between Inria and Samsung Electronics.
- Over the past six years we have collaborated with Aldebaran Robotics (now SoftBank). This collaboration was part of two EU STREP projects, HUMAVIPS (2010-2012) and EARS (2014-2016). This enabled our team to establish strong connections with SoftBank, to design a stereoscopic camera head and to jointly develop several demonstrators using three different generations of the NAO robot.
  Website: https://team.inria.fr/perception/nao/
- In 2015 we started a collaboration with Xerox Research Center India (XRCI), Bangalore. This three-year collaboration (2015-2017) is funded by a grant awarded by the **Xerox Foundation University Affairs Committee (UAC)** and the topic of the project is *Advanced and Scalable Graph Signal Processing Techniques*. The work is done in collaboration with EPI MISTIS and our Indian collaborators are Arijit Biswas and Anirban Mondal.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR

8.1.1.1. MIXCAM

Type: ANR BLANC

Duration: March 2014 - February 2016

Coordinator: Radu Horaud

Partners: 4D View Solutions SAS

Abstract: Humans have an extraordinary ability to see in three dimensions, thanks to their sophisticated binocular vision system. While both biological and computational stereopsis have been thoroughly studied for the last fifty years, the film and TV methodologies and technologies have exclusively used 2D image sequences, including the very recent 3D movie productions that use two image sequences, one for each eye. This state of affairs is due to two fundamental limitations: it is difficult to obtain 3D reconstructions of complex scenes and glass-free multi-view 3D displays, which are likely to need real 3D content, are still under development. The objective of MIXCAM is to develop novel scientific concepts and associated methods and software for producing live 3D content for glass-free multi-view 3D displays. MIXCAM will combine (i) theoretical principles underlying computational stereopsis, (ii) multiple-camera reconstruction methodologies, and (iii) active-light sensor technology in order to develop a complete content-production and -visualization methodological pipeline, as well as an associated proof-of-concept demonstrator implemented on a multiple-sensor/multiple-PC platform supporting real-time distributed processing. MIXCAM plans to develop an original approach based on methods that combine color cameras with time-of-flight (TOF) cameras: TOF-stereo robust matching, accurate and efficient 3D reconstruction, realistic photometric rendering, real-time distributed processing, and the development of an advanced mixed-camera platform. The MIXCAM consortium is composed of two French partners (Inria and 4D View Solutions). The MIX-CAM partners will develop scientific software that will be demonstrated using a prototype of a novel platform, developed by 4D Views Solutions, and which will be available at Inria, thus facilitating scientific and industrial exploitation.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. EARS

Title: Embodied Audition for RobotS

Program: FP7

Duration: January 2014 - December 2016

Coordinator: Friedrich Alexander Universität Erlangen-Nünberg

Partners:

Aldebaran Robotics (France)

Ben-Gurion University of the Negev (Israel)

Friedrich Alexander Universität Erlangen-Nünberg (Germany)

Imperial College of Science, Technology and Medicine (United Kingdom)

Humboldt-Universitat Zu Berlin (Germany)

Inria contact: Radu Horaud

The success of future natural intuitive human-robot interaction (HRI) will critically depend on how responsive the robot will be to all forms of human expressions and how well it will be aware of its environment. With acoustic signals distinctively characterizing physical environments and speech being the most effective means of communication among humans, truly humanoid robots must be able to fully extract the rich auditory information from their environment and to use voice communication as much as humans do. While vision-based HRI is well developed, current limitations in robot audition do not allow for such an effective, natural acoustic human-robot communication in real-world environments, mainly because of the severe degradation of the desired acoustic signals due to noise, interference and reverberation when captured by the robot's microphones. To overcome these limitations, EARS will provide intelligent 'ears' with close-to-human auditory capabilities and use it for HRI in complex real-world environments. Novel microphone arrays and powerful signal processing algorithms shall be able to localise and track multiple sound sources of interest and to extract and recognize the desired signals. After fusion with robot vision, embodied robot cognition will then derive HRI actions and knowledge on the entire scenario, and feed this back to the acoustic interface for further auditory scene analysis. As a prototypical application, EARS will consider a welcoming robot in a hotel lobby offering all the above challenges. Representing a large class of generic applications, this scenario is of key interest to industry and, thus, a leading European robot manufacturer will integrate EARS's results into a robot platform for the consumer market and validate it. In addition, the provision of open-source software and an advisory board with key players from the relevant robot industry should help to make EARS a turnkey project for promoting audition in the robotics world.

8.2.1.2. VHIA

Title: Vision and Hearing in Action

Program: FP7

Type: ERC

Duration: February 2014 - January 2019

Coordinator: Inria

Inria contact: Radu Horaud

The objective of VHIA is to elaborate a holistic computational paradigm of perception and of perception-action loops. We plan to develop a completely novel twofold approach: (i) learn from mappings between auditory/visual inputs and structured outputs, and from sensorimotor contingencies, and (ii) execute perception-action interaction cycles in the real world with a humanoid robot. VHIA will achieve a unique fine coupling between methodological findings and proof-of-concept implementations using the consumer humanoid NAO manufactured in Europe. The proposed multimodal approach is in strong contrast with current computational paradigms influenced by unimodal biological theories. These theories have hypothesized a modular view, postulating quasi-independent and parallel perceptual pathways in the brain. VHIA will also take a radically different view than today's audiovisual fusion models that rely on clean-speech signals and on accurate frontal-images of faces; These models assume that videos and sounds are recorded with hand-held or head-mounted sensors, and hence there is a human in the loop who intentionally supervises perception and interaction. Our approach deeply contradicts the belief that complex and expensive humanoids (often manufactured in Japan) are required to implement research ideas. VHIA's methodological program addresses extremely difficult issues: how to build a joint audiovisual space from heterogeneous, noisy, ambiguous and physically different visual and auditory stimuli, how to model seamless interaction, how to deal with high-dimensional input data, and how to achieve robust and efficient human-humanoid communication tasks through a well-thought tradeoff between offline training and online execution. VHIA bets on the high-risk idea that in the next decades, social robots will have a considerable economical impact, and there will be millions of humanoids, in our homes, schools and offices, which will be able to naturally communicate with us.

8.3. International Initiatives

8.3.1. Inria International Partners

8.3.1.1. Informal International Partners

- Professor Sharon Gannot, Bar Ilan University, Tel Aviv, Israel,
- Dr. Miles Hansard, Queen Mary University London, UK,
- Professor Nicu Sebe, University of Trento, Trento, Italy,
- Professor Adrian Raftery, University of Washington, Seattle, USA,
- Dr. Rafael Munoz-Salinas, University of Cordoba, Spain,
- Dr. Noam Shabatai, Ben Gourion University of the Negev, Israel.
- Dr. Christine Evers, Imperial College of Science and Medecine, UK.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

- Professor Sharon Gannot, Bar Ilan University, Tel Aviv, Israel,
- Yuval Dorfan, Bar Ilan University, Tel Aviv, Israel,
- Dr. Rafael Munoz-Salinas, University of Cordoba, Spain,
- Dr. Noam Shabatai, Ben Gourion University of the Negev, Israel.
- Dr. Christine Evers, Imperial College of Science and Medecine, UK.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Journal

9.1.1.1. Member of the Editorial Boards

Radu Horaud is a member of the following editorial boards:

- advisory board member of the *International Journal of Robotics Research, Sage*,
- associate editor of the *International Journal of Computer Vision, Kluwer*, and
- area editor of *Computer Vision and Image Understanding, Elsevier*.

9.1.2. Invited Talks

- Xavier Alameda-Pineda gave invited talks Polytechnic University of Catalunya (May, Barcelona), Telecom ParisTech (May), Columbia University (June, New York, USA), and Carnegie Mellon University (June, Pittsburgh, USA).
- Radu Horaud gave invited talks at the Working Group on Model Based Clustering (July, Paris), at Google Research (July, Mountain View, USA), SRI International (July, Menlo Park, USA), and Amazon (July, Seattle, USA).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Tutorial: *Multimodal Human Behaviour Analysis in the Wild: Recent Advances and Open Problems* at the IEEE ICPR'16 Conference, December 2016, 4 hours. Teachers: Xavier Alameda-Pineda, Nicu Sebe and Elisa Ricci (University of Trento).

9.2.2. Supervision

PhD in progress: Israel Dejene Gebru, October 2013, Radu Horaud and Xavier Alameda-Pineda.

PhD in progress: Dionyssos Kounades-Bastian, October 2013, Radu Horaud, Laurent Girin, and Xavier Alameda-Pineda.

PhD in progress: Vincent Drouard, October 2014, Radu Horaud and Sileye Ba.

PhD in progress: Benoit Massé, October 2014, Radu Horaud and Sileye Ba.

PhD in progress: Stéphane Lathuilière, October 2014, Radu Horaud.

PhD in progress: Yutong Ban, October 2015, Radu Horaud and Laurent Girin

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Major publications by the team in recent years

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Team PERVASIVE INTERACTION

Pervasive Interaction

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Robotics and Smart environments

Table of contents

Team PERVASIVE INTERACTION

Creation of the Team: 2016 April 01

Keywords:

Computer Science and Digital Science:

1.2.5. - Internet of things
1.4. - Ubiquitous Systems
2.6.2. - Middleware
3.2.3. - Inference
3.2.5. - Ontologies
3.4.1. - Supervised learning
3.4.2. - Unsupervised learning
3.4.3. - Reinforcement learning
3.4.5. - Bayesian methods
3.4.6. - Neural networks
5. - Interaction, multimedia and robotics
5.1. - Human-Computer Interaction
5.1.3. - Haptic interfaces
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5.1.6. - Tangible interfaces
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5.3.3. - Pattern recognition
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5.4.6. - Object localization
5.6. - Virtual reality, augmented reality
5.7.1. - Sound
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5.7.4. - Analysis
5.10. - Robotics
5.10.1. - Design
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5.10.7. - Learning
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8. - Artificial intelligence
8.1. - Knowledge
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8.5. - Robotics
8.7. - AI algorithmics

Other Research Topics and Application Domains:

1.3.2. - Cognitive science
2.1. - Well being
6.4. - Internet of things
8.1. - Smart building/home
8.2. - Connected city

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2. Overall Objectives

2.1. Overall Objectives

Pervasive Interaction will develop theories and models for context aware, sociable interaction with systems and services that are dynamically composed from collections of interconnected smart objects. The project is structured a focused 4-year project to explore the use of situation modelling as a technological foundation for situated behavior for smart objects.

The research program Pervasive Interaction is designed to respond to the following four research questions:

- Q1: What are the most appropriate computational techniques for acquiring and using situation models for situated behavior by smart objects?
- Q2: What perception and action techniques are most appropriate for situated smart objects?
- Q3: Can we use situation modelling as a foundation for sociable interaction with smart objects?
- Q4: Can we use situated smart objects as a form of immersive media?

3. Research Program

3.1. Situation Models

Situation Modelling, Situation Awareness, Probabilistic Description Logistics

The objectives of this research area are to develop and refine new computational techniques that improve the reliability and performance of situation models, extend the range of possible application domains, and reduce the cost of developing and maintaining situation models. Important research challenges include developing machine-learning techniques to automatically acquire and adapt situation models through interaction, development of techniques to reason and learn about appropriate behaviors, and the development of new algorithms and data structures for representing situation models.

Over the next four years we will address the following research challenges:

Techniques for learning and adapting situation models: Hand crafting of situation models is currently an expensive process requiring extensive trial and error. We will investigate combination of interactive design tools coupled with supervised and semi-supervised learning techniques for constructing initial, simplified prototype situation models in the laboratory. One possible approach is to explore developmental learning to enrich and adapt the range of situations and behaviors through interaction with users.

Reasoning about actions and behaviors: Constructing systems for reasoning about actions and their consequences is an important open challenge. We will explore integration of planning techniques for operationalizing actions sequences within behaviors, and for constructing new action sequences when faced with unexpected difficulties. We will also investigate reasoning techniques within the situation modeling process for anticipating the consequences of actions, events and phenomena.

Algorithms and data structures for situation models: In recent years, we have experimented with an architecture for situated interaction inspired by work in human factors. This model organises perception and interaction as a cyclic process in which directed perception is used to detect and track entities, verify relations between entities, detect trends, anticipate consequences and plan actions. Each phase of this process raises interesting challenges questions algorithms and programming techniques. We will experiment alternative programming techniques representing and reasoning about situation models both in terms of difficulty of specification and development and in terms of efficiency of the resulting implementation. We will also investigate the use of probabilistic graph models as a means to better accommodate uncertain and unreliable information. In particular, we will experiment with using probabilistic predicates for defining situations, and maintaining likelihood scores over multiple situations within a context. Finally, we will investigate the use of simulation as technique for reasoning about consequences of actions and phenomena.

Probabilistic Description Logics: In our work, we will explore the use of probabilistic predicates for representing relations within situation models. As with our earlier work, entities and roles will be recognized using multi-modal perceptual processes constructed with supervised and semi-supervised learning [Brdiczka 07], [Barraquand 12]. However, relations will be expressed with probabilistic predicates. We will explore learning based techniques to probabilistic values for elementary predicates, and propagate these through probabilistic representation for axioms using Probabilistic Graphical Models and/or Bayesian Networks.

The challenges in this research area will be addressed through three specific research actions covering situation modelling in homes, learning on mobile devices, and reasoning in critical situations.

3.1.1. Learning Routine patterns of activity in the home.

The objective of this research action is to develop a scalable approach to learning routine patterns of activity in a home using situation models. Information about user actions is used to construct situation models in which key elements are semantic time, place, social role and actions. Activities are encoded as sequences of situations. Recurrent activities are detected as sequences of activities that occur at a specific time and place each day. Recurrent activities provide routines what can be used to predict future actions and anticipate needs and services. An early demonstration has been to construct an intelligent assistant that can respond to and filter communications.

This research action is carried out as part of the doctoral research of Julian Cumin in cooperation with researchers at Orange labs, Meylan. Results are to be published at Ubicomp, Ambient intelligence, Intelligent Environments and IEEE Transactions on System Man and Cybernetics. Julien Cumin will complete and defend his doctoral thesis in 2018.

3.1.2. Learning Patterns of Activity with Mobile Devices

The objective of this research action is to develop techniques to observe and learn recurrent patterns of activity using the full suite of sensors available on mobile devices such as tablets and smart phones. Most mobile devices include seven or more sensors organized in 4 groups: Positioning Sensors, Environmental Sensors, Communications Subsystems, and Sensors for Human-Computer Interaction. Taken together, these sensors can provide a very rich source of information about individual activity.

In this area we explore techniques to observe activity with mobiles devices in order to learn daily patterns of activity. We will explore supervised and semi-supervised learning to construct systems to recognize places and relevant activities. Location and place information, semantic time of day, communication activities, interpersonal interactions, and travel activities (walking, driving, riding public transportation, etc.) are recognized as probabilistic predicates and used to construct situation models. Recurrent sequences of situations will be detected and recorded to provide an ability to predict upcoming situations and anticipate needs for information and services.

Our goal is to develop a theory for building context aware services that can be deployed as part of the mobile applications that companies such as SNCF and RATP use to interact with clients. For example, a current project concerns systems that observe daily travel routines for the Paris region RATP metro and SNCF commuter trains. This system learns individual travel routines on the mobile device without the need to divulge information about personal travel to a cloud based system. The resulting service will consult train and metro schedules to assure that planned travel is feasible and to suggest alternatives in the case of travel disruptions. Similar applications are under discussion for the SNCF inter-city travel and Air France for air travel.

This research action is conducted in collaboration with the Inria Startup Situ8ed. The current objective is to deploy and evaluate a first prototype App during 2017. Techniques will be used commercially by Situ8ed for products to be deployed as early as 2019.

3.1.3. Observing and Modelling Competence and Awareness in Critical Situations

The aim of this research action is to experimentally evaluate and compare current theories for mental modelling for problem solving and attention in stressful situations, as well as to refine theories and techniques for observing visual fixation, attention and emotion. We are currently investigating differences in visual attention, emotional response and mental states of chess experts and chess novices solving chess problems and participating in chess matches. We observe physiological responses, mental states and visual attention using eye-tracking, long term and instantaneous face-expressions (micro-expressions), skin conductivity, blood flow (BVP), posture and other information extracted from audio-visual recordings of players.

We expect that a high degree of expertise in chess should be reflected in patterns of eye movement and emotional reaction in accordance with the game situation. Information from visual attention will be used to determine and model the degree to which a player understands the game situation in terms of abstract configurations of chess pieces rather than the positions of individual pieces. Information about the emotional reactions of players will be expressed as trajectories in the physiological space of pleasure, arousal and dominance to determine if a players understanding of the game situation can be observed from emotional reaction to game play.

This work is supported by the ANR project CEEGE in cooperation with the department of NeuroCognition of Univ. Bielefeld, as well as the LIG internal project AirBorne in cooperation with the French Air Force training center at ISTRE. Work in this area includes the Doctoral research of Thomas Guntz to be defended in 2019.

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3.2. Perception of People, Activities and Emotions

Machine perception is fundamental for situated behavior. Work in this area will concern construction of perceptual components using computer vision, acoustic perception, accelerometers and other embedded sensors. These include low-cost accelerometers [Bao 04], gyroscopic sensors and magnetometers, vibration sensors, electromagnetic spectrum and signal strength (wifi, bluetooth, GSM), infrared presence detectors, and bolometric imagers, as well as microphones and cameras. With electrical usage monitoring, every power switch can be used as a sensor [Fogarty 06], [Coutaz 16]. We will develop perceptual components for integrated vision systems that combine a low-cost imaging sensors with on-board image processing and wireless communications in a small, low-cost package. Such devices are increasingly available, with the enabling manufacturing technologies driven by the market for integrated imaging sensors on mobile devices. Such technology enables the use of embedded computer vision as a practical sensor for smart objects.

Research challenges to be addressed in this area include development of practical techniques that can be deployed on smart objects for perception of people and their activities in real world environments, integration and fusion of information from a variety of sensor modalities with different response times and levels of abstraction, and perception of human attention, engagement, and emotion using visual and acoustic sensors.

Work in this research area will focus on three specific Research Actions

3.2.1. Multi-modal perception and modeling of activities

The objective of this research action is to develop techniques for observing and scripting activities for common household tasks such as cooking and cleaning. An important part of this project involves acquiring annotated multi-modal datasets of activity using an extensive suite of visual, acoustic and other sensors. We are interested in real-time on-line techniques that capture and model full body movements, head motion and manipulation actions as 3D articulated motion sequences decorated with semantic labels for individual actions and activities with multiple RGB and RGB-D cameras.

We will explore the integration of 3D articulated models with appearance based recognition approaches and statistical learning for modeling behaviors. Such techniques provide an important enabling technology for context aware services in smart environments [Coutaz 05], [Crowley 15], investigated by Pervasive Interaction team, as well as research on automatic cinematography and film editing investigated by the Imagine team [Gandhi 13] [Gandhi 14] [Ronfard 14] [Galvane 15]. An important challenge is to determine which techniques are most appropriate for detecting, modeling and recognizing a large vocabulary of actions and activities under different observational conditions.

We will explore representations of behavior that encodes both temporal-spatial structure and motion at multiple levels of abstraction. We will further propose parameters to encode temporal constraints between actions in the activity classification model using a combination of higher-level action grammars [Pirsiavash 14] and episodic reasoning [Santofimia 14] [Edwards 14].

Our method will be evaluated using long-term recorded dataset that contains recordings of activities in home environments. This work will be reported in the IEEE Conference on Face and Gesture Recognition, IEEE transactions on Pattern Analysis and Machine Intelligence, (PAMI) et IEEE Transactions on Systems man and Cybernetics. This work is carried out in the doctoral research of Nachwa Abubakr in cooperation with Remi Ronfard of the Imagine Team of Inria.

3.2.2. Perception with low-cost integrated sensors

In this research action, we will continue work on low-cost integrated sensors using visible light, infrared, and acoustic perception. We will continue development of integrated visual sensors that combine micro-cameras and embedded image processing for detecting and recognizing objects in storage areas. We will combine visual and acoustic sensors to monitor activity at work-surfaces. Low cost real-time image analysis procedures will be designed that acquire and process images directly as they are acquired by the sensor.

Bolometric image sensors measure the Far Infrared emissions of surfaces in order to provide an image in which each pixel is an estimate of surface temperature. Within the European MIRTIC project, Grenoble startup, ULIS has created a relatively low-cost Bolometric image sensor (Retina) that provides small images of 80 by 80 pixels taken from the Far-infrared spectrum. Each pixel provides an estimate of surface temperature. Working with Schneider Electric, engineers in the Pervasive Interaction team had developed a small, integrated sensor that combines the MIRTIC Bolometric imager with a microprocessor for on-board image processing. The package has been equipped with a fish-eye lens so that an overhead sensor mounted at a height of 3 meters has a field of view of approximately 5 by 5 meters. Real-time algorithms have been demonstrated for detecting, tracking and counting people, estimating their trajectories and work areas, and estimating posture.

Many of the applications scenarios for Bolometric sensors proposed by Schneider Electric assume a scene model that assigns pixels to surfaces of the floor, walls, windows, desks or other items of furniture. The high cost of providing such models for each installation of the sensor would prohibit most practical applications. We have recently developed a novel automatic calibration algorithm that determines the nature of the surface under each pixel of the sensor.

Work in this area will continue to develop low-cost real time infrared image sensing, as well as explore combinations of far-infrared images with RGB and RGBD images.

3.2.3. Observation of emotion from physiological responses in critical situations

Recent research in Cognitive Science indicates that the human emotions result in physiological manifestations in the heart rate, skin conductance, skin color, body movements and facial expressions. It has been proposed that these manifestations can be measured by observation of skin color, body motions, and facial expressions and modeled as activation levels in three dimensions known as Valence, Arousal and Dominance. The goal if this project is to evaluate the effectiveness of visual and acoustic perception technique for measuring these physiological manifestations.

Experimental data will be collected by observing subjects engaged in playing chess. A special apparatus has been constructed that allows synchronized recording from a color camera, Kinect2 3D camera, and Tobi Eye Tracker of a player seated before a computer generated display of a chess board. The masters student will participate in the definition and recording of scenarios for recording test data, apply recently proposed techniques from the scientific literature for measuring emotions, and provide a comparative performance evaluation of various techniques. The project is expected to reveal the relative effectiveness of computer vision and other techniques for observing human emotions.

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3.3. Sociable Interaction with Smart Objects

Reeves and Nass argue that a social interface may be the truly universal interface [Reeves 98]. Current systems lack ability for social interaction because they are unable to perceive and understand humans or to learn from interaction with humans. One of the goals of the research to be performed in Pervasive Interaction is to provide such abilities.

Work in research area RA3 will demonstrate the use of situation models for sociable interaction with smart objects and companion robots. We will explore the use of situation models as a representation for sociable interaction. Our goal in this research is to develop methods to endow an artificial agent with the ability to acquire social common sense using the implicit feedback obtained from interaction with people. We believe that such methods can provide a foundation for socially polite man-machine interaction, and ultimately for other forms of cognitive abilities. We propose to capture social common sense by training the appropriateness of behaviors in social situations. A key challenge is to employ an adequate representation for social situations.

Knowledge for sociable interaction will be encoded as a network of situations that capture both linguistic and non-verbal interaction cues and proper behavioral responses. Stereotypical social interactions will be represented as trajectories through the situation graph. We will explore methods that start from simple stereotypical situation models and extending a situation graph through the addition of new situations and the splitting of existing situations. An important aspect of social common sense is the ability to act appropriately in social situations. We propose to learn the association between behaviors and social situation using reinforcement learning. Situation models will be used as a structure for learning appropriateness of actions and behaviors that may be chosen in each situation, using reinforcement learning to determine a score for appropriateness based on feedback obtained by observing partners during interaction.

Work in this research area will focus on four specific Research Actions

3.3.1. Moving with people

Our objective in this area is to establish the foundations for robot motions that are aware of human social situation that move in a manner that complies with the social context, social expectations, social conventions and cognitive abilities of humans. Appropriate and socially compliant interactions require the ability for real time perception of the identity, social role, actions, activities and intents of humans. Such perception can be used to dynamically model the current situation in order to understand the situation and to compute the appropriate course of action for the robot depending on the task at hand.

To reach this objective, we propose to investigate three interacting research areas:

- Modeling the context and situation of human activities for motion planning
- Planning and acting in a social context.
- Identifying and modeling interaction behaviors.

In particular, we will investigate techniques that allow a tele-presence robot, such as the BEAM system, to autonomously navigate in crowds of people as may be found at the entry to a conference room, or in the hallway of a scientific meeting. We will also continue experiments on autonomous motion for personal assistance robots (project PRAMAD). Work in this area includes the doctoral work of Jos‚Äö√Ñ√∂‚àö‚Ć√∂¬¨¬© da Silva, to be defended in 2019.

3.3.2. Understanding and communicating intentions from motion

This research area concerns the communication through motion. When two or more people move as a group, their motion is regulated by implicit rules that signal a shared sense of social conventions and social roles. For example, moving towards someone while looking directly at them signals an intention for engagement. In certain cultures, subtle rules dictate who passes through a door first or last. When humans move in groups, they implicitly communicate intentions with motion. In this research area, we will explore the scientific literature on proxemics and the social sciences on such movements, in order to encode and evaluate techniques for socially appropriate motion by robots.

3.3.3. Socially aware interaction

This research area concerns socially aware man-machine interaction. Appropriate and socially compliant interaction requires the ability for real time perception of the identity, social role, actions, activities and intents of humans. Such perception can be used to dynamically model the current situation in order to understand the context and to compute the appropriate course of action for the task at hand. Performing such interactions in manner that respects and complies with human social norms and conventions requires models for social roles and norms of behavior as well as the ability to adapt to local social conventions and individual user preferences. In this research area, we will complement research area 3.2 with other forms of communication and interaction, including expression with stylistic face expressions rendered on a tablet, facial gestures, body motions and speech synthesis. We will experiment with use of commercially available tool for spoken language interaction in conjunction with expressive gestures.

3.3.4. Stimulating affection and persuasion with affective devices.

This research area concerns technologies that can stimulate affection and engagement, as well as induce changes in behavior. When acting as a coach or cooking advisor, smart objects must be credible and persuasive. One way to achieve this goal is to express affective feedbacks while interacting. This can be done using sound, light and/or complex moves when the system is composed of actuators.

Research in this area will address 3 questions:

1. How do human perceive affective signals expressed by smart objects (including robots)?
2. How does physical embodiment effect perception of affect by humans?
3. What are the most effective models and tools for animation of affective expression?

Both the physical form and the range of motion have important impact on the ability of a system to inspire affection. We will create new models to propose a generic animation model, and explore the effectiveness of different forms of motion in stimulating affect.

3.3.5. Bibliography

[Reeves 98] B. Reeves and C. Nass, The Media Equation: how People Treat Computers, Television, and New Media Like Real People and Places. Cambridge University Press, 1998.

3.4. Interaction with Pervasive Smart Objects and Displays

Currently, the most effective technologies for new media for sensing, perception and experience are provided by virtual and augmented realities [Van Krevelen 2010]. At the same time, the most effective means to augment human cognitive abilities are provided by access to information spaces such as the world-wide-web using graphical user interfaces. A current challenge is to bring these two media together.

Display technologies continue to decrease exponentially, driven largely by investment in consumer electronics as well as the overall decrease in cost of microelectronics. A consequence has been an increasing deployment of digital displays in both public and private spaces. This trend is likely to accelerate, as new technologies and growth in available communications bandwidth enable ubiquitous low-cost access to information and communications.

The arrival of pervasive displays raises a number of interesting challenges for situated multi-modal interaction. For example:

1. Can we use perception to detect user engagement and identify users in public spaces?
2. Can we replace traditional pointing hardware with gaze and gesture based interaction?
3. Can we tailor information and interaction for truly situated interaction, providing the right information at the right time using the right interaction modality?
4. How can we avoid information overload and unnecessary distraction with pervasive displays?

It is increasingly possible to embed sensors and displays in clothing and ordinary devices, leading to new forms of tangible and wearable interaction with information. This raises challenges such as

1. What are the tradeoffs between large-scale environmental displays and wearable displays using technologies such as e-textiles and pico-projector?
2. How can we manage the tradeoffs between implicit and explicit interaction with both tangible and wearable interaction?
3. How can we determine the appropriate modalities for interaction?
4. How can we make users aware of interaction possibilities without creating distraction?

In addition to display and communications, the continued decrease in microelectronics has also driven an exponential decrease in cost of sensors, actuators, and computing resulting in an exponential growth in the number of smart objects in human environments. Current models for systems organization are based on centralized control, in which a controller or local hub, orchestrates smart objects, generally in connection with cloud computing. This model creates problems with privacy and ownership of information. An alternative is to organize local collections of smart objects to provide distributed services without the use of a centralized controller. The science of ecology can provide an architectural model for such organization.

This approach raises a number of interesting research challenges for pervasive interaction:

1. Can we devise distributed models for multi-modal fusion and interaction with information on heterogeneous devices?
2. Can we devise models for distributed interaction that migrates over available devices as the user changes location and task?
3. Can we manage migration of interaction over devices in a manner that provides seamless immersive interaction with information, services and media?
4. Can we provide models of distributed interaction that conserve the interaction context as services migrate?

Research Actions for Interaction with Pervasive Smart Objects for the period 2017 - 2020 include

3.4.1. Situated interaction with pervasive displays

The emergence of low-cost interactive displays will enable a confluence of virtual and physical environments. Our goal in this area is to go beyond simple graphical user interfaces in such environments to provide immersive multi-sensorial interaction and communication. A primary concern will be interaction technologies that blend visual with haptic/tactile feedback and 3D interaction and computer vision. We will investigate the use of visual-tactile feedback as well as vibratory signals to augment multi-sensorial interaction and communication. The focus will be on the phenomena of immersive interaction in real worlds that can be made possible by the blending of physical and virtual in ordinary environments.

3.4.2. Wearable and tangible interaction with smart textiles and wearable projectors

Opportunities in this area result from the emergence of new forms of interactive media using smart objects. We will explore the use of smart objects as tangible interfaces that make it possible to experience and interact with information and services by grasping and manipulating objects. We will explore the use of sensors and actuators in clothing and wearable devices such as gloves, hats and wrist bands both as a means of unobtrusively sensing human intentions and emotional states and as a means of stimulating human senses through vibration and sound. We will explore the new forms of interaction and immersion made possible by deploying interactive displays over large areas of an environment.

3.4.3. Pervasive interaction with ecologies of smart objects in the home

In this research area, we will explore and evaluate interaction with ecologies of smart objects in home environments. We will explore development of a range of smart objects that provide information services, such as devices for Episodic Memory for work surfaces and storage areas, devices to provide energy efficient control of environmental conditions, and interactive media that collect and display information. We propose to develop a new class of socially aware managers that coordinate smart objects and manage logistics in functional areas such as the kitchen, living rooms, closets, bedrooms, bathroom or office.

3.4.4. Bibliography

[Van Krevelen 10] D. W. F. Van Krevelen and R. Poelman, A survey of augmented reality technologies, applications and limitations. International Journal of Virtual Reality, 9(2), 1, 2010

4. Application Domains

4.1. Smart Energy Systems

Participants: Amr Alyafi, Patrick Reignier Partners: UMR G-SCOP, UMR LIG (Persuasive Interaction, IIHM), CEA Liten, PACTE, Vesta Systems and Elithis.

Work in this area explores techniques for a user centric energy management system, where user needs and tacit knowledge drive the search of solutions. These are calculated using a flexible energy model of the living areas. The system is personified by energy consultants with which building actors such as building owners, building managers, technical operators but also occupants, can interact with in order to co-define energy strategies, benefiting of both assets: tacit knowledge of human actors, and measurement with computation capabilities of calculators. Putting actors in the loop, i.e. making energy not only visible but also controllable is the needed step before large deployment of energy management solutions. It is proposed to develop interactive energy consultants for all the actors, which are energy management aided systems embedding models in order to support the decision making processes. MIRROR (interactive monitoring), WHAT-IF (interactive quantitative simulation), EXPLAIN (interactive qualitative simulation), SUGGEST-AND-ADJUST (interactive management) and RECOMMEND (interactive diagnosis) functionalities will be developed.

4.2. E-Textile

Participant: Sabine Coquillart

Partner: LIMSI

Collaboration with the HAPCO team from LIMSI on e-textiles.

4.3. Interaction with Pervasive Media

Participants: Sabine Coquillart, Jingtao Chen

Partners: Inria GRA, GIPSA, G-SCOP

Pseudo-haptic feedback is a technique aiming to simulate haptic sensations without active haptic feedback devices. Peudo-haptic techniques have been used to simulate various haptic feedbacks such as stiffness, torques, and mass. In the framework of Jingtao Chen PhD thesis, a novel pseudo-haptic experiment has been set up. The aim of this experiment is to study the EMG signals during a pseudo-haptic task. A stiffness discrimination task similar to the one published in Lecuyer's PhD thesis has been chosen. The experimental set-up has been developed, as well as the software controlling the experiment. Pre-tests are under way. They will be followed by the tests with subjects.

4.4. Bayesian Reasoning

Participants: Emmanuel Mazer, Marvin Faix

The development of modern computers is mainly based on increase of performances and decrease of size and energy consumption, with no notable modification of the basic principles of computation. In particular, all the components perform deterministic and exact operations on sets of binary signals. These constraints obviously impede further sizable progresses in terms of speed, miniaturization and power consumption. The main goal of the project MicroBayes is to investigate a radically different approach, using stochastic bit streams to perform computations. The aim of this project is to show that stochastic architectures can outperform standard computers to solve complex inference problems both in terms of execution speed and of power consumption. We will demonstrate the feasibility on two applications involving low level information processing from sensor signals, namely sound source localization and separation.

5. New Software and Platforms

5.1. DomiCube

- Participant: Rémi Pincent
- Contact: Rémi Pincent

5.2. EmoPRAMAD

KEYWORDS: Health - Home care
FUNCTIONAL DESCRIPTION

Within the Pramad project, we want to offer a full affective loop between the companion robot and the elderly people at home. This affective loop is necessary within the context of everyday interaction of elderly and the companion robot. A part of this loop is to make the robot express emotions in response to the emotional state of the user. To do that, we need to test our working hypothesis about the visual representation of emotions with the 3D face of robot. EmoPRAMAD is an evaluation tool designed to conduct comparative studies between human faces and the 3D faces expressing a defined set of emotions.

The evaluation conducted though EmoPRAMAD concerns both unimodal (facial only) and bimodal conditions (facial/sound). The emotions set is composed of 4 basic emotions (joy, fear, anger, sadness) and a neutral state. While experimenting, the software collects several parameters in order to evaluate more than correctness of the answers: time to respond, length of mouse moves, etc.

- Contact: Dominique Vaufreydaz

5.3. Online Movie Director

- Participants: Patrick Reignier, Dominique Vaufreydaz and James Crowley
- Contact: Dominique Vaufreydaz

5.4. SmartEnergy

FUNCTIONAL DESCRIPTION

Inhabitants play a key role in buildings global energy consumption but it is difficult to involve them in energy management. Our objective is to make energy consumption visible by simulating inside a serious game the energy impact of inhabitants behaviours. A serious game is curently under development, coupling a 3D virtual environment and a building energy simulator. The 3D virtual environment is based on the JMonkey 3D engine. New houses can be easily imported using SweetHome 3D and Blender. The building energy simulator is EnergyPlus. The 3D engine and the energy engine are coupled using the Functional Mock-up Interface (FMI) standard. Using this standard will allow to easily switch between existing building energy simulators.

- Participant: Patrick Reignier
- Contact: Patrick Reignier

5.5. SmartServoFramework

- Participants: Dominique Vaufreydaz and Emeric Grange
- Contact: James Crowley

SmartServoFramework is a C++ multiplatform framework used to drive "smart servo" devices such as Dynamixel or HerkuleX actuators. The Framework, developed by members of the PRIMA team runs under Linux (and most Unix systems), Mac OS X and Windows operating systems. SmartServoFramework can run on Raspberry Pi or other similar boards. This framework can be used with any Dynamixel or HerkuleX devices. Dynamixel devices from Robotis and HerkuleX devices from Dongbu Robot are high-performance networked actuators for robots available in wide range of sizes and strengths. They have adjustable torque, speed, angle limits, and provide various feedback like position, load, voltage and temperature.

5.6. MobileRGBD

KEYWORDS: Benchmark corpus - Health - Home Care

- Contact: Dominique Vaufreydaz
- http://mobilergbd.inrialpes.fr

FUNCTIONAL DESCRIPTION MobileRGBD is corpus dedicated to low level RGB-D algorithms benchmarking on mobile platform. We reversed the usual corpus recording paradigm. Our goal is to facilitate ground truth annotation and reproducibility of records among speed, trajectory and environmental variations. As we want to get rid of unpredictable human moves, we used dummies in order to play static users in the environment (see figure). Interest of dummies resides in the fact that they do not move between two recordings. It is possible to record the same robot move in order to evaluate performance of detection algorithms varying speed. This benchmark corpus is intended for ¬´low level¬ª RGB-D algorithm family like 3D-SLAM, body/skeleton tracking or face tracking using a mobile robot. Using this open corpus, researchers can find a way to answer several questions: System performance under variations in operating conditions? on a mobile robot, what is the maximum linear/angular speed supported by the algorithm? which variables impact the algorithm? evaluate suitable height/angle of the mounted RGB-D sensor to reach goals: monitoring everyday live is different from searching fallen persons on the floor; finally, what is the performance on an algorithm with regards to others?

5.7. Unix Interface for InfraRed Sensor

- Author: Pierre Baret
- Contact: James Crowley

5.8. Virtual Reality rehabilitation platform for Complex Regional Pain Syndrome

Participants: Charles-Henry Dufetel, Jing Tao Chen, Sabine Coquillart Design and development of a Virtual Reality rehabilitation platform for CRPS (Complex Regional Pain Syndrome). This application is aimed at studying the impact of visual feedback on the rehabilitation process of a patient. It focuses on the hand by allowing the physical therapist to perturb (amplify or decrease) the feedback that the patient gets from his/her hand movment. First pilot tests have been conducted.

5.9. EquipEx AmiQual4Home - Ambient Intelligence for Quality of Life

The AmiQual4Home Innovation Factory is an open research facility for innovation and experimentation with human-centered services based on the use of large-scale deployment of interconnected digital devices capable of perception, action, interaction and communication. The Innovation Factory is composed of a collection of workshops for rapid creation of prototypes, surrounded by a collection of living labs and supported by an industrial innovation and transfer service. Creation of the Innovation Factory has been made possible by a grant from French National programme Investissement d'avenir, together with substantial contributions of resources by Grenoble INP, Univ Joseph Fourier, UPMF, CNRS, Schneider Electric and the Communaute de Communes of Montbonnot. The objective is to provide the academic and industrial communities with an open platform to enable research on design, integration and evaluation of systems and services for smart habitats.

The AmiQual4Home Innovation Factory is a unique combination of three different innovation instruments:

1. Workshops for rapid prototyping of devices that embed perception, action, interaction and communication in ordinary objects based on the MIT FabLab model,
2. Facilities for real-world test and evaluation of devices and services organized as open Living Labs,
3. Resources for assisting students, researchers, entrepreneurs and industrial partners in creating new economic activities.

The AmiQual4Home Innovation Factory works with the Inovallee TARMAC technology incubator as well as the SAT Linksium to proved innovation and transfer services to enable students, researchers and local entrepreneurs to create and grow new commercial activities based on smart objects and services.

6. New Results

6.1. Simulating Haptic Sensations

Participants: Jingtao Chen, Sabine Coquillart, Partners: Inria GRA, LIG, GIPSA, G-SCOP

Pseudo-haptic feedback is a technique aiming to simulate haptic sensations without active haptic feedback devices. Peudo-haptic techniques have been used to simulate various haptic feedbacks such as stiffness, torques, and mass. In the framework of the Persyval project, a novel pseudo-haptic experiment has been set up. The aim of this experiment is to study the force and EMG signals during a pseudo-haptic task. A stiffness discrimination task similar to the one published in Lecuyer's PhD thesis has been chosen. The experimental set-up has been developed, as well as the software controlling the experiment. Pre-tests have been conducted. They have been followed by formal tests with subjects.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. Learning daily routines by observing activity in a smart home.

Members of the Pervasive interaction team are working with Orange Labs on techniques for observing activity and learning routines in a smart home. Activity is observed by monitoring use of electrical appliances and Communications media (Telephone, Television, Internet). Activities are described using Bayesian Situation Modeling techniques demonstrated in earlier projects. A log of daily activities is used to discover daily routines expressed as temporal sequences of contexts, where each context is expressed as a network of situations. Experiments will be performed using the Smart home living lab that has been constructed as part of the EquipEx Amiqual4home.

7.1.2. IRT Silver Economy

Participants: James Crowley, Pierre Baret, Maxime Belgodere Partners: CEA, Schneider Electric.

Members of the Pervasive Interaction team are working with the CEA and Schneider Electric to develop environmental sensors that can detect when a hospital patient or elderly person has fallen and is unable to get up. The project uses an infrared Bolometric image sensor to observe human activity. Image processing and fall detection logic are to be performed by an embedded image processor on board.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR Project Involved

Participants: Amr Alyafi, Patrick Reignier.

Other Partners: UMR G-SCOP, UMR LIG (Persuasive Interaction, IIHM), CEA Liten, PACTE, Vesta Systems and Elithis.

Dates: Jan 2015 to Dec 2018

The ANR project Involved focuses on bringing solutions to building actors for upcoming challenges in energy management in residential buildings. The project explores a user centric energy management system, where user needs and tacit knowledge drive the search of solutions. These are calculated using a flexible energy model of the living areas. The system is personified by energy consultants with which building actors such as building owners, building managers, technical operators but also occupants, can interact with in order to co-define energy strategies, benefiting of both assets: tacit knowledge of human actors, and measurement with computation capabilities of calculators. Putting actors in the loop, i.e. making energy not only visible but also controllable is the needed step before large deployment of energy management solutions. It is proposed to develop interactive energy consultants for all the actors, which are energy management aided systems embedding models in order to support the decision making processes. MIRROR (interactive monitoring), WHAT-IF (interactive quantitative simulation), EXPLAIN (interactive qualitative simulation), SUGGEST-AND-ADJUST (interactive management) and RECOMMEND (interactive diagnosis) functionalities will be developed.

8.1.2. ANR Project CEEGE: Chess Expertise from Eye Gaze and Emotion

Participants: James Crowley, Dominique Vaufreydaz, Rafaellea Balzarini

Other Partners: Dept of NeuroCognition, CITEN, Bielefeld University

Dates: Jan 2016 to Dec 2019

CEEGE is a multidisciplinary scientific research project conducted by the Inria PRIMA team in cooperation with the Dept of Cognitive Neuroscience at the University of Bielefeld. The primary impacts will be improved scientific understanding in the disciplines of Computer Science and Cognitive NeuroScience. The aim of this project is to experimentally evaluate and compare current theories for mental modelling for problem solving and attention, as well as to refine and evaluate techniques for observing the physiological reactions of humans to situation that inspire pleasure, displeasure, arousal, dominance and fear.

In this project, we will observe the visual attention, physiological responses and mental states of subject with different levels of expertise solving classic chess problems, and participating in chess matches. We will observe chess players using eye-tracking, sustained and instantaneous face-expressions (micro-expressions), skin conductivity, blood flow (BVP), respiration, posture and other information extracted from audio-visual recordings and sensor readings of players. We will use the recorded information to estimate the mental constructs with which the players understand the game situation. Information from visual attention as well as physiological reactions will be used to determine and model the degree to which a player understands the game situation in terms of abstract configurations of chess pieces. This will provide a structured environment that we will use for experimental evaluation of current theories of mental modeling and emotional response during problem solving and social interaction.

The project is organized in three phases. During the first phase, we will observe individual players of different levels of chess expertise solving known chess problems. We will correlate scan-path from eye tracking and other information about visual attention to established configurations of pieces and known solutions to chess problems. This will allow us to construct a labeled corpus of chess play that can be used to evaluate competing techniques for estimating mental models and physiological responses. In a second phase, we will observe the attention and face expressions of pairs of players of different levels of chess ability during game play. In particular, we will seek to annotate and segment recordings with respect to the difficulty of the game situation as well as situations that elicit particularly strong physiological reactions. In the final phase, we will use these recordings to evaluate the effectiveness of competing techniques for mental modeling and observation of emotions in terms of their abilities to predict the chess abilities of players, game outcomes and individual moves and player self reports. Results of our work will be published in scientific conferences and journals concerned with cognitive science and cognitive neuroscience as well as computer vision, multimodal interaction, affective computing and pervasive computing. Possible applications include construction of systems that can monitor the cognitive abilities and emotional reactions of users of interactive systems to provide assistance that is appropriate but not excessive, companion systems that can aid with active healthy ageing, and tutoring systems that can assist users in developing skills in a variety of domains including chess.

8.2. European Initiatives

8.2.1. ICT FET Bambi (FET Open FP7-ICT-2013-C)

Participants: Emmanuel Mazer, Marvin Faix

Partners: Hebrew University of Jerusalem, Probayes, Universit√© de Liege, Instituto de Sistemas e Robotica (Portugal),CNRS (LIG,ISIR,IEF,UMIPhi)

Dates January 2014 to December 2016

FET Open BAMBI explores a theory and a hardware implementation of probabilistic computation inspired by biochemical cell signalling. The project studies probabilistic computation following three axes: algebra, biology, and hardware. In each case, we will develop a bottom-up hierarchical approach starting from the elementary components, and study how to combine them to build more complex systems. It proposes a Bayesian Gate operating on probability distributions on binary variables as the building blocks of our probabilistic algebra. These Bayesian gates can be seen as a generalization of logical operators in Boolean algebra. The consortium interprets elementary cell signalling pathways as biological implementation of these probabilistic gates. In turn, the key features of biochemical processes give new insights for new probabilistic hardware implementation. They associate conventional electronics and novel stochastic nano-devices to build the required hardware elements. Combining these will lead to new artificial information processing systems, which could, in the future, outperform classical computers in tasks involving a direct interaction with the physical world. For this purpose, this project associates research in Bayesian probability theory, molecular biology, nanophysics, computer science and electronics.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. General Chair, Scientific Chair

- Sabine Coquillart has served as general co-chair for IEEE VR 2016, Greenville South Carolina.

9.1.2. Member of the Conference Program Committees

- Patrick Reignier served as a member program committee for the National Conference on Artificial Intelligence
- James L. Crowley served as a member program committee for Ubicomp 2016
- Dominique Vaufreydaz served on the program committee of the 11th IEEE International Workshop on Multimedia Technologies for E-Learning (MTEL2016).
- Dominique Vaufreydaz served on the program committee for the 8th international on Knowledge and Systems Engineering (KSE 2016)
- Thierry Fraichasd served as a member of the programme committee of the 1st Int. Workshop on Robot Learning and Planning (RLP) in conjunction with the "Robotics: Science and Systems" conference.

9.1.3. Reviewer for conferences

- Patrick Reignier served as a review for the International Journal of Datascience and Analytics
- James L. Crowley served as review for IEEE CVPR 2016

- James L. Crowley served as review for ICPR 2016
- James L. Crowley served as review for CNIA 2016
- James L. Crowley served as review for ECCV 2016
- James L. Crowley served as review for RFIA 2016
- Dominique Vaufreydaz served as review for Robotics and Autonomous Systems Journal
- Dominique Vaufreydaz served as review for UbiComp 2016
- Dominique Vaufreydaz served as review for ICSR 2016
- Thierry Fraichard served as a reviewer for the following conferences: RLP, IEEE Int. Conf. on Robotics and Automation (ICRA), and IEEE Int. Conf. on Advanced Intelligent Mechatronics (AIM).
- Thierry Fraichard reviewed articles for the following journals: Int. Journal of Aerospace Engineering, IEEE Trans. Intelligent Vehicles, and IEEE Trans. on Industrial Electronics.

9.1.4. Journals

- Thierry Fraichard reviewed articles for the Int. Journal of Aerospace Engineering, IEEE Trans. Intelligent Vehicles, and IEEE Trans. on Industrial Electronics.

9.1.4.1. Member of the Editorial Boards

- Sabine Coquillart is a member of the Editorial Board of the Advances in Human-Computer Interaction
- Sabine Coquillart is a member of the Scientific Committee of the Journal of Virtual Reality and Broadcasting.
- Sabine Coquillart is a member of the Advisory/Editorial Board for the International Journal of Computer Graphics SERSC.
- Sabine Coquillart is a Member of the Editorial Board of Peer Computer Science open access Journal in Computer Science.
- Sabine Coquillart is a member of the Editorial board (computer Sciences) of the Scientific World Journal.
- Sabine Coquillart is Review Editor for the Frontiers in Virtual Environments journal.
- Patrick Reignier is a member of the "comite de redaction" of the Modeling and Using Context journal (ISTE OpenScience)
- Thierry Fraichard is serving as an Associate Editor for IEEE Robotics and Automation Letters. He also served as an Associate Editor for IEEE/RSJ Int. Conf. on Robots and Systems (IROS).

9.1.5. Leadership within the scientific community

- Sabine Coquillart is elected member of the EUROGRAPHICS Executive Committee.
- Sabine Coquillart is member of the EUROGRAPHICS Working Group and Workshop board.
- Patrick Reignier is an elected member of the Association Française pour l'Intelligence Artificielle Executive Committee

9.1.6. Scientific expertise

- James L. Crowley served on the selection committee for Institut Universitaire de France (IUF)
- James L. Crowley served on the selection panel for the EC H2020 ICT Robotics program
- Dominique Vaufreydaz served as evaluator pour l'ANR
- Patrick Reignier served on the selection committee for an associate professor position at the University Grenoble Alps
- Thierry Fraichard served as an expert reviewer for the European Commission (H2020 FET and ICT calls).

9.1.7. Research administration

- James L. Crowley has been elected member of the Conseil d'Administration of the COMUE University Grenoble Alpes
- James L. Crowley has been elected member of the Conseil du Laboratoire of the Laboratoire Informatique de Grenoble.
- James L. Crowley serves on the Administrative Office (Bureau) for the Laboratoire Informatique de Grenoble.
- James L. Crowley Serves on the Commission d'Habilitation de Diriger la Recherche (HDR) for the Pole Informatics and Mathematics of the University Grenoble Alpes.
- James L. Crowley Serves on the Comittee Scientific (CoS) d'Inria Grenoble Rhone-Alpes Research Center
- James L. Crowley Serves on Steering Committee of the Inovallee TARMAC technology Incubator.
- James L. Crowley is director of the Amiqual4Home Equipment of Excellence (EquipEx).
- Patrick Reignier is head of the engineering support group of the Laboratoire d'Informatique de Grenoble
- Patrick Reignier serves on the Administrative Office (Bureau) for the Laboratoire Informatique de Grenoble.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

9.2.1.1. James Crowley

James Crowley is Director of the Master of Science in Informatics at Grenoble (MoSIG).

Master : Computer Vision, Course 27h EqTD, M2 year, Master of Science in Informatics at Grenoble

Master 1: Intelligent Systems, Cours 54h EqTD, ENSIMAG and UFRIM2AG

ENSIMAG 3 : Pattern Recognition and Machine Learning, Cours 27h EqTD, ENSIMAG

9.2.1.2. Sabine Coquillart

- Master : Sabine Coquillart Taught a course on Virtual Reality and 3D User Interfaces for the GVR Master 2R
- Master : Sabine Coquillart teaches a one day course on 3D User Interfaces and Augmented Reality for the Numerical Modeling and Virtual Reality Master 2 in Laval.

9.2.1.3. Thierry Fraichard

Master MOSIG 1st year: Introduction to Perception and Robotics, 22.5 hEqTD.

Master MOSIG 2nd year: Autonomous Robotics, 22.5 heqTD

9.2.1.4. Dominique Vaufreydaz

Co-responsibility of the Graphic, Vision and Robotics track of the MOSIG Master programme.

Licence: Competences Numerique, 80h eqTD,L1, Universite Grenoble Alpes, France.

Licence: Informatique appliquee a l'economie et a la gestion, enseignement a distance, Licence, Universite Grenoble Alpes, France.

Licence: Pratique avancee du Tableur, 72 h eqTD, L3, Universite Grenoble Alpes, France.

Licence Professionnelle: Enquêtes et traitement d'enquêtes avec le logiciel Sphinx, 12h eqTD, Licence pro Metiers de l'Emploi et de la Formation, Universite Grenoble Alpes, France.

Licence Professionnelle: Administration en environnement heterogene, 20h eqTD, Licence pro Administration et Securite des Systemes et des Reseaux, Universite Grenoble Alpes, France.

IUT annee speciale: Programmation C++, 18h eqTD, Annee Speciale IUT Informatique, Universite Grenoble Alpes, France.

Master: Pratique avancee du Tableur, 22 h eqTD, M1 economie internationale et strategies d'acteurs, Universite Grenoble Alpes, France.

Master: Mise a niveau Informatique pour l'economie, 22h eqTD, M1 Economie des Organisations, Universite Grenoble Alpes, France

Master: Traitement des donnees du Web, 15h eqTD, M2 Mathematiques et Informatique Appliquees aux Sciences Humaines et Sociales, Universite Grenoble Alpes, France

Master: Developpement Web Mobile, 15h eqTD, M2 Mathematiques et Informatique Appliquees aux Sciences Humaines et Sociales, Universite Grenoble Alpes, France

Master: co-responsable de l'option Graphic Vision Robotic (GVR) du Master 2 MOSIG.

9.2.1.5. Thierry Fraichard

- Master: Thierry Fraichard, Advanced Robotics, 54h eqTD, M2 MOSIG, Univ. of Grenoble, France.

9.2.1.6. Patrick Reignier

- Patrick Reignier has been elected member of the Conseil des Etudes et de la Vie Universitaire of Grenoble INP
- Patrick Reignier has been nominated as a member of the Conseil de la Formation Continue de Grenoble INP
- Patrick Reignier Supervises the industrial part of the “formation en apprentissage” of the ENSIMAG engineering school.
- Master: Patrick Reignier, Projet Genie Logiciel, 55h eqTD, M1, ENSIMAG/Grenoble INP, France.
- Master : Patrick Reignier, Developpement d'applications communicantes, 18h eqTD, M2, ENSIMAG/Grenoble - INP, France
- Master : Patrick Reignier, Introduction aux applications reparties, 18h eqTD, M2, ENSIMAG/Grenoble - INP, France
- Master : Patrick Reignier, Applications Web et Mobiles , 27h eqTD, M1, ENSIMAG/Grenoble - INP, France
- Master : Patrick Reignier, Projet Systeme, 12h eq TD, M1, ENSIMAG/Grenoble - INP, France
- Master : Patrick Reignier, Algorithmique, 50h eq TD, M1, ENSIMAG/Grenoble INP, France
- Licence: Patrick Reignier, Projet C, 20h eqTD, L3, ENSIMAG/Grenoble INP, France.

9.2.2. Juries

Thierry Fraichard served as a rapporteur for a doctoral jury at Universitat Politecnica de Valencia

Thierry Fraichard served as a rapporteur for a doctoral jury at INP Toulouse.

James Crowley served as a reporter for the doctoral jury of Ninghang Hu at the University of Amsterdam

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[12] R. BRÉGIER, F. DEVERNAY, L. LEYRIT, J. CROWLEY.*Defining the Pose of any 3D Rigid Object and an Associated Metric*, September 2016, working paper or preprint, https://hal.inria.fr/hal-01415027.

Team POLARIS

Performance analysis and optimization of LARge Infrastructures and Systems

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Distributed and High Performance Computing

Table of contents

Team POLARIS

Creation of the Team: 2016 January 01

Keywords:

Computer Science and Digital Science:

1.1.1. - Multicore
1.1.2. - Hardware accelerators (GPGPU, FPGA, etc.)
1.1.4. - High performance computing
1.1.5. - Exascale
1.2. - Networks
1.2.3. - Routing
1.2.5. - Internet of things
1.6. - Green Computing
5.2. - Data visualization
6. - Modeling, simulation and control
6.2.3. - Probabilistic methods
6.2.4. - Statistical methods
6.2.6. - Optimization
6.2.7. - High performance computing
7.3. - Optimization
7.11. - Performance evaluation
7.14. - Game Theory

Other Research Topics and Application Domains:

4.4. - Energy delivery
4.4.1. - Smart grids
4.5.1. - Green computing
6.2. - Network technologies
6.2.1. - Wired technologies
6.2.2. - Radio technology
6.4. - Internet of things
8.3. - Urbanism and urban planning
9.5.7. - Geography
9.6. - Reproducibility
9.7.2. - Open data

1. Members

Research Scientists

Arnaud Legrand [Team leader, CNRS, Researcher, HDR]
Nicolas Gast [Inria, Researcher]
Bruno Gaujal [Inria, Senior Researcher, HDR]
Panayotis Mertikopoulos [CNRS, Researcher]

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Vincent Danjean [Univ. Grenoble Alpes, Associate Processor]
Guillaume Huard [Univ. Grenoble Alpes, Associate Processor]
Florence Perronnin [Univ. Grenoble Alpes, Associate Processor]
Jean-Marc Vincent [Univ. Grenoble Alpes, Associate Processor]
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Franz Christian Heinrich [Inria]
Baptiste Jonglez [Inria]
Alexandre Marcastel [Univ. Cergy-Pontoise]
Alexis Martin [Inria]
Stephan Plassart [Inria, from Sep 2016]
Benoît Vinot [Schneider Electric, granted by CIFRE]
Rafael Keller Tesser [UFRGS, from August 2015]
Vinicius Garcia Pinto [UFRGS/Univ. Grenoble Alpes, From Sep 2015]

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Josu Doncel [Inria, until Nov 2016]
Ahmed El Rheddane [Inria, until Feb 2016]
Carmen Higuera Chan [Inria, from Sep 2016]
Guillaume Massonnet [Inria, until Aug 2016]
Lucas Mello Schnorr [Inria]

Administrative Assistant

Annie Simon [Inria]

Others

Mathieu Baille [Inria, Intern M1, Jun 2015 until Jul 2016]
Vania Martin [Univ. Grenoble Alpes, Faculty Member]
Sebastien Ochier [Inria, Intern, from Feb 2016 until Jun 2016]
Michael Picard [Inria, Intern, from Jun 2016 until Jul 2016]
Loic Poncet [Inria, Intern, from Jun 2016 until Jul 2016]
Florian Popek [Inria, Intern, until Aug 2016]
Steven Quinito Masnada [CNRS, Intern M2, until Jun 2016]
Angelika Studeny [Inria, Post-Doctoral Fellow, until June 2016]

2. Overall Objectives

2.1. Context

Large distributed infrastructures are rampant in our society. Numerical simulations form the basis of computational sciences and high performance computing infrastructures have become scientific instruments with similar roles as those of test tubes or telescopes. Cloud infrastructures are used by companies in such an intense way that even the shortest outage quickly incurs the loss of several millions of dollars. But every citizen also relies on (and interacts with) such infrastructures via complex wireless mobile embedded devices whose nature is constantly evolving. In this way, the advent of digital miniaturization and interconnection has enabled our homes, power stations, cars and bikes to evolve into smart grids and smart transportation systems that should be optimized to fulfill societal expectations.

Our dependence and intense usage of such gigantic systems obviously leads to very high expectations in terms of performance. Indeed, we strive for low-cost and energy-efficient systems that seamlessly adapt to changing environments that can only be accessed through uncertain measurements. Such digital systems also have to take into account both the users' profile and expectations to efficiently and fairly share resources in an online way. Analyzing, designing and provisioning such systems has thus become a real challenge.

Such systems are characterized by their **ever-growing size**, intrinsic **heterogeneity** and **distributedness**, **user-driven** requirements, and an unpredictable variability that renders them essentially **stochastic**. In such contexts, many of the former design and analysis hypotheses (homogeneity, limited hierarchy, omniscient view, optimization carried out by a single entity, open-loop optimization, user outside of the picture) have become obsolete, which calls for radically new approaches. Properly studying such systems requires a drastic rethinking of fundamental aspects regarding the system's **observation** (measure, trace, methodology, design of experiments), **analysis** (modeling, simulation, trace analysis and visualization), and **optimization** (distributed, online, stochastic).

2.2. Objectives

The goal of the POLARIS project is to **contribute to the understanding of the performance of very large scale distributed systems** by applying ideas from diverse research fields and application domains. We believe that studying all these different aspects at once without restricting to specific systems is the key to push forward our understanding of such challenges and to proposing innovative solutions. This is why we intend to investigate problems arising from application domains as varied as large computing systems, wireless networks, smart grids and transportation systems.

The members of the POLARIS project cover a very wide spectrum of expertise in performance evaluation and models, distributed optimization, and analysis of HPC middleware. Specifically, POLARIS' members have worked extensively on:

Experiment design: Experimental methodology, measuring/monitoring/tracing tools, experiment control, design of experiments, and reproducible research, especially in the context of large computing infrastructures (such as computing grids, HPC, volunteer computing and embedded systems).

Trace Analysis: Parallel application visualization (paje, triva/viva, framesoc/ocelotl, ...), characterization of failures in large distributed systems, visualization and analysis for geographical information systems, spatio-temporal analysis of media events in RSS flows from newspapers, and others.

Modeling and Simulation: Emulation, discrete event simulation, perfect sampling, Markov chains, Monte Carlo methods, and others.

Optimization: Stochastic approximation, mean field limits, game theory, discrete and continuous optimization, learning and information theory.

In the rest of this document, we describe in detail our new results in the above areas.

3. Research Program

3.1. Sound and Reproducible Experimental Methodology

Participants: Vincent Danjean, Nicolas Gast, Guillaume Huard, Arnaud Legrand, Jean-Marc Vincent.

Experiments in large scale distributed systems are costly, difficult to control and therefore difficult to reproduce. Although many of these digital systems have been built by men, they have reached such a complexity level that we are no longer able to study them like artificial systems and have to deal with the same kind of experimental issues as natural sciences. The development of a sound experimental methodology for the evaluation of resource management solutions is among the most important ways to cope with the growing complexity of computing environments. Although computing environments come with their own specific challenges, we believe such general observation problems should be addressed by borrowing good practices and techniques developed in many other domains of science.

This research theme builds on a transverse activity on *Open science and reproducible research* and is organized into the following two directions: (1) *Experimental design* (2) *Smart monitoring and tracing*. As we will explain in more detail hereafter, these transverse activity and research directions span several research areas and our goal within the POLARIS project is foremost to transfer original ideas from other domains of science to the distributed and high performance computing community.

3.2. Multi-Scale Analysis and Visualization

Participants: Vincent Danjean, Guillaume Huard, Arnaud Legrand, Jean-Marc Vincent, Panayotis Mertikopoulos.

As explained in the previous section, the first difficulty encountered when modeling large scale computer systems is to observe these systems and extract information on the behavior of both the architecture, the middleware, the applications, and the users. The second difficulty is to *visualize* and *analyze* such *multi-level traces to understand how the performance* of the application *can be improved*. While a lot of efforts are put into visualizing scientific data, in comparison little effort have gone into to developing techniques specifically tailored for understanding the behavior of distributed systems. Many visualization tools have been developed by renowned HPC groups since decades (e.g., BSC [87], Jülich and TU Dresden [86], [55], UIUC [74], [90], [77] and ANL [104], Inria Bordeaux [61] and Grenoble [106], ...) but most of these tools build on the classical information visualization mantra [95] that consists in always first presenting an overview of the data, possibly by plotting everything if computing power allows, and then to allow users to zoom and filter, providing details on demand. However in our context, the amount of data comprised in such traces is several orders of magnitude larger than the number of pixels on a screen and displaying even a small fraction of the trace leads to harmful visualization artifacts [82]. Such traces are typically made of events that occur at very different time and space scales, which unfortunately hinders classical approaches. Such visualization tools have focused on easing interaction and navigation in the trace (through gantcharts, intuitive filters, pie charts and kiviats) but they are very difficult to maintain and evolve and they require some significant experience to identify performance bottlenecks.

Therefore many groups have more recently proposed in combination to these tools some techniques to help identifying the structure of the application or regions (applicative, spatial or temporal) of interest. For example, researchers from the SDSC [85] propose some segment matching techniques based on clustering (Euclidean or Manhattan distance) of start and end dates of the segments that enables to reduce the amount of information to display. Researchers from the BSC use clustering, linear regression and Kriging techniques [94], [81], [73] to identify and characterize (in term of performance and resource usage) application phases and present aggregated representations of the trace [93]. Researchers from Jülich and TU Darmstadt have proposed techniques to identify specific communication patterns that incur wait states [101], [48]

3.3. Fast and Faithful Performance Prediction of Very Large Systems

Participants: Vincent Danjean, Bruno Gaujal, Arnaud Legrand, Florence Perronnin, Jean-Marc Vincent.

Evaluating the scalability, robustness, energy consumption and performance of large infrastructures such as exascale platforms and clouds raises severe methodological challenges. The complexity of such platforms mandates empirical evaluation but direct experimentation via an application deployment on a real-world testbed is often limited by the few platforms available at hand and is even sometimes impossible (cost, access, early stages of the infrastructure design, ...). Unlike direct experimentation via an application deployment on a real-world testbed, simulation enables fully repeatable and configurable experiments that can often be conducted quickly for arbitrary hypothetical scenarios. In spite of these promises, current simulation practice is often not conducive to obtaining scientifically sound results. To date, most simulation results in the parallel and distributed computing literature are obtained with simulators that are ad hoc, unavailable, undocumented, and/or no longer maintained. For instance, Naicken et al. [47] point out that out of 125 recent papers they surveyed that study peer-to-peer systems, 52% use simulation and mention a simulator, but 72% of them use a custom simulator. As a result, most published simulation results build on throw-away (short-lived and non validated) simulators that are specifically designed for a particular study, which prevents other researchers from building upon it. There is thus a strong need for recognized simulation frameworks by which simulation results can be reproduced, further analyzed and improved.

The *SimGrid* simulation toolkit [59], whose development is partially supported by POLARIS, is specifically designed for studying large scale distributed computing systems. It has already been successfully used for simulation of grid, volunteer computing, HPC, cloud infrastructures and we have constantly invested on the software quality, the scalability [51] and the validity of the underlying network models [49], [99]. Many simulators of MPI applications have been developed by renowned HPC groups (e.g., at SDSC [97], BSC [45], UIUC [105], Sandia Nat. Lab. [100], ORNL [58] or ETH Zürich [75] for the most prominent ones). Yet, to scale most of them build on restrictive network and application modeling assumptions that make them difficult to extend to more complex architectures and to applications that do not solely build on the MPI API. Furthermore, simplistic modeling assumptions generally prevent to faithfully predict execution times, which limits the use of simulation to indication of gross trends at best. Our goal is to improve the quality of SimGrid to the point where it can be used effectively on a daily basis by practitioners to *reproduce the dynamic of real HPC systems*.

We also develop another simulation software, *PSI* (Perfect SImulator) [63], [56], dedicated to the simulation of very large systems that can be modeled as Markov chains. PSI provides a set of simulation kernels for Markov chains specified by events. It allows one to sample stationary distributions through the Perfect Sampling method (pioneered by Propp and Wilson [88]) or simply to generate trajectories with a forward Monte-Carlo simulation leveraging time parallel simulation (pioneered by Fujimoto [67], Lin and Lazowska [80]). One of the strength of the PSI framework is its expressiveness that allows us to easily study networks with finite and infinite capacity queues [57]. Although PSI already allows to simulate very large and complex systems, our main objective is to push its scalability even further and *improve its capabilities by one or several orders of magnitude*.

3.4. Local Interactions and Transient Analysis in Adaptive Dynamic Systems

Participants: Nicolas Gast, Bruno Gaujal, Florence Perronnin, Jean-Marc Vincent, Panayotis Mertikopoulos.

Many systems can be effectively described by stochastic population models. These systems are composed of a set of n entities interacting together and the resulting stochastic process can be seen as a continuous-time Markov chain with a finite state space. Many numerical techniques exist to study the behavior of Markov chains, to solve stochastic optimal control problems [89] or to perform model-checking [46]. These techniques, however, are limited in their applicability, as they suffer from the *curse of dimensionality*: the state-space grows exponentially with n.

This results in the need for approximation techniques. Mean field analysis offers a viable, and often very accurate, solution for large n. The basic idea of the mean field approximation is to count the number of entities that are in a given state. Hence, the fluctuations due to stochasticity become negligible as the number of entities grows. For large n, the system becomes essentially deterministic. This approximation has been originally developed in statistical mechanics for vary large systems composed of more than 10^{20} particles (called entities here). More recently, it has been claimed that, under some conditions, this approximation can be successfully used for stochastic systems composed of a few tens of entities. The claim is supported by various convergence results [68], [78], [103], and has been successfully applied in various domains: wireless networks [50], computer-based systems [71], [84], [98], epidemic or rumour propagation [60], [76] and bike-sharing systems [64]. It is also used to develop distributed control strategies [102], [83] or to construct approximate solutions of stochastic model checking problems [52], [53], [54].

Within the POLARIS project, we will continue developing both the theory behind these approximation techniques and their applications. Typically, these techniques require a homogeneous population of objects where the dynamics of the entities depend only on their state (the state space of each object must not scale with n the number of objects) but neither on their identity nor on their spatial location. Continuing our work in [68], we would like to be able to handle heterogeneous or uncertain dynamics. Typical applications are caching mechanisms [71] or bike-sharing systems [65]. A second point of interest is the use of mean field or large deviation asymptotics to compute the time between two regimes [92] or to reach an equilibrium state. Last, mean-field methods are mostly descriptive and are used to analyse the performance of a given system. We wish to extend their use to solve optimal control problems. In particular, we would like to implement numerical algorithms that use the framework that we developed in [69] to build distributed control algorithms [62] and optimal pricing mechanisms [70].

3.5. Distributed Learning in Games and Online Optimization

Participants: Nicolas Gast, Bruno Gaujal, Arnaud Legrand, Panayotis Mertikopoulos.

Game theory is a thriving interdisciplinary field that studies the interactions between competing optimizing agents, be they humans, firms, bacteria, or computers. As such, game-theoretic models have met with remarkable success when applied to complex systems consisting of interdependent components with vastly different (and often conflicting) objectives – ranging from latency minimization in packet-switched networks to throughput maximization and power control in mobile wireless networks.

In the context of large-scale, decentralized systems (the core focus of the POLARIS project), it is more relevant to take an inductive, "bottom-up" approach to game theory, because the components of a large system cannot be assumed to perform the numerical calculations required to solve a very-large-scale optimization problem. In view of this, POLARIS' overarching objective in this area is to *develop novel algorithmic frameworks that offer robust performance guarantees when employed by all interacting decision-makers.*

A key challenge here is that most of the literature on learning in games has focused on *static* games with a *finite number of actions* per player [66], [91]. While relatively tractable, such games are ill-suited to practical applications where players pick an action from a continuous space or when their payoff functions evolve over time – this being typically the case in our target applications (e.g., routing in packet-switched networks or energy-efficient throughput maximization in wireless). On the other hand, the framework of online convex optimization typically provides worst-case performance bounds on the learner's *regret* that the agents can attain irrespectively of how their environment varies over time. However, if the agents' environment is determined chiefly by their interactions these bounds are fairly loose, so more sophisticated convergence criteria should be applied.

From an algorithmic standpoint, a further challenge occurs when players can only observe their own payoffs (or a perturbed version thereof). In this bandit-like setting regret-matching or trial-and-error procedures guarantee convergence to an equilibrium in a weak sense in certain classes of games. However, these results apply exclusively to static, finite games: learning in games with continuous action spaces and/or nonlinear payoff functions cannot be studied within this framework. Furthermore, even in the case of finite games, the complexity of the algorithms described above is not known, so it is impossible to decide a priori which algorithmic scheme can be applied to which application.

4. Application Domains

4.1. Large Computing Infrastructures

Supercomputers typically comprise thousands to millions of multi-core CPUs with GPU accelerators interconnected by complex interconnection networks that are typically structured as an intricate hierarchy of network switches. Capacity planning and management of such systems not only raises challenges in term of computing efficiency but also in term of energy consumption. Most legacy (SPMD) applications struggle to benefit from such infrastructure since the slightest failure or load imbalance immediately causes the whole program to stop or at best to waste resources. To scale and handle the stochastic nature of resources, these applications have to rely on dynamic runtimes that schedule computations and communications in an opportunistic way. Such evolution raises challenges not only in terms of programming but also in terms of observation (complexity and dynamicity prevents experiment reproducibility, intrusiveness hinders large scale data collection, ...) and analysis (dynamic and flexible application structures make classical visualization and simulation techniques totally ineffective and require to build on *ad hoc* information on the application structure).

4.2. Next-Generation Wireless Networks

Considerable interest has arisen from the seminal prediction that the use of multiple-input, multiple-output (MIMO) technologies can lead to substantial gains in information throughput in wireless communications, especially when used at a massive level. In particular, by employing multiple inexpensive service antennas, it is possible to exploit spatial multiplexing in the transmission and reception of radio signals, the only physical limit being the number of antennas that can be deployed on a portable device. As a result, the wireless medium can accommodate greater volumes of data traffic without requiring the reallocation (and subsequent re-regulation) of additional frequency bands. In this context, throughput maximization in the presence of interference by neighboring transmitters leads to games with convex action sets (covariance matrices with trace constraints) and individually concave utility functions (each user's Shannon throughput); developing efficient and distributed optimization protocols for such systems is one of the core objectives of Theme 5.

Another major challenge that occurs here is due to the fact that the efficient physical layer optimization of wireless networks relies on perfect (or close to perfect) channel state information (CSI), on both the uplink and the downlink. Due to the vastly increased computational overhead of this feedback – especially in decentralized, small-cell environments – the ongoing transition to fifth generation (5G) wireless networks is expected to go hand-in-hand with distributed learning and optimization methods that can operate reliably in feedback-starved environments. Accordingly, one of POLARIS' application-driven goals will be to leverage the algorithmic output of Theme 5 into a highly adaptive resource allocation framework for next-gneration wireless systems that can effectively "learn in the dark", without requiring crippling amounts of feedback.

4.3. Energy and Transportation

Participant: Nicolas Gast.

This work is mainly done within the Quanticol European project.

Smart urban transport systems and smart grids are two examples of collective adaptive systems. They consist of a large number of heterogeneous entities with decentralised control and varying degrees of complex autonomous behaviour. Within the QUANTICOL project, we develop an analysis tools to help to reason about such systems. Our work relies on tools from fluid and mean-field approximation to build decentralized algorithms that solve complex optimization problems. We focus on two problems: decentralized control of electric grids and capacity planning in vehicle-sharing systems to improve load balancing.

5. New Software and Platforms

5.1. Framesoc

FUNCTIONAL DESCRIPTION

Framesoc is the core software infrastructure of the SoC-Trace project. It provides a graphical user environment for execution-trace analysis, featuring interactive analysis views as Gantt charts or statistics views. It provides also a software library to store generic trace data, play with them, and build other analysis tools (e.g., Ocelotl).

- Participants: Jean-Marc Vincent and Arnaud Legrand
- Contact: Guillaume Huard
- URL: http://soctrace-inria.github.io/framesoc/

5.2. GameSeer

FUNCTIONAL DESCRIPTION

GameSeer is a tool for students and researchers in game theory that uses Mathematica to generate phase portraits for normal form games under a variety of (user-customizable) evolutionary dynamics. The aim of GameSeer is a) to provide a numerical integration kernel for phase portrait and equilibrium set generation; and b) to provide a graphical user interface that allows the user to employ said capabilities from a simple and intuitive front-end.

- Contact: Panayotis Mertikopoulos
- URL: http://mescal.imag.fr/membres/panayotis.mertikopoulos/publications.html

5.3. Moca

Memory Organization Cartography and Analysis
MOCA is an efficient tool for the collection of complete spatiotemporal memory traces. Its objective is twofold, namely to *a*) avoid missuses of the memory hierarchy (such as false sharing of cache lines or contention); and *b*) to take advantage of the various cache levels and the memory hardware prefetcher. It is based on a Linux kernel module and provides a coarse-grained trace of a superset of all the memory accesses performed by an application over its addressing space during the time of its execution.

KEYWORDS: High-Performance Computing - Performance analysis

- Contact: Guillaume Huard
- URL: https://github.com/dbeniamine/MOCA

5.4. Ocelotl

Multidimensional Overviews for Huge Trace Analysis
FUNCTIONAL DESCRIPTION

Ocelotl is an innovative visualization tool, which provides overviews for execution trace analysis by using a data aggregation technique. This technique enables to find anomalies in huge traces containing up to several billions of events, while keeping a fast computation time and providing a simple representation that does not overload the user.

- Participants: Arnaud Legrand and Jean-Marc Vincent
- Contact: Jean-Marc Vincent
- URL: http://soctrace-inria.github.io/ocelotl/

5.5. PSI

Perfect Simulator
FUNCTIONAL DESCRIPTION

Perfect simulator is a simulation software of markovian models. It is able to simulate discrete and continuous time models to provide a perfect sampling of the stationary distribution or directly a sampling of functional of this distribution by using coupling from the past. The simulation kernel is based on the CFTP algorithm, and the internal simulation of transitions on the Aliasing method.

- Contact: Jean-Marc Vincent
- URL: http://psi.gforge.inria.fr/

5.6. SimGrid

KEYWORDS: Large-scale Emulators - Grid Computing - Distributed Applications
SCIENTIFIC DESCRIPTION

SimGrid is a toolkit that provides core functionalities for the simulation of distributed applications in heterogeneous distributed environments. The simulation engine uses algorithmic and implementation techniques toward the fast simulation of large systems on a single machine. The models are theoretically grounded and experimentally validated. The results are reproducible, enabling better scientific practices.

Its models of networks, CPUs and disks are adapted to (Data)Grids, P2P, Clouds, Clusters and HPC, allowing multi-domain studies. It can be used either to simulate algorithms and prototypes of applications, or to emulate real MPI applications through the virtualization of their communication, or to formally assess algorithms and applications that can run in the framework.

The formal verification module explores all possible message interleavings in the application, searching for states violating the provided properties. We recently added the ability to assess liveness properties over arbitrary and legacy codes, thanks to a system-level introspection tool that provides a finely detailed view of the running application to the model checker. This can for example be leveraged to verify both safety or liveness properties, on arbitrary MPI code written in C/C++/Fortran.

- Participants: Frederic Suter, Martin Quinson, Arnaud Legrand, Adrien Lebre, Jonathan Pastor, Mario Sudholt, Luka Stanisic, Augustin Degomme, Jean-Marc Vincent, Florence Perronnin and Jonathan Rouzaud-Cornabas
- Partners: CNRS - ENS Rennes
- Contact: Martin Quinson
- URL: http://simgrid.gforge.inria.fr/

5.7. Tabarnac

Tool for Analyzing the Behavior of Applications Running on NUMA ArChitecture
KEYWORDS: High-Performance Computing - Performance analysis - NUMA

- Contact: David Beniamine
- URL: https://dbeniamine.github.io/Tabarnac/

5.8. marmoteCore

Markov Modeling Tools and Environments - the Core
KEYWORDS: Modeling - Stochastic models - Markov model
FUNCTIONAL DESCRIPTION

marmoteCore is a C++ environment for modeling with Markov chains. It consists in a reduced set of high-level abstractions for constructing state spaces, transition structures and Markov chains (discrete-time and continuous-time). It provides the ability of constructing hierarchies of Markov models, from the most general to the particular, and equip each level with specifically optimized solution methods.

This software is developed within the ANR MARMOTE project: ANR-12-MONU-00019.

- Participants: Alain Jean-Marie, Issam Rabhi, Jean-Marc Vincent, Benjamin Briot, Jean-Michel Fourneau and Franck Quessette
- Partner: UVSQ
- Contact: Alain Jean-Marie
- URL: http://marmotecore.gforge.inria.fr/

6. New Results

6.1. Asymptotic Models

The analysis of a set of n stochastic entities interacting with each others can be particularly difficult. The *mean field approximation* is a very effective technique to characterize the transient probability distribution or steady-state regime of such systems when the number of entities n grows very large. The idea of mean-field approximation is to replace a complex stochastic system by a simpler deterministic dynamical system. This dynamical system is constructed by assuming that the objects are asymptotically independent. Each object is viewed as interacting with an average of the other objects (the *mean*-field). When each object has a finite or countable state-space, this dynamical system is usually a non-linear ordinary differential equation (ODE). An introduction to these techniques is provided in the book chapter [29].

- Mean-field games model the rational behavior of an infinite number of indistinguishable players in interaction [79]. An important assumption of mean-field games is that, as the number of player is infinite, the decisions of an individual player do not affect the dynamics of the mass. Each player plays against the mass. A mean-field equilibrium corresponds to the case when the optimal decisions of a player coincide with the decisions of the mass. This leads to a simpler computation of the equilibrium.

  It has been shown in [72], [96] that for some games with a finite number of players, the Nash equilibria converge to mean-field equilibria as the number of players tends to infinity. Hence, many authors argue that mean-field games are a good approximation of symmetric stochastic games with a large number of players. The classical argument is that the impact of one player becomes negligible when the number of players goes to infinity. In [17], [36], we show that, in general, this convergence does not hold. We construct an example for which the mean-field limit only describes a sub-set of the limiting equilibria. Each finite-player game has an equilibrium with a good social cost, this is not the case for the limit game.
- Computer system and network performance can be significantly improved by caching frequently used information. When the cache size is limited, the cache replacement algorithm has an important impact on the effectiveness of caching. In [21], [3], [20] we introduce approximations to determine the cache hit probability of two classes of cache replacement algorithms: the recently introduced h-LRU and LRU(m). These approximations only require the requests to be generated according to a general Markovian arrival process (MAP). This includes phase-type renewal processes and the IRM model as special cases. We provide both numerical and theoretical support for the claim that the proposed TTL approximations are asymptotically exact. We further show, by using synthetic and trace-based workloads, that h-LRU and LRU(m) perform alike, while the latter requires less work when a hit/miss occurs.
- In [16], we consider stochastic models in presence of uncertainty, originating from lack of knowledge of parameters or by unpredictable effects of the environment. We focus on population processes, encompassing a large class of systems, from queueing networks to epidemic spreading. We set up a formal framework for imprecise stochastic processes, where some parameters are allowed to vary in time within a given domain, but with no further constraint. We then consider the limit behaviour of these systems as the population size goes to infinity. We prove that this limit is given by a differential inclusion that can be constructed from the (imprecise) drift. We also we discuss different numerical algorithms to compute bounds of the so-obtained differential inclusions. We are currently working on an implementation of these algorithms in a numerical toolbox.
- In [37], we develop a fluid-limit approach to compute the expected absorbing time T_n of a n-dimensional discrete time Markov chain. We show that the random absorbing time T_n is well approximated by a deterministic time t_n that is the first time when a fluid approximation of the chain approaches the absorbing state at a distance $1/n$. We show the applicability of this approach with three different problems: the coupon collector, the erasure channel lifetime and the coupling times of random walks in high dimensional spaces.

6.2. Simulation

Simgrid is a toolkit providing core functionalities for the simulation of distributed applications in heterogeneous distributed environments. Although it was initially designed to study large distributed computing environments such as grids, we have recently applied it to performance prediction of HPC configurations.

- Finite difference methods are, in general, well suited to execution on parallel machines and are thus commonplace in High Performance Computing. Yet, despite their apparent regularity, they often exhibit load imbalance that damages their efficiency. In [38], we characterize the spatial and temporal load imbalance of Ondes3D, a seismic wave propagation simulator used to conduct regional scale risk assessment. Our analysis reveals that this imbalance originates from the structure of the input data and from low-level CPU optimizations. We then show that the CHARM++ runtime can effectively dynamically rebalance the load by migrating data and computation at the granularity of an MPI rank. We propose a methodology that leverages the capabilities of the SimGrid simulation framework and allows to conduct an experimental study at low computational cost.
- The article [35] summarizes our recent work and developments on SMPI, a flexible simulator of MPI applications. In this tool, we took a particular care to ensure our simulator could be used to produce fast and accurate predictions in a wide variety of situations. Although we did build SMPI on SimGrid whose speed and accuracy had already been assessed in other contexts, moving such techniques to a HPC workload required significant additional effort. Obviously, an accurate modeling of communications and network topology was one of the key to such achievements. Another less obvious key was the choice to combine in a single tool the possibility to do both offline and online simulation.

6.3. Trace and Statistical Analysis

- In [19], we present visual analysis techniques to evaluate the performance of HPC task-based applications on hybrid architectures. Our approach is based on composing modern data analysis tools (pjdump, R, ggplot2, plotly), enabling an agile and flexible scripting framework with minor development cost. We validate our proposal by analyzing traces from the full-fledged implementation of the Cholesky decomposition available in the MORSE library running on a hybrid (CPU/GPU) platform. The analysis compares two different workloads and three different task schedulers from the StarPU runtime system. Our analysis based on composite views allows to identify allocation mistakes, priority problems in scheduling decisions, GPU tasks anomalies causing bad performance, and critical path issues.
- Media events are an area of major concern for the science of territory, with a combination of empirical, methodological and theoretical fields of research. The paper [22] presents three variations of increasing complexity around the questions of the application of the concepts of "territory", "territoriality" and "territorialization" to the description of media events. Each variation is illustrated by recent results from the research project ANR Geomedia on a corpus of international RSS flows produced by newspapers of French, English and Spanish language located in various countries of the world.

6.4. Electricity Markets

The increased penetration of renewable energy sources in existing power systems has led to necessary developments in electricity market mechanisms. Most importantly, renewable energy generation is increasingly made accountable for deviations between scheduled and actual energy generation. However, there is no mechanism to enforce accountability for the additional costs induced by power fluctuations. These costs are socialized and eventually supported by electricity customers. In [1], we propose some metrics for assessing the contribution of all market participants to power regulation needs, as well as an attribution mechanism for fairly redistributing related power regulation costs. We discuss the effect of various metrics used by the attribution mechanisms, and we illustrate, in a game-theoretical framework, their consequences on the strategic behavior of market participants. We also illustrate, by using the case of Western Denmark, how these mechanisms may affect revenues and the various market participants.

6.5. Power control in random wireless networks

Ever since the early development stages of wireless networks, the importance of radiated power has made power control an essential component of network design. In [13], we analyzed the problem of power control in large, random wireless networks that are obtained by "erasing" a finite fraction of nodes from a regular d-dimensional lattice of N transmit-receive pairs. Drawing on tools and ideas from statistical physics, we showed that this problem can be mapped to the Anderson impurity model for diffusion in random media; in this way, by employing the so-called *coherent potential approximation* (CPA) method, we calculated the average power in the system (and its variance) for 1-D and 2-D networks. In this regard, even though infinitely large systems are always unstable beyond a critical value of the users' SINR target, finite systems remain stable with high probability even beyond this critical SINR threshold. We calculated this probability by analyzing the density of low lying eigenvalues of an associated random Schrödinger operator, and we showed that the network can exceed this critical SINR threshold by a factor of at least $O((\log N)^{-2/d})$ before undergoing a phase transition to the unstable regime.

6.6. Energy efficiency in wireless networks

[6] The recent increase in the use of wireless networks for video transmission has led to the increase in the use of rate-adaptive protocols to maximize the resource utilization and increase the efficiency in the transmission. However, a number of these protocols lead to interactions among the users that are subjective in nature and affect the overall performance. In [6], we analyzed the interplay between the wireless network and video transmission dynamics in the light of subjective perceptions of the end users in their interactions – specifically, the trade-off between maximizing the quality of service (QoS) or quality of experience (QoE) and minimizing the transmission cost. By using methods from game theory, we derived an optimized transmission scheme that allows the efficient use of traditional protocols by taking into account the subjective interactions that occur in practical scenarios.

6.7. Cognitive radio and beyond

In cognitive radio networks, secondary (unlicensed) users (SUs) can access the spectrum opportunistically, whenever they sense an opening by the network's primary (licensed) users (PUs). In [7], we analyzed the minimization of overall power consumption over several orthogonal frequency bands under constraints on the minimum quality of service (QoS) and maximum peak and average interference to the network's PUs. To that end, we proposed a projected sub-gradient algorithm which quickly converges to an optimal configuration if the users' channels are fast fading.

Despite such benefits, the conventional cognitive radio network (CCRN) paradigm is not particularly attractive for opportunistic spectrum access because the network's PUs can recapture SU channels at will, thus interrupting the transmission of the latter. To address this crucial limitation, we proposed in [24] a semi-cognitive radio network (SCRN) paradigm where PUs are constrained to first use any free channels before being allowed to capture channels that are in use by SUs. These constraints slightly degrade the performance of the network's PUs, but *a*) they offer remarkable performance improvements to the network's SUs; and *b*) they can be compensated by imposing a monetary (or other) penalty to the network's secondary owners. In [24], we provided a game-theoretic analysis of the performance trade-offs involved for both the PUs and the SUs, and we derived both centralized and distributed learning algorithms that allow the system control process to converge to a stable state.

6.8. Online resource allocation in dynamic wireless networks

The vast majority of works on wireless resource allocation (spectrum, power, etc.) has focused on two limit cases: In the *static regime*, the attributes of the network are assumed effectively static and the system's optimality analysis relies on techniques from (static) optimization. On the other hand, in the so-called *stochastic regime*, the network is assumed to evolve randomly following some fixed probability law, and the allocation of wireless resources is optimized using tools from stochastic optimization and control. In practical wireless networks however, both assumptions fail because of factors that introduce an unpredictable variability to the system (such as user mobility, users going arbitrarily on- and off-line, etc.).

The works [15], [27], [28] treat this problem by providing no-regret learning algorithms for single-user rate maximization and power control in multi-carrier cognitive radio and Internet of Things networks. The extension of these works to multi-antenna systems was carried out in [44], where we derived a matrix exponential learning algorithm for dynamic power allocation and control in time-varying MIMO systems. Building on this, we also showed in [8] that regret minimization techniques can also be applied to the much more challenging problem of energy efficiency maximization in dynamic networks – i.e. the maximization of successfully received bits per Watt of transmitted power in environments that fluctuate unpredictably over time. Finally, as was shown in [39], [23], [9], these unilateral performance gains also extend to large networks comprising hundreds (or even thousands) of users: there, the proposed matrix exponential learning algorithm converges to a stable state within a few iterations, even for very large of antennas and subcarriers.

6.9. Adaptive multi-path routing

Routing plays a crucial part in the efficient operation of packet-switched data networks, especially with regard to latency reduction and energy efficiency. However, in addition to being distributed (so as to cope with the prolific size of today's networks), optimized routing schemes must also be able to adapt to changes in the underlying network (e.g. due to variations in traffic demands, link quality, etc.).

First, to address the issue of latency reduction, we provided in [32] an adaptive multi-flow routing algorithm to select end-to-end paths in packet-switched networks. The algorithm is based only on local information, so it is suitable for distributed implementation; furthermore, it provides guarantees that the network configuration converges to a stable state and exhibits several robustness properties that make it suitable for use in dynamic real-life networks (such as robustness to measurement errors, outdated information and update desynchronization).

Concerning energy efficiency, [41] examines the problem of routing in optical networks with the aim of minimizing traffic-driven power consumption. To tackle this, [41] proposed a pricing scheme which, combined with a distributed learning method based on the Boltzmann distribution of statistical mechanics, exhibits remarkable operation properties even under uncertainty. Specifically, the long-term average of the network's power consumption converges quickly to its minimum value (in practice, within a few iterations of the algorithm), and this convergence remains robust in the face of uncertainty of arbitrarily high magnitude.

6.10. Learning in finite games

One of the most widely used algorithms for learning in finite games is the so-called *best response algorithm* (BRA); nonetheless, even though sevaral worst-case bounds are known for its convergence time, the algorithm's performance in typical game-theoretic scenarios seems to be far better than these worst-case bounds suggest. In [26], [18], [25], [31], we computed the average execution time of the BR algorithm using Markov chain coupling techniques that recast the average execution time of this discrete algorithm as the solution of an ordinary differential equation. In so doing, we showed that the worst-case complexity of the BR algorithm in a potential game with N players and A actions per player is $AN(N-1)$, while its average complexity over random potential games is $O(N)$, independently of A.

In [34], we also studied the convergence rate of the HEDGE algorithm (which, contrary to the BR algorithm, leads to no regret even in adversarial settings). Motivated by applications to data networks where fast convergence is essential, we analyzed the problem of learning in generic N-person games that admit Nash equilibria in pure strategies. Despite the (unbounded) uncertainty in the players' observations, we show that hedging eliminates dominated strategies (a.s.) and, with high probability, it converges locally to pure Nash equilibria at the exponential rate $O(\exp(-c\sum_{j=1}^{t}\gamma_j))$, where γ_j is the algorithm s step size.

These results are strongly related to the long-term rationality properties (elimination of dominated strategies, convergence to pure Nash equilibria and evolutionarily stable states, etc.) of an underlying class of game dynamics based on regularization and Riemannian geometry. Specifically, in [42], we introduced a class of evolutionary game dynamics whose defining element is a state-dependent geometric structure on the set of population states. When this geometric structure satisfies a certain integrability condition, the resulting dynamics preserve many further properties of the replicator and projection dynamics and are equivalent to a class of reinforcement learning dynamics studied in [10]. Finally, as we showed in [2], these properties also hold even in the presence of noise, i.e. when the players only have noisy observations of their payoff vectors.

6.11. Learning in games with continuous action spaces

A key limitation of existing game-theoretic learning algorithms is that they invariably revolve around games with a finite number of actions per players. However, this assumption is often unrealistic (especially in network-based applications of game theory), a factor which severely limits the applicability of learning techniques in real-life problems.

To address this issue, we studied in [14] a class of control problems that can be formulated as potential games with continuous action sets, and we proposed an actor-critic reinforcement learning algorithm that provably converges to equilibrium in said class. The method employed is to analyse the learning process under study through a mean-field dynamical system that evolves in an infinite-dimensional function space (the space of probability distributions over the players' continuous controls). To do so, we extend the theory of finite-dimensional two-timescale stochastic approximation to an infinite-dimensional, Banach space setting, and we proved that the continuous dynamics of the process converge to equilibrium in the case of potential games. These results combine to give a provably-convergent learning algorithm in which players do not need to keep track of the controls selected by the other agents.

Finally, to address cases where mixing over a continuum of actions is unrealistic, we examined in [40] the convergence properties of a class of learning schemes for N-person games with continuous action spaces based on a continuous optimization technique known as "dual averaging". To study this multi-agent, pure-strategy learning process, we introduced the notion of *variational stability* (VS), and we showed that stable equilibria are locally attracting with high probability whereas globally stable states are globally attracting with probability 1. Finally, we examined the scheme's convergence speed and we showed that if the game admits a strict equilibrium and the players' mirror maps are surjective, then, with high probability, the process converges to equilibrium in a finite number of steps, no matter the level of uncertainty in the players' observations (or payoffs).

6.12. Stochastic optimization

A key feature of modern data networks is their distributed nature and the stochasticity surrounding users and their possible actions. To account for these issues in a general optimization context, we proposed in [4] a distributed, asynchronous algorithm for stochastic semidefinite programming which is a stochastic approximation of the continous-time matrix exponential scheme derived in [9]. This algorithm converges almost surely to an ϵ-approximation of an optimal solution requiring only an unbiased estimate of the gradient of the problem's stochastic objective. When applied to throughput maximization in wireless multiple-input and multiple-output (MIMO) systems, the proposed algorithm retains its convergence properties under a wide array of mobility impediments such as user update asynchronicities, random delays and/or ergodically changing channels.

More generally, in view of solving convex optimization problems with noisy gradient input, we also analyzed in [43] the asymptotic behavior of gradient-like flows that are subject to stochastic disturbances. For concreteness, we focused on the widely studied class of mirror descent methods for constrained convex programming and we examined the dynamics' convergence and concentration properties in the presence of noise. In the small noise limit, we showed that the dynamics converge to the solution set of the underlying problem with probability 1. Otherwise, in the case of persistent noise, we estimated the measure of the dynamics' long-run concentration around interior solutions and their convergence to boundary solutions that are sufficiently "robust". Finally, we showed that a rectified variant of the method with a decreasing sensitivity parameter converges irrespective of the magnitude of the noise or the structure of the underlying convex program, and we derived an explicit estimate for its rate of convergence.

6.13. Benchmarking

In modern High Performance Computing architectures, the memory subsystem is a common performance bottleneck. When optimizing an application, the developer has to study its memory access patterns and adapt accordingly the algorithms and data structures it uses. The objective is twofold: on one hand, it is necessary to avoid missuses of the memory hierarchy such as false sharing of cache lines or contention in a NUMA interconnect. On the other hand, it is essential to take advantage of the various cache levels and the memory hardware prefetcher. Still, most profiling tools focus on CPU metrics. The few of them able to provide an overview of the memory patterns involved by the execution rely on hardware instrumentation mechanisms and have two drawbacks. The first one is that they are based on sampling which precision is limited by hardware capabilities. The second one is that they trace a subset of all the memory accesses, usually the most frequent, without information ab out the other ones. In [30] we present Moca, an efficient tool for the collection of complete spatio-temporal memory traces. Moca is based on a Linux kernel module and provides a coarse grained trace of a superset of all the memory accesses performed by an application over its addressing space during the time of its execution. The overhead of Moca is reasonable when taking into account the fact that it is able to collect complete traces which are also more precise than the ones collected by comparable tools.

Benchmarking has proven to be crucial for the investigation of the behavior and performances of a system. However, the choice of relevant benchmarks still remains a challenge. To help the process of comparing and choosing among benchmarks, in [33] we propose a solution for automatic benchmark profiling. It computes unified benchmark profiles reflecting benchmarks' duration, function repartition, stability, CPU efficiency, parallelization and memory usage. It identifies the needed system information for profile computation, collects it from execution traces and produces profiles through efficient and reproducible trace analysis treatments. The paper presents the design, implementation and the evaluation of the approach.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry: Alcatel Lucent-Bell

A common laboratory between Inria and the Alcatel Lucent-Bell Labs was created in early 2008 and consists on three research groups (ADR). POLARIS leads the ADR on self-optimizing networks (SELFNET). The researchers involved in this project are Bruno Gaujal and Panayotis Mertikopoulos.

- Contract with Schneider Electric (2015–2018). Distributed optimization in electrical distribution networks. Associated to a CIFRE PhD grant (Benoît Vinot, started in 4/2015). Partners: Inria (Polaris), Schneider Electric, G2ELab.

7.2. National Initiatives

7.2.1. ANR

- *GAGA (2014–2017)*
  GAGA is an ANR starting grant (JCJC) whose aim is to explore the Geometric Aspects of GAmes. The GAGA team is spread over three different locations in France (Paris, Toulouse and Grenoble), and is coordinated by Vianney Perchet (ENS Cachan). Its aim is to perform a systematic study of the geometric aspects of game theory and, in so doing, to establish new links between application areas that so far appeared unrelated (such as the use of Hessian Riemannian optimization techniques in wireless communication networks).

- *MARMOTE (2013–2016)*
  Partners: Inria Sophia (MAESTRO), Inria Rocquencourt (DIOGEN), Université Versailles-Saint-Quentin (PRiSM lab), Telecom SudParis (SAMOVAR), Université Paris-Est Créteil (*Spécification et vérification de systèmes*), Université Pierre-et-Marie-Curie/LIP6.
  The project aims at realizing a software prototype dedicated to Markov chain modeling. It gathers seven teams that will develop advanced resolution algorithms and apply them to various domains (reliability, distributed systems, biology, physics, economy).
- *NETLEARN (2013–2017)*
  Partners: Université Versailles – Saint-Quentin (PRiSM lab), Université Paris Dauphine, Inria Grenoble (POLARIS), Institut Mines–Telecom (Telecom ParisTech), Alcatel–Lucent Bell Labs (ALBF), and Orange Labs.
  The main objective of the project is to propose a novel approach of distributed, scalable, dynamic and energy efficient algorithms for mobile network resource management. This new approach relies on the design of an orchestration mechanism of a portfolio of algorithms. The ultimate goal of the proposed mechanism is to enhance the user experience, while at the same time ensuring the more efficient utilization of the operator's resources.
- *ORACLESS (2016–2021)*
  ORACLESS is an ANR starting grant (JCJC) coordinated by Panayotis Mertikopoulos. The goal of the project is to develop highly adaptive resource allocation methods for wireless communication networks that are provably capable of adapting to unpredictable changes in the network. In particular, the project will focus on the application of online optimization and online learning methodologies to multi-antenna systems and cognitive radio networks.
- *ANR SONGS, 2012–2016*. Partners: Inria Nancy (Algorille), Inria Sophia (MASCOTTE), Inria Bordeaux (CEPAGE, HiePACS, RunTime), Inria Lyon (AVALON), University of Strasbourg, University of Nantes.

  The last decade has brought tremendous changes to the characteristics of large scale distributed computing platforms. Large grids processing terabytes of information a day and the peer-to-peer technology have become common even though understanding how to efficiently exploit such platforms still raises many challenges. As demonstrated by the USS SimGrid project funded by the ANR in 2008, simulation has proved to be a very effective approach for studying such platforms. Although even more challenging, we think the issues raised by petaflop/exaflop computers and emerging cloud infrastructures can be addressed using similar simulation methodology.

  The goal of the SONGS project (Simulation of Next Generation Systems) is to extend the applicability of the SimGrid simulation framework from grids and peer-to-peer systems to clouds and high performance computation systems. Each type of large-scale computing system will be addressed through a set of use cases and led by researchers recognized as experts in this area. Any sound study of such systems through simulations relies on the following pillars of simulation methodology: Efficient simulation kernel; Sound and validated models; Simulation analysis tools; Campaign simulation management. Such aspects are also addressed in the SONGS project.

7.2.2. National Organizations

- Jean-Marc Vincent is member of the scientific committees of the CIST (Centre International des Sciences du Territoire).
- *REAL.NET (2016)*
  REAL.NET is a CNRS PEPS starting grant (JCJC) coordinated by Panayotis Mertikopoulos. Its objective is to provide dynamic control methodologies for nonstationary stochastic optimization problems that arise in wireless communication networks.

8. Partnerships and Cooperations

8.1. European Initiatives

8.1.1. FP7 & H2020 Projects

8.1.1.1. Mont-Blanc 2

Program: FP7 Programme

Project acronym: Mont-Blanc 2

Project title: Mont-Blanc: European scalable and power efficient HPC platform based on low-power embedded technology

Duration: October 2013 - September 2016

Coordinator: BSC (Barcelone)

Other partners: BULL - Bull SAS (France), STMicroelectronics - (GNB SAS) (France), ARM - (United Kingdom), JUELICH - (Germany), BADW-LRZ - (Germany), USTUTT - (Germany), CINECA - (Italy), CNRS - (France), Inria - (France), CEA - (France), UNIVERSITY OF BRISTOL - (United Kingdom), ALLINEA SW LIM - (United Kingdom)

Abstract: Energy efficiency is already a primary concern for the design of any computer system and it is unanimously recognized that future Exascale systems will be strongly constrained by their power consumption. This is why the Mont-Blanc project has set itself the following objective: to design a new type of computer architecture capable of setting future global High Performance Computing (HPC) standards that will deliver Exascale performance while using 15 to 30 times less energy. Mont-Blanc 2 contributes to the development of extreme scale energy-efficient platforms, with potential for Exascale computing, addressing the challenges of massive parallelism, heterogeneous computing, and resiliency. Mont-Blanc 2 has great potential to create new market opportunities for successful EU technology, by placing embedded architectures in servers and HPC.

The Mont-Blanc 2 proposal has 4 objectives:
1. To complement the effort on the Mont-Blanc system software stack, with emphasis on programmer tools (debugger, performance analysis), system resiliency (from applications to architecture support), and ARM 64-bit support.
2. To produce a first definition of the Mont-Blanc Exascale architecture, exploring different alternatives for the compute node (from low-power mobile sockets to special-purpose high-end ARM chips), and its implications on the rest of the system.
3. To track the evolution of ARM-based systems, deploying small cluster systems to test new processors that were not available for the original Mont-Blanc prototype (both mobile processors and ARM server chips).
4. To provide continued support for the Mont-Blanc consortium, namely operations of the Mont-Blanc prototype, and hands-on support for our application developers

8.1.1.2. QUANTICOL

Program: The project is a member of Fundamentals of Collective Adaptive Systems (FOCAS), a FET-Proactive Initiative funded by the European Commission under FP7.

Project acronym: QUANTICOL

Project title: A Quantitative Approach to Management and Design of Collective and Adaptive Behaviours

Duration: 04 2013 – 03 2017

Coordinator: Jane Hillston (University of Edinburgh, Scotland)

Other partners: University of Edinburgh (Scotland); Istituto di Scienza e Tecnologie della Informazione (Italy); IMT Lucca (Italy) and University of Southampton (England).

Abstract: The main objective of the QUANTICOL project is the development of an innovative formal design framework that provides a specification language for collective adaptive systems (CAS) and a large variety of tool-supported, scalable analysis and verification techniques. These techniques will be based on the original combination of recent breakthroughs in stochastic process algebras and associated verification techniques, and mean field/continuous approximation and control theory. Such a design framework will provide scalable extensive support for the verification of developed models, and also enable and facilitate experimentation and discovery of new design patterns for emergent behaviour and control over spatially distributed CAS.

8.1.1.3. HPC4E

Title: HPC for Energy

Program: H2020

Duration: 01 2016 – 01 2018

Coordinator: Barcelona Supercomputing Center

Inria contact: Stephane Lanteri

Other partners:

- Europe: Lancaster University (ULANC), Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Repsol S.A. (REPSOL), Iberdrola Renovables Energía S.A. (IBR), Total S.A. (TOTAL).
- Brazil: Fundação Coordenação de Projetos, Pesquisas e Estudos Tecnoclógicos (COPPE), National Laboratory for Scientific Computation (LNCC), Instituto Tecnológico de Aeronáutica (ITA), Petroleo Brasileiro S. A. (PETROBRAS), Universidade Federal do Rio Grande do Sul (INF-UFRGS), Universidade Federal de Pernambuco (CER-UFPE)

Abstract: The main objective of the HPC4E project is to develop beyond-the-state-of-the-art high performance simulation tools that can help the energy industry to respond future energy demands and also to carbon-related environmental issues using the state-of-the-art HPC systems. The other objective is to improve the cooperation between energy industries from EU and Brazil and the cooperation between the leading research centres in EU and Brazil in HPC applied to energy industry. The project includes relevant energy industrial partners from Brazil and EU, which will benefit from the project's results. They guarantee that TRL of the project technologies will be very high. This includes sharing supercomputing infrastructures between Brazil and EU. The cross-fertilization between energy-related problems and other scientific fields will be beneficial at both sides of the Atlantic.

8.1.2. Collaborations with Major European Organizations

EPFL: Laboratoire pour les communications informatiques et leurs applications 2, Institut de systèmes de communication ISC, Ecole polytechnique fédérale de Lausanne (Switzerland). We collaborate with Jean-Yves Leboudec (EPFL) and Pierre Pinson (DTU) on electricity markets.

TU Wien: Research Group Parallel Computing, Technische Universität Wien (Austria). We collaborate with Sascha Hunold on experimental methodology and reproducibility of experiments in HPC. In particular we co-organize the REPPAR workshop on “Reproducibility in Parallel Computing”.

BSC (Barcelona): Barcelona Supercomputer Center (Spain). We collaborate with the performance evaluation group through the HPC4E project, the Mont-blanc 2 project, and the JLESC.

University of Edinburgh and Istituto di Scienza e Tecnologie della Informazione: we strongly collaborate through the Quanticol European project.

8.2. International Initiatives

8.2.1. Inria International Labs

8.2.1.1. North America

- JLESC (former JLPC) (Joint Laboratory for Extreme-Scale Computing) with University of University of Illinois Urbana Champaign, Argonne Nat. Lab and BSC. Several members of POLARIS are partners of this laboratory, and have done several visits to Urbana-Champaign or NCSA.

8.2.2. Inria Associate Teams not involved in an Inria International Labs

8.2.2.1. EXASE

Title: Exascale Computing Scheduling and Energy

International Partner (Institution - Laboratory - Researcher):

Universidade Federal do Rio Grande do Sul (Brazil) - INF (INF) - Nicolas MAILLARD

Start year: 2014

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

The main scientific goal of this collaboration for the three years is the development of state-of-the-art energy-aware scheduling algorithms for exascale systems. Three complementary research directions have been identified : (1) Fundamentals for the scaling of schedulers: develop new scheduling algorithms for extreme exascale machines and use existing workloads to validate the proposed scheduling algorithms (2) Design of schedulers for large-scale infrastructures : propose energy-aware schedulers in large-scale infrastructures and develop adaptive scheduling algorithms for exascale machines (3) Tools for the analysis of large scale schedulers : develop aggregation methodologies for scheduler analysis to propose synthetic visualizations for large traces analysis and then analyze schedulers and energy traces for correlation analysis

8.2.3. Inria International Partners

8.2.3.1. Declared Inria International Partners

- POLARIS has strong connections with both UFRGS (Porto Alegre, Brazil) and USP (Sao Paulo, Brazil). The creation of the LICIA common laboratory (see next section) has made this collaboration even tighter.
- POLARIS has strong bounds with the University of Illinois Urbana Champaign and Barcelona Supercompter Center, within the (Joint Laboratory on Petascale Computing, see previous section).

8.2.4. Participation in Other International Programs

8.2.4.1. South America

- *LICIA:* The CNRS, Inria, the Universities of Grenoble, Grenoble INP, and Universidade Federal do Rio Grande do Sul have created the LICIA (*Laboratoire International de Calcul intensif et d'Informatique Ambiante*). LICIA's main research themes are high performance computing, language processing, information representation, interfaces and visualization as well as distributed systems. Jean-Marc Vincent is the director of the laboratory on the French side and visited Porto Alegre for two weeks in November 2016.

  More information can be found at http://www.inf.ufrgs.br/licia/.
- *ECOS-Sud:* POLARIS is a member of the Franco-Chilean collaboration network LEARN with CONICYT (the Chilean national research agency), formed under the ECOS-Sud framework. The main research themes of this network is the application of continuous optimization and game-theoretic learning methods to traffic routing and congestion control in data networks. Panayotis Mertikopoulos was an invited researcher at the University of Chile in October 2016.

  More information can be found at http://www.conicyt.cl/pci/2016/02/11/programa-ecos-conicyt-adjudica-proyectos-para-el-ano-2016.

8.3. International Research Visitors

8.3.1. Visits of International Scientists

- Matthieu Jonckeere (Buenos Aires University) visited for 3 weeks.
- Mario Bravo (University of Santiago, Chile) visited POLARIS for 1 week in Feb. 2016.
- Mathias Staudigl (Maastricht University) visited POLARIS for 2 weeks in July 2016.

8.3.2. Visits to International Teams

8.3.2.1. Sabbatical programme

- Florence Perronnin spent one year in sabbatical leave (rachat de service) at the Université Versailles-Saint-Quentin (DAVID lab)

8.3.2.2. Research Stays Abroad

- Panayotis Mertikopoulos was an invited professor at the University of Athens, Athens, Greece, for four months (March–June 2016).
- Panayotis Mertikopoulos was an invited professor at LUISS Guido Carli University, Rome, Italy, for one month (Sept. 2016).

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organization

9.1.1.1. General Chair, Scientific Chair

- Panayotis Mertikopoulos was the general co-chair of the GEL 2016 international workshop on Geometry, Evolution and Learning in Games

9.1.1.2. Member of the Organizing Committees

- Nicolas Gast served as Publicity Chair for ACM Sigmetrics 2016
- Jean-Marc Vincent served in the Organization Committee of the "Decision-making and Optimization under Uncertainty" summer school for young researchers, and the joint LICIA-EXASE workshop

9.1.2. Scientific Events Selection

9.1.2.1. Chair of Conference Program Committees

Arnaud Legrand was chair of the performance evaluation track of Europar 2016.

9.1.2.2. Member of the Conference Program Committees

The members of the team regularly review numerous papers for international conferences.

- Bruno Gaujal and Nicolas Gast were members of the Technical Program Committee of ACM Sigmetrics 2016
- Nicolas Gast was a member of the Technical Program Committee of ACM E-Energy 2016.
- Panayotis Mertikopoulos was a member of the Technical Program Committee of VALUETOOLS 2016.
- E. Veronica Belmega was a member of the Technical Program Committee of IEEE Globecom 2016, IEEE ICC 2016, IEEE BlackSeaComm 2016, and IEEE WCNC 2016
- Jean-Marc Vincent was a member of the Technical Program Committees of ASMTA 2016, SimulTech 2016 and EPEW 2016
- Arnaud Legrand was a member of the Technical Program Committees of HiPC 2016, ICPP 2016, and COMPAS 2016.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- E. Veronica Belmega is an executive editor for the Transactions on Emerging Telecommunications Technologies.

9.1.3.2. Reviewer - Reviewing Activities

The members of the POLARIS team regularly review articles for JPDC, DAM, IEEE Transactions on Networking/Automatic Control/Cloud Computing/Parallel and Distributed Computing/Information Theory/Signal Processing/Wireless Communications, SIAM Journal on Optimization/Control and Optimization, and others.

9.1.4. Invited Talks

- Bruno Gaujal was a plenary speaker at ECQT 2016 (European Conference on Queuing Theory)
- Bruno Gaujal was a plenary speaker at “Journées SDA2 2016” (Groupe de Travail "Systèmes Dynamiques, Automates et Algorithmes” of the CNRS thematic group GDR Informatique Mathématique.
- Panayotis Mertikopoulos was a plenary speaker at the ADGO 2016 workshop on Algorithms and Dynamics for Games and Optimization
- Panayotis Mertikopoulos gave an invited tutorial on “*Online Optimization for Wireless Communications*” at the Orange workshop on Learning and Networks.
- Panayotis Mertikopoulos gave a two-part tutorial on “*Game Theory, Learning and Cognitive Radio*” at CROWNCOM 2016.

9.1.5. Leadership within the Scientific Community

Arnaud Legrand has organized a series of webinars on reproducible research and whose aim is to introduce the audience to one particular aspect of reproducible research and to illustrate how this aspect can be addressed with state-of-the-art tools. To this end, experts of a given topic are invited and their seminar is screencast so that researchers from other universities can easily follow it. So far, the following topics have been covered:

1. Introduction (reproducible research, challenges, ethic, ...) to reproducible research. Producing replicable articles and managing a laboratory notebook.
2. Controlling your experimental environment
3. Numerical reproducibility
4. Logging and backing up your work: a not so short introduction to git for research
5. Preserving software: ensuring availability and tracking provenance
6. Reproducible science in bioinformatics: current status, solutions and research opportunities

All the corresponding videos and materials are available at the following address: https://github.com/alegrand/RR_webinars/

9.1.6. Scientific Expertise

- E. Veronica Belmega was a member of the jury for the GRETSI–GdR ISIS thematic research group “best thesis” award
- Panayotis Mertikopoulos is a member of the steering committee (*comité de liaison*) of the optimization and decision theory group of the French Society for Industrial and Applied Mathematics (SMAI).
- Jean-Marc Vincent is a member of the scientific committees of the CIST (Centre International des Sciences du Territoire)

9.1.7. Research Administration

- Bruno Gaujal is member of the “bureau du LIG” (Laboratoire d’informatique de Grenoble)

- Bruno Gaujal is member of the “bureau du CP” of Inria Grenoble.
- Bruno Gaujal was member of the CR2 admissibility jury of Inria-Grenoble.
- Panayotis Mertikopoulos serves as the graduate students liaison (*chargé de mission doctorants*) for the Laboratoire d’Informatique de Grenoble
- Arnaud Legrand was coordinator of the Inria evaluation of the “Distributed and High Performance Computing” theme.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master: Bruno Gaujal and Nicolas Gast, *“Advanced Performance Evaluation”*, 18h (M2), ENSIMAG

Master: Guillaume Huard, *“Conception des Systèmes d’Exploitation”* (M1), Université Grenoble-Alpes

Master: Arnaud Legrand and Jean-Marc Vincent, *“Scientific Methodology and Performance Evaluation”*, 15h (22.5h) M2, M2R MOSIG

Master: Arnaud Legrand, *“Parallel Systems”*, 21h (31.5h) M2R, M2R Mosig.

Master: Arnaud Legrand, *“Scientific Methodology and Performance Evaluation”*, 24h (36h), ENS Lyon.

Master: Panayotis Mertikopoulos, *“Selected Topics in the Theory of Stochastic Processes”*, 16h M2, University of Athens, Athens, Greece

Master: Florence Perronnin, *“Simulation”*, M1, Université Versailles – Saint-Quentin

Master: Florence Perronnin, *“Probabilités–Simulation”*, RICM4 Polytech Grenoble

Master: Arnaud Legrand and Jean-Marc Vincent, Probability and simulation, performance evaluation 72 h, (M1), RICM, Polytech Grenoble.

Master: Jean-Marc Vincent, Mathematics for computer science, 18 h , (M1) Mosig.

DU: Jean-Marc Vincent, *“Informatique et sciences du numérique”*, 20 h, (Professeurs de lycée).

9.2.2. Supervision

Post-Doc: Angelika Studeny, Université Grenoble-Alpes (Jean-Marc Vincent)

PhD: David Beniamine, *“Analyse du comportement mémoire d’application paralleles de calcul scientifique”*, Université Grenoble-Alpes, 05/12/2016 (Guillaume Huard)

PhD: Joaquim Assunção, *“Fitting techniques to knowledge discovery through stochastic models”*, 08/12/2016 (Jean-Marc Vincent)

PhD in progress: Alexandre Marcastel, *“Online resource allocation in dynamic wireless networks”*, 10/2016 (Panayotis Mertikopoulos, E. V. Belmega)

PhD in progress: Stéphane Durand, *“Game theory and control in distributed systems”* (Bruno Gaujal)

PhD in progress: Stephan Plassart, *“Optimization of critical embedded systems”* (Bruno Gaujal)

PhD in progress: Baptiste Jonglez, *“Diversity exploitation in communication networks”* (Bruno Gaujal)

PhD in progress: Umar Ozeer, OrangeLabs, 12/2016 (Jean-Marc Vincent)

PhD in progress: Christian Heinrich, *“Performance Evaluation of HPC Systems Through Simulation”*, 12/2015 (Arnaud Legrand)

PhD in progress: Rafael Keller Tesser, *“Performance Evaluation of Dynamic Load Balancing for Legacy Iterative Parallel Applications*”, 12/2015 (Arnaud Legrand, Cotutelle with Philippe Navaux from UFRGS)

PhD in progress: Vinicius Garcia Pinto, *"Visual Performance Analysis of HPC applications running over Dynamic Task-based Runtimes"*, 12/2015 (Arnaud Legrand, Cotutelle with Nicolas Maillard and Lucas Schnorr from UFRGS)

9.2.2.1. Internships

- Jean-Marc Vincent supervised the eng. internship of Benjamin Briot (02–03/2016)
- Jean-Marc Vincent supervised the master internship Mathieu Baille (Magistère + TER M1)
- Guillaume Huard supervised the Licence internship of Michael Picard
- Guillaume Huard supervised the Licence internship of Loic Poncet
- Arnaud Legrand and Vincent Danjean supervised the eng. internship of Florian Popek (06–08/2016)
- Arnaud Legrand supervised the master internship of Steven Quinito Masnada (02–08/2016) in collaboration with the CORSE team (Brice Videau and Frédéric Desprez)

9.2.3. Juries

- E. Veronica Belmega was a member of the jury for the PhD defense of Kenza Hamidouche (12/2016, Supélec)
- Bruno Gaujal was a reviewer for the HDR defense of Bruno Scherrer
- Bruno Gaujal was a member of the jury for the HDR defense of Patrick Loiseau
- Arnaud Legrand was reviewer for the PhD defense of Rafife Nheili

9.3. Popularization

The POLARIS team is actively involved in various scientific popularization activities. In addition to participating in the Fête de la Science (Guillaume Huard, Florence Perronnin, Jean-Marc Vincent), the POLARIS team also participates in the organization of the "Conférence Inria". Jean-Marc Vincent has also organized (and/or participated in) several training courses for computer science teachers (at a high school level) and has supervised several MathC2+ trainees.

Jean-Marc Vincent also organized the 2-day-long atelier "Computer Science without Computers" for elementary school students; the atelier was nominated for the Shannon trophy (awarded by the Institut Henri Poincaré).

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Project-Team PRIVATICS

Privacy Models, Architectures and Tools for the Information Society

IN COLLABORATION WITH: Centre of Innovation in Telecommunications and Integration of services

IN PARTNERSHIP WITH:
Institut national des sciences appliquées de Lyon

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Security and Confidentiality

Table of contents

Project-Team PRIVATICS

Creation of the Team: 2013 January 01, updated into Project-Team: 2014 July 01

Keywords:

Computer Science and Digital Science:

1. - Architectures, systems and networks
1.1. - Architectures
1.2. - Networks
1.3. - Distributed Systems
1.4. - Ubiquitous Systems
3. - Data and knowledge
4. - Security and privacy
4.1. - Threat analysis
4.3. - Cryptography
4.8. - Privacy-enhancing technologies

Other Research Topics and Application Domains:

9. - Society and Knowledge
9.8. - Privacy
9.9. - Risk management
9.10. - Ethics

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2. Overall Objectives

2.1. Context

The promises of new technologies: Many advances in new technologies are very beneficial to the society and provide services that can drastically improve life's quality. A good example is the emergence of reality mining. Reality mining is a new discipline that infers human relationships and behaviors from information collected by cell-phones. Collected information include data collected by the sensors, such as location or physical activities, as well as data recorded by the phones themselves, such as call duration and dialed numbers. Reality mining could be used by individuals to get information about themselves, their state or performances ("quantified self"). More importantly, it could help monitoring health. For example, the motions of a mobile phone might reveal changes in gait, which could be an early indicator of ailments or depression. The emergence of location-based or mobile/wireless services is also often very beneficial. These systems provide very useful and appreciated services, and become almost essential and inevitable nowadays. For example, RFID cards allow users to open doors or pay their metro tickets. GPS systems help users to navigate and find their ways. Some services tell users where their friends are or provide services personalized to their current location (such as indicating the closest restaurant or hotel). Some wireless parking meters send users a text message when their time is running out. The development of smart grids, smart houses, or more generally smart spaces/environments, can also positively contribute to the well-being of the society. Smart-grids and smart houses attempt to minimize energy consumption by monitoring users' energy consumptions and applying adequate actions. These technologies can help reducing pollution and managing energy resources.

Privacy threats of new technologies: While the potential benefits provided by these systems are numerous, they also pose considerable privacy threats that can potentially turn new technologies into a nightmare. Most of these systems leave digital traces that can potentially be used to profile or monitor users. Content on the Internet (documents, emails, chats, images, videos etc) is often disseminated and replicated on different peers or servers. As a result, users lose the control of their content as soon as they release it. Furthermore most users are unaware of the information that is collected about them beyond requested data. It was shown that consumption data provided by smart meters to electricity providers is so accurate that it can be used to infer physical activities (e.g. when the house occupant took a shower or switched-on TV). Also, a picture taken by a user may reveal additional contextual information inferred from the background or the style of any associated text. For example, photos and videos taken with smart phones or cameras contain geo-location information. This may be considered as a potential source of information leakage and may lead to a privacy breach if used for location tracking or in conjunction with data retrieved from OSN (Online Social Networks). The risk becomes higher as the border between OSN and LBS (Location Based Services) becomes fuzzier. For instance, OSN such as FourSquare and Gowalla are designed to encourage users to share their geolocated data. Information posted on social applications such as Twitter can be used to infer whether or not an individual is at home. Other applications, such as Google Latitude, allow users to track the movements of their friends' cellphones and display their position on a map. In addition to social applications, there are other public sources of information that can be exploited by potential adversaries, such as the free geographic data provided by Google Maps, Yahoo! Maps and Google Earth. The danger is to move into a surveillance society where all our online and physical activities are recorded and correlated. Some companies already offer various services that gather different types of information from users. The combination and concentration of all these information provide a powerful tool to accurately profile users. For example, Google is one of the main third-party aggregators and tracks users across most web sites [30]. In addition, it also runs the most popular search engine and, as such, stores web histories of most users (i.e. their search requests), their map searches (i.e. their requests to the Google Map service), their images and so on [8]. Web searches have been shown to often be sensitive. Furthermore, Google is also going into the mobile and energy business, which will potentially allow it to correlate online profile with physical profiles.

The "Internet of the future" should solve these privacy problems. However, privacy is not something that occurs naturally online, it must be deliberately designed. This architecture of Privacy must be updated and reconsidered as the concept of privacy evolves and new technologies appear.

Even if our main goal is to develop general techniques with a potentially broad impact, Privatics will consider different and various concrete case studies to ensure the relevance and significance of its results. We plan to work on several case studies related to the Internet, online social networks (OSN), mobile services and smart spaces/environments (such as smart grids, smart houses,..), which correspond to challenging application domains with great impact on society.

3. Application Domains

3.1. Domain 1: Privacy in smart environments.

Privacy in smart environments. One illustrative example is our latest work on privacy-preserving smart-metering [2]. Several countries throughout the world are planning to deploy smart meters in house-holds in the very near future. Traditional electrical meters only measure total consumption on a given period of time (i.e., one month or one year). As such, they do not provide accurate information of when the energy was consumed. Smart meters, instead, monitor and report consumption in intervals of few minutes. They allow the utility provider to monitor, almost in real-time, consumption and possibly adjust generation and prices according to the demand. Billing customers by how much is consumed and at what time of day will probably change consumption habits to help matching energy consumption with production. In the longer term, with the advent of smart appliances, it is expected that the smart grid will remotely control selected appliances to reduce demand. Although smart metering might help improving energy management, it creates many new privacy problems. Smart-meters provide very accurate consumption data to electricity providers. As the interval of data collected by smart meters decreases, the ability to disaggregate low-resolution data increases. Analysing high-resolution consumption data, Non-intrusive Appliance Load Monitoring (NALM) can be used to identify a remarkable number of electric appliances (e.g., water heaters, well pumps, furnace blowers, refrigerators, and air conditioners) employing exhaustive appliance signature libraries. We developed DREAM, DiffeRentially privatE smArt Metering, a scheme that is private under the differential privacy model and therefore provides strong and provable guarantees. With our scheme, an (electricity) supplier can periodically collect data from smart-meters and derive aggregated statistics while learning only limited information about the activities of individual households. For example, a supplier cannot tell from a user's trace when he watched TV or turned on heating.

3.2. Domain 2: Big Data and Privacy

We believe that another important problem will be related to privacy issues in big data. Public datasets are used in a variety of applications spanning from genome and web usage analysis to location-based and recommendation systems. Publishing such datasets is important since they can help us analyzing and understanding interesting patterns. For example, mobility trajectories have become widely collected in recent years and have opened the possibility to improve our understanding of large-scale social networks by investigating how people exchange information, interact, and develop social interactions. With billion of handsets in use worldwide, the quantity of mobility data is gigantic. When aggregated, they can help understand complex processes, such as the spread of viruses, and build better transportation systems. While the benefits provided by these datasets are indisputable, they unfortunately pose a considerable threat to individual privacy. In fact, mobility trajectories might be used by a malicious attacker to discover potential sensitive information about a user, such as his habits, religion or relationships. Because privacy is so important to people, companies and researchers are reluctant to publish datasets by fear of being held responsible for potential privacy breaches. As a result, only very few of them are actually released and available. This limits our ability to analyze such data to derive information that could benefit the general public. It is now an urgent need to develop Privacy-Preserving Data Analytics (PPDA) systems that collect and transform raw data into a version that is immunized against privacy attacks but that still preserves useful information for data analysis. This is one of the objectives of Privatics. There exists two classes of PPDA according to whether the entity that is collecting and anonymizing the data is trusted or not. In the trusted model, that we refer to as Privacy-Preserving Data Publishing (PPDP), individuals trust the publisher to which they disclose their data. In the untrusted model, that we refer to as Privacy-Preserving Data Collection (PPDC), individuals do not trust the data publisher. They may add some noise to their data to protect sensitive information from the data publisher.

Privacy-Preserving Data Publishing: In the trusted model, individuals trust the data publisher and disclose all their data to it. For example, in a medical scenario, patients give their true information to hospitals to receive proper treatment. It is then the responsibility of the data publisher to protect privacy of the individuals' personal data. To prevent potential data leakage, datasets must be sanitized before possible release. Several proposals have been recently proposed to release private data under the Differential Privacy model [25, 56, 26, 57, 50]. However most of these schemes release a "snapshot" of the datasets at a given period of time. This release often consists of histograms. They can, for example, show the distributions of some pathologies (such as cancer, flu, HIV, hepatitis, etc.) in a given population. For many analytics applications, "snapshots" of data are not enough, and sequential data are required. Furthermore, current work focusses on rather simple data structures, such as numerical data. Release of more complex data, such as graphs, are often also very useful. For example, recommendation systems need the sequences of visited websites or bought items. They also need to analyse people connection graphs to identify the best products to recommend. Network trace analytics also rely on sequences of events to detect anomalies or intrusions. Similarly, traffic analytics applications typically need sequences of visited places of each user. In fact, it is often essential for these applications to know that user A moved from position 1 to position 2, or at least to learn the probability of a move from position 1 to position 2. Histograms would typically represent the number of users in position 1 and position 2, but would not provide the number of users that moved from position 1 to position 2. Due to the inherent sequentiality and high-dimensionality of sequential data, one major challenge of applying current data sanitization solutions on sequential data comes from the uniqueness of sequences (e.g., very few sequences are identical). This fact makes existing techniques result in poor utility. Schemes to privately release data with complex data structures, such as sequential, relational and graph data, are required. This is one the goals of Privatics. In our current work, we address this challenge by employing a variable-length n-gram model, which extracts the essential information of a sequential database in terms of a set of variable-length n - grams [15]. We then intend to extend this approach to more complex data structures.

Privacy-Preserving Data Collection: In the untrusted model, individuals do not trust their data publisher. For example, websites commonly use third party web analytics services, such as Google Analytics to obtain aggregate traffic statistics such as most visited pages, visitors' countries, etc. Similarly, other applications, such as smart metering or targeted advertising applications, are also tracking users in order to derive aggregated information about a particular class of users. Unfortunately, to obtain this aggregate information, services need to track users, resulting in a violation of user privacy. One of our goals is to develop Privacy-Preserving Data Collection solutions. We propose to study whether it is possible to provide efficient collection/aggregation solutions without tracking users, i.e. without getting or learning individual contributions.

4. Highlights of the Year

4.1. Highlights of the Year

In 2014, Jagdish Prasad Achara, Mathieu Cunche and Vincent Roca published with Aurelien Francillon from Eurecom a study on the Wi-Fi permissions used by mobile applications and their privacy implications. Two years after our research was published, the Federal Trade Commission (FTC) reached a $950,000 settlement with InMobi for tracking millions of consumers' locations, including children, without their knowledge. The FTC allege that InMobi abused the WiFi State information on the Android system to track the location of people without their consent, which is exactly what we showed in our research. Its policy prevents the FTC of releasing the sources of its investigations, therefore there is no way to affirm that our research triggered this investigation or was used during this investigation. We can only be sure that we identified a privacy issue that was serious enough to justify an investigation of the FTC and a penalty of $950,000. In addition to this, the company is under surveillance for their privacy behaviour for the next 20 years.

4.1.1. Awards

The software `MyTrackingChoices` designed by Claude Castellucia and Jagdish Prasad Achara from Privatics in collaboration with Javier Parra (former member of Privatics and now at Universitat Politecnica de Catalunya) was awarded 'Data protection by design' award by the Catalan Data Protection Authority.

5. New Software and Platforms

5.1. FECFRAME

FEC Framework following RFC 6363 specifications (https://datatracker.ietf.org/doc/rfc6363/)
KEYWORDS: Error Correction Code - Content delivery protocol - Robust transmission
FUNCTIONAL DESCRIPTION

This sofware implements the FECFRAME IETF standard (RFC 6363) co-authored by V. ROCA, and is compliant with 3GPP specifications for mobile terminals. It enables the simultaneous transmission of multimedia flows to one or several destinations, while being robust to packet erasures that happen on wireless networks (e.g., 4G or Wifi). This software relies on the OpenFEC library (the open-source http://openfec.org version or the commercial version) that provides the erasure correction codes (or FEC) and thereby offer robustness in front of packet erasures.

- Author: Vincent Roca
- Contact: Vincent Roca
- URL: http://openfec.org/

5.2. Mobilitics

FUNCTIONAL DESCRIPTION

Mobilitics is a joint project, started in 2012 between Inria and CNIL, which targets privacy issues on smartphones. The goal is to analyze the behavior of smartphones applications and their operating system regarding users private data, that is, the time they are accessed or sent to third party companies usually neither with user's awareness nor consent.

In the presence of a wide range of different smartphones available in terms of operating systems and hardware architecture, Mobilitics project focuses actually its study on the two mostly used mobile platforms, IOS (Iphone) and Android. Both versions of the Mobilitics software: (1) capture any access to private data, any modification (e.g., ciphering or hashing of private data), or transmission of data to remote locations on the Internet, (2) store these events in a local database on the phone for offline analysis, and (3) provide the ability to perform an in depth database analysis in order to identify personnal information leakage.

- Authors: Jagdish Achara, James-Douglass Lefruit, Claude Castelluccia, Vincent Roca, Gwendal Le Grand, Geoffrey Delcroix, Franck Baudot and Stéphane Petitcolas
- Contact: Claude Castelluccia
- URL: https://team.inria.fr/privatics/mobilitics/

5.3. MyTrackingChoices

KEYWORDS: Privacy - User control

FUNCTIONAL DESCRIPTION

This extension lets you control how you are being tracked on the Internet. It allows you to choose the categories (e.g., health, adult) of the websites where you don't want to be tracked on. When you browse the web, your visited webpages will be categorized on the fly and, depending on your choices, the extension will block the trackers (webpage by webpage) or not.

Existing anti-tracking (Ghostery, Disconnect etc.) and ad-blocking (AdBlock Plus etc.) tools block almost ALL trackers and as a result, ads. This has a negative impact on the Internet economy because free services/content on the Internet are fuelled by ads. As a result, websites are starting to block access to their content if they detect use of Ad-blockers or they ask users to move to a subscription-based model (where users have to pay to get access to the website).

This extension is testing another approach: It is trying to find a trade-off between privacy and economy, that would allow users to protect their privacy while still accessing to free content.

It is based on the assumption that most people are not against advertisements, but want to keep control over their data. We believe that some sites are more sensitive than others. In fact, most people don't want to be tracked on "sensitive" websites (for example related to religion, health,...), but don't see any problem to be tracked on less sensitive ones (such as news, sport,...). This extension allows you to take control and specify which on which categories of sites you don't want to be tracked on! Furthermore, the extension also gives you the option to block the trackers on specific websites.

- Contact: Claude Castelluccia
- URL: https://addons.mozilla.org/FR/firefox/addon/mytrackingchoices/

5.4. OMEN+

FUNCTIONAL DESCRIPTION

Omen+ is a password cracker following our previous work. It is used to guess possible passwords based on specific information about the target. It can also be used to check the strength of user password by effectively looking at the similarity of that password with both usual structures and information relative to the user, such as his name, birth date...

It is based on a Markov analysis of known passwords to build guesses. The previous work Omen needs to be cleaned in order to be scaled to real problems and to be distributed or transfered to the security community (maintainability): eventually it will become an open source software. The main challenge of Omen+ is to optimize the memory consumption.

- Participants: Pierre Rouveyrol and Claude Castelluccia
- Contact: Claude Castelluccia

5.5. OPENFEC

FUNCTIONAL DESCRIPTION

OpenFEC is an open-source C-language implementation of several Application-Level Forward Erasure Correction (AL-FEC) codecs, namely: 2D-parity, Reed-Solomon (RFC 5510) and LDPC-Staircase (RFC 5170) codes. The OpenFEC project also provides a complete performance evaluation tool-set, capable of automatically assessing the performance of various codecs, both in terms of erasure recovery and encoding/decoding speed or memory consumption.

- Participants: Mathieu Cunche, Jonathan Detchart, Julien Laboure, Christophe Neumann, Vincent Roca, Jérome Lacan and Kevin Chaumont
- Contact: Vincent Roca
- URL: http://openfec.org/

6. New Results

6.1. MobileAppScrutinator: A Simple yet Efficient Dynamic Analysis Approach for Detecting Privacy Leaks across Mobile OSs

Participants: Jagdish Achara, Vincent Roca, Claude Castelluccia.

Smartphones, the devices we carry everywhere with us, are being heavily tracked and have undoubtedly become a major threat to our privacy. As " Tracking the trackers " has become a necessity, various static and dynamic analysis tools have been developed in the past. However, today, we still lack suitable tools to detect, measure and compare the ongoing tracking across mobile OSs. To this end, we propose MobileAppScrutinator [24], based on a simple yet efficient dynamic analysis approach, that works on both Android and iOS (the two most popular OSs today). To demonstrate the current trend in tracking, we select 140 most representative Apps available on both Android and iOS AppStores and test them with MobileAppScrutinator. In fact, choosing the same set of apps on both Android and iOS also enables us to compare the ongoing tracking on these two OSs. Finally, we also discuss the effectiveness of privacy safeguards available on Android and iOS. We show that neither Android nor iOS privacy safeguards in their present state are completely satisfying.

6.2. MyTrackingChoices: Pacifying the Ad-Block War by Enforcing User Privacy Preferences

Participants: Jagdish Achara, Claude Castelluccia.

Free content and services on the Web are often supported by ads. However, with the proliferation of intrusive and privacy-invasive ads, a significant proportion of users have started to use ad blockers. As existing ad blockers are radical (they block all ads) and are not designed taking into account their economic impact, ad-based economic model of the Web is in danger today. In this paper, we target privacy-sensitive users and provide them with fine-grained control over tracking. Our working assumption is that some categories of web pages (for example, related to health, religion, etc.) are more privacy-sensitive to users than others (education, science, etc.). Therefore, our proposed approach consists in providing users with an option to specify the categories of web pages that are privacy-sensitive to them and block trackers present on such web pages only. As tracking is prevented by blocking network connections of third-party domains, we avoid not only tracking but also third-party ads. Since users will continue receiving ads on web pages belonging to non-sensitive categories, our approach essentially provides a trade-off between privacy and economy. To test the viability of our solution, we implemented it as a Google Chrome extension, named MyTrackingChoices (available on Chrome Web Store). Our real-world experiments with MyTrackingChoices [23] show that the economic impact of ad blocking exerted by privacy-sensitive users can be significantly reduced.

6.3. Security or privacy?

Participants: Amrit Kumar, Cédric Lauradoux.

Security softwares such as anti-viruses, IDS or filters help Internet users to protect their privacy from hackers. The cost of this protection is that the users privacy is stripped away by the companies providing these security solutions. Currently, Internet users can choose between no security with the risk of being hacked or use security software and lose all personal data to security companies. As a example of this dilemma, we analyze the solution proposed by Google and Yandex for Safe Browsing [8] and shows that their privacy policies do not match the reality: Google can perform tracking.

6.4. Near-Optimal Fingerprinting with Constraints

Participants: Gabor Gulyas, Gergely Acs, Claude Castelluccia.

Several recent studies have demonstrated that people show large behavioural uniqueness. This has serious privacy implications as most individuals become increasingly re-identifiable in large datasets or can be tracked while they are browsing the web using only a couple of their attributes, called as their fingerprints. Often, the success of these attacks depend on explicit constraints on the number of attributes learnable about individuals, i.e., the size of their fingerprints. These constraints can be budget as well as technical constraints imposed by the data holder. For instance, Apple restricts the number of applications that can be called by another application on iOS in order to mitigate the potential privacy threats of leaking the list of installed applications on a device. In [15], we address the problem of identifying the attributes (e.g., smartphone applications) that can serve as a fingerprint of users given constraints on the size of the fingerprint. We give the best fingerprinting algorithms in general, and evaluate their effectiveness on several real-world datasets. Our results show that current privacy guards limiting the number of attributes that can be queried about individuals is insufficient to mitigate their potential privacy risks in many practical cases.

6.5. Data anonymization Evaluation

Participants: Claude Castelluccia, Gergely Acs, Daniel Le Metayer.

Anonymization is a critical issue because data protection regulations such as the European Directive 95/46/EC and the European General Data Protection Regulation (GDPR) explicitly exclude from their scope anonymous information" and personal data rendered anonymous"1. However, turning this general statement into effective criteria is not an easy task. In order to facilitate the implementation of this provision, the Working Party 29 (WP29) has published in April 2014 an Opinion on Anonymization Techniques. This Opinion puts forward three criteria corresponding to three risks called respectively "singling out", "linkability" and "inference". In this work, we first evaluated these criteria and showed that they are neither necessary nor effective to decide upon the robustness of an anonymization algorithm. Then we proposed an alternative approach relying on the notions of acceptable versus unacceptable inferences in [4] and we introduced differential testing, a practical way to implement this approach using machine learning techniques.

6.6. Wi-Fi and privacy

Participants: Mathieu Cunche, Celestin Matte.

- **Geolocation spoofing attack** We present several novel techniques to track (unassociated) mobile devices by abusing features of the Wi-Fi standard. This shows that using random MAC addresses, on its own, does not guarantee privacy. First, we show that information elements in probe requests can be used to fingerprint devices. We then combine these fingerprints with incremental sequence numbers, to create a tracking algorithm that does not rely on unique identifiers such as MAC addresses. Based on real-world datasets, we demonstrate that our algorithm can correctly track as much as 50% of devices for at least 20 minutes. We also show that commodity Wi-Fi devices use predictable scrambler seeds. These can be used to improve the performance of our tracking algorithm. Finally, we present two attacks that reveal the real MAC address of a device, even if MAC address randomization is used. In the first one, we create fake hotspots to induce clients to connect using their real MAC address. The second technique relies on the new 802.11u standard, commonly referred to as Hotspot 2.0, where we show that Linux and Windows send Access Network Query Protocol (ANQP) requests using their real MAC address.

- **Extraction of semantical information from Wi-Fi network identifiers** MAC address randomization in Wi-Fi-enabled devices has recently been adopted to prevent passive tracking of mobile devices. However, Wi-Fi frames still contain fields that can be used to fingerprint devices and potentially allow tracking. Panoptiphone is a tool inspired by the web browser fingerprinting tool Panopticlick, which aims to show the identifying information that can be found in the frames broadcast by a Wi-Fi-enabled device. Information is passively collected from devices that have their Wi-Fi interface enabled, even if they are not connected to an access point. Panoptiphone uses this information to create a fingerprint of the device and empirically evaluate its uniqueness among a database of fingerprints. The user is then shown how much identifying information its device is leaking through Wi-Fi and how unique it is.

6.7. Formal and legal issues of privacy

Participant: Daniel Le Metayer.

- **Privacy by design** Based on our previous work on the use of formal methods to reason about privacy properties of system architectures, we have proposed a logic to reason about properties of architectures including group authentication functionalities. By group authentication, we mean that a user can authenticate on behalf of a group of users, thereby keeping a form of anonymity within this set. Then we show that this extended framework can be used to reason about privacy properties of a biometric system in which users are authenticated through the use of group signatures.
- **Privacy Risk Analysis** Privacy Impact Assessments (PIA) are recognized as a key step to enhance privacy protection in new IT products and services. They will be required for certain types of products in Europe when the future General Data Protection Regulation becomes effective. From a technical perspective, the core of a PIA is a privacy risk analysis (PRA), which has so far received relatively less attention than organizational and legal aspects of PIAs. We have proposed a rigorous and systematic methodology for conducting a PRA and illustrated it with a quantified-self use-case.

  The smart grid initiative promises better home energy management. However, there is a growing concern that utility providers collect, through smart meters, highly granular energy consumption data that can reveal a lot about the consumer's personal life. This exposes consumers to a large number of privacy harms, of various degrees of severity and likelihood: surveillance by the government and law-enforcement bodies, various forms of discrimination etc. A privacy impact assessment is vital for early identification of potential privacy breaches caused by an IT product or service and for choosing the most appropriate protection measures. So, a data protection impact assessment (DPIA) template for smart grids has been developed by the Expert Group 2 (EG2) of the European Commission's Smart Grid Task Force (SGTF). To carry out a true privacy risk analysis and go beyond a traditional security analysis, it is essential to distinguish the notions of feared events and their impacts, called "privacy harms" here, and to establish a link between them. The Working Party 29 highlights the importance of this link in its feedback on EG2's DPIA. We have provided in [11] a clear relationship among harms, feared events, privacy weaknesses and risk sources and described their use in the analysis of smart grid systems.

  Although both privacy by design and privacy risk analysis have received the attention of researchers and privacy practitioners during the last decade, to the best of our knowledge, no method has been documented yet to establish a clear connection between these two closely related notions. We have proposed a methodology to help designers select suitable architectures based on an incremental privacy risk analysis. The analysis proceeds in three broad phases: 1) a generic privacy risk analysis phase depending only on the specifications of the system and yielding generic harm trees; 2) an architecture-based privacy risk analysis that takes into account the definitions of the possible architectures of the system and yields architecture-specific harm trees by refining the generic harm trees and 3) a context-based privacy risk analysis that takes into account the context of deployment of the system (e.g., a casino, an office cafeteria, a school) and further refines the architecture-specific harm trees to yield context-specific harm trees which can be used to take decisions about the most suitable architectures. To illustrate our approach, we have considered the design of a biometric access control system. Such systems are now used commonly in many contexts such as border security controls, work premises, casinos, airports, chemical plants, hospitals, schools, etc. However, the collection, storage and processing of biometric data raise complex privacy issues. To deal with these privacy problems in biometric access control, a wide array of dedicated techniques (such as secure sketches or fuzzy vaults) as well as adaptations of general privacy preserving techniques (such as encryption, homomorphic encryption, secure multi-party computation) have been proposed. However, each technique solves specific privacy problems and is suitable in specific contexts. Therefore, it is useful to provide guidance to system designers and help them select a solution and justify it with respect to privacy risks. We have used as an illustration of context a deployment in casinos. The verification of the identities of casino customers is required by certain laws (to prevent access by minors or individuals on blacklists) which can justify the implementation of a biometric access control system to speed up the verification process.

6.8. Building blocks

Participants: Marine Minier, Vincent Roca.

- **Symmetric cryptography**

  In [7], we introduce Constraint Programming (CP) models to solve a cryptanalytic problem: the chosen key differential attack against the standard block cipher AES. The problem is solved in two steps: In Step 1, bytes are abstracted by binary values; In Step 2, byte values are searched. We introduce two CP models for Step 1: Model 1 is derived from AES rules in a straightforward way; Model 2 contains new constraints that remove invalid solutions filtered out in Step 2. We also introduce a CP model for Step 2. We evaluate scale-up properties of two classical CP solvers (Gecode and Choco) and a hybrid SAT/CP solver (Chuffed). We show that Model 2 is much more efficient than Model 1, and that Chuffed is faster than Choco which is faster than Gecode on the hardest instances of this problem. Furthermore, we prove that a solution claimed to be optimal in two recent cryptanalysis papers is not optimal by providing a better solution.

  Using dedicated hardware is common practice in order to accelerate cryptographic operations: complex operations are managed by a dedicated co-processor and RAM/crypto-engine data transfers are fully managed by DMA operations. The CPU is therefore free for other tasks, which is vital in embedded environments with limited CPU power. In this work we discuss and benchmark XTS-AES, using either software or mixed approaches, using Linux and dm-crypt, and a low-power At-mel(tm) board. This board featurs an AES crypto-engine that supports ECB-AES but not the XTS-AES mode. We show that the `dm-crypt` module used in Linux for full disk encryption has limitations that can be relaxed when considering larger block sizes. In particular we demonstrate in [14] that performance gains almost by a factor two are possible, which opens new opportunities for future use-cases.

6.9. Other results

Participants: Mathieu Cunche, Vincent Roca.

- **Error-correcting codes**

  Recent work have shown that Reed-Muller (RM) codes achieve the erasure channel capacity. However, this performance is obtained with maximum-likelihood decoding which can be costly for practical applications. In [12], we propose an encoding/decoding scheme for Reed-Muller codes on the packet erasure channel based on Plotkin construction. We present several improvements over the generic decoding. They allow, for a light cost, to compete with maximum-likelihood decoding performance, especially on high-rate codes, while significantly outperforming it in terms of speed.

In [3], we provide fundamentals in the design and analysis of Generalized Low Density Parity Check (GLDPC)-Staircase codes over the erasure channel. These codes are constructed by extending an LDPC-Staircase code (base code) using Reed Solomon (RS) codes (outer codes) in order to benefit from more powerful decoders. The GLDPC-Staircase coding scheme adds, in addition to the LDPC-Staircase repair symbols, extra-repair symbols that can be produced on demand and in large quantities, which provides small rate capabilities. Therefore, these codes are extremely flexible as they can be tuned to behave either like predefined rate LDPC-Staircase codes at one extreme, or like a single RS code at another extreme, or like small rate codes. Concerning the code design, we show that RS codes with " quasi " Hankel matrix-based construction fulfill the desired structure properties, and that a hybrid (IT/RS/ML) decoding is feasible that achieves Maximum Likelihood (ML) correction capabilities at a lower complexity. Concerning performance analysis, we detail an asymptotic analysis method based on Density evolution (DE), EXtrinsic Information Transfer (EXIT) and the area theorem. Based on several asymptotic and finite length results, after selecting the optimal internal parameters, we demonstrate that GLDPC-Staircase codes feature excellent erasure recovery capabilities, close to that of ideal codes, both with large and very small objects. From this point of view they outperform LDPC-Staircase and Raptor codes, and achieve correction capabilities close to those of RaptorQ codes. Therefore all these results make GLDPC-Staircase codes a universal Application-Layer FEC (AL-FEC) solution for many situations that require erasure protection such as media streaming or file multicast transmission.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. IPSec with pre-shared key for MISTIC security

Title: IPSec with pre-shared key for MISTIC security.

Type: CIFRE.

Duration: Juillet 2014 - Juillet 2017.

Coordinator: Inria

Others partners: Privatics, Moais and Incas-ITSec.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. FUI

8.1.1.1. HuMa

Title: HuMa.

Type: FUI.

Duration: Juin 2015 - Mai 2018.

Coordinator: INTRINSEC.

Others partners: Inria, SYDO, Wallix, INSA Lyon, CASSIDIAN Cybersecurity, Oberthur, INTRINSEC.

Abstract:

The goal of huMa is to improve the tools used to distinguish legitimate network flows from attacks in complex systems including IoT.

8.1.2. ANR

8.1.2.1. BIOPRIV

Title: Application of privacy by design to biometric access control.

Type: ANR.

Duration: April 2013 - March 2017.

Coordinator: Morpho (France).

Others partners: Morpho (France), Inria (France), Trusted Labs (France).

See also: http://planete.inrialpes.fr/biopriv/.

Abstract: The objective of BIOPRIV is the definition of a framework for privacy by design suitable for the use of biometric technologies. The case study of the project is biometric access control. The project will follow a multidisciplinary approach considering the theoretical and technical aspects of privacy by design but also the legal framework for the use of biometrics and the evaluation of the privacy of the solutions.

8.1.3. Inria Project Labs

8.1.3.1. CAPPRIS

Title: CAPPRIS

Type: Inria Project Lab

Duration: January 2011 - 2016.

Coordinator: PRIVATICS

Others partners: Inria (CIDRE, Comete, Secsi,Smis), Eurecom, LAAS and CRIDS

Abstract: Cappris (Collaborative Action on the Protection of Privacy Rights in the Information Society) is an Inria Project Lab initiated in 2013. The general goal of Cappris is to foster the collaboration between research groups involved in privacy in France and the interaction between the computer science, law and social sciences communities in this area.

8.1.4. Inria CNIL project

8.1.4.1. MOBILITICS

Title: MOBILITICS

Type: joint project.

Duration: January 2012 - Ongoing.

Coordinator: CNIL.

Others partners: CNIL.

Abstract: Platform for mobile devices privacy evaluation. This project strives to deploy an experimental mobile platform for studying and analyzing the weaknesses of current online (smartphone) applications and operating systems and the privacy implications for end-users. For instance, one of the objectives is to understand trends and patterns collected when they are aimed at obtaining general knowledge that does not pertain to any specific individual. Examples of such tasks include learning of commuting patterns, inference of recommendation rules, and creation of advertising segments.

8.2. European Initiatives

8.2.1. Collaborations in European Programs, ANR Chistera

8.2.1.1. COPES

Title: COnsumer-centric Privacy in smart Energy gridS

Programm: CHISTERA

Duration: December 2015 - december 2018

Coordinator: KTH Royal Institute of Technology

Inria contact: Cédric Lauradoux

Smart meters have the capability to measure and record consumption data at a high time resolution and communicate such data to the energy provider. This provides the opportunity to better monitor and control the power grid and to enable demand response at the residential level. This not only improves the reliability of grid operations but also constitutes a key enabler to integrate variable renewable generation, such as wind or solar. However, the communication of high resolution consumption data also poses privacy risks as such data allows the utility, or a third party, to derive detailed information about consumer behavior. Hence, the main research objective of COPES is to develop new technologies to protect consumer privacy, while not sacrificing the ”smartness”, i.e., advanced control and monitoring functionalities. The core idea is to overlay the original consumption pattern with additional physical consumption or generation, thereby hiding the consumer privacy sensitive consumption. The means to achieve this include the usage of storage, small scale distributed generation and/or elastic energy consumptions. Hence, COPES proposes and develops a radically new approach to alter the physical energy flow, instead of purely relying on encryption of meter readings, which provides protection against third party intruders but does not prevent the use of this data by the energy provider.

8.2.1.2. UPRISE-IoT

Title: User-centric PRIvacy & Security in IoT

Programm: CHISTERA

Duration: December 2016 - december 2019

Coordinator: SUPSI (Suisse)

Inria contact: Claude Castelluccia

The call states that “Traditional protection techniques are insufficient to guarantee users’ security and privacy within the future unlimited interconnection”: UPRISE-IoT will firstly identify the threats and model the behaviours in IoT world, and further will build new privacy mechanisms centred around the user. Further, as identified by the call “all aspects of security and privacy of the user data must be under the control of their original owner by means of as simple and efficient technical solutions as possible”, UPRISE-IoT will rise the awareness of data privacy to the users. Finally, it will deeply develop transparency mechanisms to “guarantee both technically and regulatory the neutrality of the future internet.” as requested by the call. The U-HIDE solution developed inn UPRISE-IoT will “empower them to understand and make their own decisions regarding their data, which is essential in gaining informed consent and in ensuring the take-up of IoT technologies”, using a methodology that includes “co-design with users to address the key, fundamental, but inter-related and interdisciplinary aspects of privacy, security and trust.”

8.3. Regional Initiatives

8.3.1. ACDC

Title: ACDC

Type: AGIR 2016 Pole MSTIC.

Duration: September 2016 - 2017.

Coordinator: Inria.

Others partners: UGA.

Abstract: The objective of this project is to evaluate the security and privacy impacts of drone. The project targets 2 milestones: the evaluation of the possiblity to tamper with the drone control/command systems and the capacity of drone to collect private information (for instance text recognition).

8.3.2. AMNECYS

- Title: AMNECYS
- Duration: 2015 - .
- Coordinator: CESICE, UPMF.
- Others partners: Inria/Privatics and LIG/Moais, Gipsa-lab, LJK, Institut Fourier, TIMA, Vérimag, LISTIC (Pole MSTIC) .
- Abstract: Privatics participates to the creation of an Alpine Multidisciplinary NEtwork on CYbersecurity Studies (AMNECYS). The academic teams and laboratories participating in this project have already developed great expertise on encryption technologies, vulnerabilities analysis, software engineering, protection of privacy and personal data, international & European aspects of cybersecurity. The first project proposal (ALPEPIC ALPs-Embedded security: Protecting Iot & Critical infrastructure) focuses on the protection of the Internet of Things (IoT) and Critical Infrastructure (CI).

8.4. International Research Visitors

8.4.1. Visits of International Scientists

Lucas Melis

Gergely Acs

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. Member of the Organizing Committees

Daniel Le Metayer: CPDP 2016 (panel chairman), Privacy protection, new technical and legal instruments (Colloque Inria CAPPRIS).

Cédric Lauradoux: Nombre et cryptographie, maison pour la science Alpes Dauphiné

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

Cédric Lauradoux: RESSI 2016 and ATC 2016.

Daniel Le Metayer: Infer 2016, STM 2016, Annual Privacy Forum 2016, IWPE 2016, CPDP 2016 and WETICE-FISA.

Marine Minier: MyCrypt 2016 and RESSI 2016.

Vincent Roca: GreHack 2016, SPACOMM 2016 and VTC2016-Spring.

Mathieu Cunche: APVP 2016, HotPlanet 2016, ICISSP 2017 and IEEE TrustCom 2016.

Claude Casteluccia: Wisec 2016, DTL 2016, AFP 2016, UEOP'16 and DAT'2016.

9.1.3. Invited Talks

Daniel Le Metayer: IFIP SEC 2016 and France Stratégie, Algorithms: transparency and responsibility panel.

Claude Casteluccia: LIG Keynote.

9.1.4. Leadership within the Scientific Community

Vincent Roca: co-chair of the research group NWCRG (Network Coding Research Group) of IRTF (Internet Research Task Force)

Daniel Le Metayer: member of the scientific committee of the CNIL-Inria Privacy Award

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Undergraduate course : Vincent Roca, *On Wireless Communications*, 12h, L1, Polytech' Grenoble, France.

Undergraduate course : Vincent Roca, *On Network Communications*, 44h, L1, IUT-2 (UPMF University) Grenoble, France.

Undergraduate course : Marine Minier, *Probabilities*, 80h, L3, INSA-Lyon, France.

Undergraduate course : Marine Minier, *Signal Processing*, 20h, L3, INSA-Lyon, France.

Undergraduate course : Marine Minier, *Analysis*, 20h, L3, INSA-Lyon, France.

Undergraduate course : Marine Minier, *Introduction to Cryptography*, 10h, L3, INSA-Lyon, France.

Undergraduate course : Marine Minier, *Information Theory*, 10h, L3, INSA-Lyon, France.

Undergraduate course : Marine Minier, *Computer Architecture*, 20h, L3, INSA-Lyon, France.

Undergraduate course : Marine Minier, *Computer Security*, 20h, L3,IUT-Lyon, France.

Undergraduate course : Mathieu Cunche, *Introduction to computer science*, 120h, L1, INSA-Lyon, France.

Master : Mathieu Cunche, *Wireless Security*, 6h, M2, INSA-Lyon, France.

Undergraduate course : Mathieu Cunche, *On Wireless Network Security*, 10h, L1, IUT-2 (UPMF - Grenoble University) , France.

Undergraduate course : Mathieu Cunche, *Advanced Topics in Security*, 20h, L3, ENSIMAG, France.

Undergraduate course : Mathieu Cunche, *Security & Privacy*, 21h, L3, INSA-Lyon, France.

Undergraduate course : Daniel Le Métayer, *Security & Privacy*, 17h, L3, INSA-Lyon, France.

Undergraduate course : Daniel Le Métayer, *Privacy*, 12h, L3, INSA-Lyon, France.

Master : Cédric Lauradoux, *Introduction to Cryptology*, 30h, M1, University of Grenoble Alpes, France.

Master : Cédric Lauradoux, *Internet Security*, M2, University of Grenoble Alpes, France.

Master : Claude Castelluccia, *Advanced Topics in Security*, 20h, M2, Ensimag/University of Grenoble Alpes, France.

Master : Claude Castelluccia, *Advanced Topics in Security*, 15h, M2, Ensimag/INPG, France.

Master : Claude Castelluccia, *Security & Privacy*, 18h, Master MOSIG, University of Grenoble Alpes, France.

Master : Claude Castelluccia, *Privacy*, 4h, M2, College de droit University of Grenoble Alpes, France.

Master : Marine Minier, *Security for wireless networks*, 20h, M2, INSA-Lyon, France.

Master : Mathieu Cunche, *Wireless Security*, 6h, M2, INSA-Lyon, France.

Master : Daniel Le Métayer, *Privacy*, 6h, M2 MASH, Université Paris Dauphine, France.

9.2.2. Supervision

PhD defended : Jagdish Achara, *Unveiling and Controlling Online Tracking*, Claude Castelluccia and Vincent Roca.

PhD defended : Amrit Kumar, *Security and Privacy of Hash-Based Software Applications* , Cedric Lauradoux.

PhD in progress : Victor Morel, *IoT privacy* , September 2016, Daniel Le Métayer.

PhD in progress : Jessye Dos Santos, *Wireless physical tracking*, October 2013, Cédric Lauradoux and Claude Castelluccia.

PhD in progress : Célestin Matte, *Système d'observation des flux humains via Wi-Fi respectueux de la vie privée*, October 2014, Marine Minier et Mathieu Cunche.

Intern (M2): Alessandro Tedesco, *The rise of Internet of things made possible the large-scale collection of personal data and metadata*, Claude Castelluccia

Intern (M2): Jose-Paul Domingez, *The geopolitics of Internet protocols*, Claude Castelluccia

Intern (M2): Zoltan Kovac, *MyRealOnlineChoices*, Claude Castelluccia

Intern (M1): Margaux Canet Sola, *decompression bombs*, Cédric Lauradoux

Intern (M1): Julie Catania, Fuzzing the `zlib`, Cédric Lauradoux

Intern (M1): Aurelien Monnet Paquet, *Anti-virus DOS attacks*, Amrit Kumar

Intern (M1): Mary-Andrea Rakotomanga, *Compression quines*, Cédric Lauradoux

9.2.3. Juries

PhD: Yagdish Achara, *Unveiling and Controlling Online Tracking*, 18/10/2016, Claude Castelluccia and Vincent Roca.

PhD: Amrit Kumar, *Security and Privacy of Hash-Based Software Applications*, Université de Grenoble, Nantes, 18/10/2016, Cédric Lauradoux.

PhD : Tarek Sayah, *Exposition seélective et probleème de fuite d'inférence dans le Linked Data*, Université Claude Bernard Lyon 1, 8/9/2016, Vincent Roca.

PhD : Karina Sokolova Perez, *Bridging the Gap between Privacy by Design and Mobile Systems by Patterns*, UTT Troyes, 27/04/2016, Daniel Le Métayer.

PhD: Tania Richmond, *Implantation sécurisée de protocoles cryptographiques basés sur les codes correcteurs d'erreurs*, Université de Saint-Etienne, 24/10/2016, Marine Minier.

PhD: Nora El Amrani, *Codes MDS additifs pour la cryptographie*, Université de Limoges, 24/02/2016, Marine Minier.

9.3. Popularization

9.3.1. Interview

Privatics team has participated to an episode of X:enius entitled: "Données personnelles : à quel point sommes-nous prévisibles ?". It features an interview of Claude Castelluccia, Daniel Le Métayer and Mathieu Cunche. The episode was broadcasted the 12th december 2016 on Arte.

9.3.2. Articles

D. Le Métayer in *France Stratégie, Algorithmes, libertés et responsabilités*, 10/03/2016.

C. Castelluccia in Le Monde, *Que reproche-t-on au TES, le « mégafichier » des 60 millions de Français*, 08/11/2016.

M. Cunche and C. Matte in GNU/Linux Magazine HS 84, *Traçage Wi-Fi : applications et contre-mesures*, 05/2016.

M. Cunche in Arte Futuremag, *Données personnelles, nos smartphones nous espionnent-ils?*, 05/2016.

9.3.3. Conferences

C. Castelluccia, *An Introduction to DataVeillance (Data + Surveillance)*, LIG UGA Keynote, 07/04/2016

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Project-Team ROMA

Optimisation des ressources : modèles, algorithmes et ordonnancement

IN COLLABORATION WITH: Laboratoire de l'Informatique du Parallélisme (LIP)

IN PARTNERSHIP WITH:
CNRS

Ecole normale supérieure de Lyon

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RESEARCH CENTER
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THEME
Distributed and High Performance Computing

Table of contents

Project-Team ROMA

Creation of the Team: 2012 February 01, updated into Project-Team: 2015 January 01

Keywords:

Computer Science and Digital Science:

1.1.1. - Multicore
1.1.2. - Hardware accelerators (GPGPU, FPGA, etc.)
1.1.3. - Memory models
1.1.4. - High performance computing
1.1.5. - Exascale
1.1.9. - Fault tolerant systems
1.6. - Green Computing
6.1. - Mathematical Modeling
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6.3. - Computation-data interaction
7.1. - Parallel and distributed algorithms
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Other Research Topics and Application Domains:

3.2. - Climate and meteorology
3.3. - Geosciences
4. - Energy
4.1. - Fossile energy production (oil, gas)
4.5.1. - Green computing
5.2.3. - Aviation
5.5. - Materials

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2. Overall Objectives

2.1. Overall Objectives

The ROMA project aims at designing models, algorithms, and scheduling strategies to optimize the execution of scientific applications.

Scientists now have access to tremendous computing power. For instance, the four most powerful computing platforms in the TOP 500 list [60] each includes more than 500,000 cores and deliver a sustained performance of more than 10 Peta FLOPS. The volunteer computing platform BOINC [56] is another example with more than 440,000 enlisted computers and, on average, an aggregate performance of more than 9 Peta FLOPS. Furthermore, it had never been so easy for scientists to have access to parallel computing resources, either through the multitude of local clusters or through distant cloud computing platforms.

Because parallel computing resources are ubiquitous, and because the available computing power is so huge, one could believe that scientists no longer need to worry about finding computing resources, even less to optimize their usage. Nothing is farther from the truth. Institutions and government agencies keep building larger and more powerful computing platforms with a clear goal. These platforms must allow to solve problems in reasonable timescales, which were so far out of reach. They must also allow to solve problems more precisely where the existing solutions are not deemed to be sufficiently accurate. For those platforms to fulfill their purposes, their computing power must therefore be carefully exploited and not be wasted. This often requires an efficient management of all types of platform resources: computation, communication, memory, storage, energy, etc. This is often hard to achieve because of the characteristics of new and emerging platforms. Moreover, because of technological evolutions, new problems arise, and fully tried and tested solutions need to be thoroughly overhauled or simply discarded and replaced. Here are some of the difficulties that have, or will have, to be overcome:

- computing platforms are hierarchical: a processor includes several cores, a node includes several processors, and the nodes themselves are gathered into clusters. Algorithms must take this hierarchical structure into account, in order to fully harness the available computing power;
- the probability for a platform to suffer from a hardware fault automatically increases with the number of its components. Fault-tolerance techniques become unavoidable for large-scale platforms;
- the ever increasing gap between the computing power of nodes and the bandwidths of memories and networks, in conjunction with the organization of memories in deep hierarchies, requires to take more and more care of the way algorithms use memory;
- energy considerations are unavoidable nowadays. Design specifications for new computing platforms always include a maximal energy consumption. The energy bill of a supercomputer may represent a significant share of its cost over its lifespan. These issues must be taken into account at the algorithm-design level.

We are convinced that dramatic breakthroughs in algorithms and scheduling strategies are required for the scientific computing community to overcome all the challenges posed by new and emerging computing platforms. This is required for applications to be successfully deployed at very large scale, and hence for enabling the scientific computing community to push the frontiers of knowledge as far as possible. The ROMA project-team aims at providing fundamental algorithms, scheduling strategies, protocols, and software packages to fulfill the needs encountered by a wide class of scientific computing applications, including domains as diverse as geophysics, structural mechanics, chemistry, electromagnetism, numerical optimization, or computational fluid dynamics, to quote a few. To fulfill this goal, the ROMA project-team takes a special interest in dense and sparse linear algebra.

The work in the ROMA team is organized along three research themes.

1. **Algorithms for probabilistic environments.** In this theme, we consider problems where some of the platform characteristics, or some of the application characteristics, are described by probability distributions. This is in particular the case when considering the resilience of applications in failure-prone environments: the possibility of faults is modeled by probability distributions.
2. **Platform-aware scheduling strategies.** In this theme, we focus on the design of scheduling strategies that finely take into account some platform characteristics beyond the most classical ones, namely the computing speed of processors and accelerators, and the communication bandwidth of network links. In the scope of this theme, when designing scheduling strategies, we focus either on the energy consumption or on the memory behavior. All optimization problems under study are multi-criteria.
3. **High-performance computing and linear algebra.** We work on algorithms and tools for both sparse and dense linear algebra. In sparse linear algebra, we work on most aspects of direct multifrontal solvers for linear systems. In dense linear algebra, we focus on the adaptation of factorization kernels to emerging and future platforms. In addition, we also work on combinatorial scientific computing, that is, on the design of combinatorial algorithms and tools to solve combinatorial problems, such as those encountered, for instance, in the preprocessing phases of solvers of sparse linear systems.

3. Research Program

3.1. Algorithms for probabilistic environments

There are two main research directions under this research theme. In the first one, we consider the problem of the efficient execution of applications in a failure-prone environment. Here, probability distributions are used to describe the potential behavior of computing platforms, namely when hardware components are subject to faults. In the second research direction, probability distributions are used to describe the characteristics and behavior of applications.

3.1.1. Application resilience

An application is resilient if it can successfully produce a correct result in spite of potential faults in the underlying system. Application resilience can involve a broad range of techniques, including fault prediction, error detection, error containment, error correction, checkpointing, replication, migration, recovery, etc. Faults are quite frequent in the most powerful existing supercomputers. The Jaguar platform, which ranked third in the TOP 500 list in November 2011 [59], had an average of 2.33 faults per day during the period from August 2008 to February 2010 [83]. The mean-time between faults of a platform is inversely proportional to its number of components. Progresses will certainly be made in the coming years with respect to the reliability of individual components. However, designing and building high-reliability hardware components is far more expensive than using lower reliability top-of-the-shelf components. Furthermore, low-power components may not be available with high-reliability. Therefore, it is feared that the progresses in reliability will far from compensate the steady projected increase of the number of components in the largest supercomputers. Already, application failures have a huge computational cost. In 2008, the DARPA white paper on "System resilience at extreme scale" [58] stated that high-end systems wasted 20% of their computing capacity on application failure and recovery.

In such a context, any application using a significant fraction of a supercomputer and running for a significant amount of time will have to use some fault-tolerance solution. It would indeed be unacceptable for an application failure to destroy centuries of CPU-time (some of the simulations run on the Blue Waters platform consumed more than 2,700 years of core computing time [54] and lasted over 60 hours; the most time-consuming simulations of the US Department of Energy (DoE) run for weeks to months on the most powerful existing platforms [57]).

Our research on resilience follows two different directions. On the one hand we design new resilience solutions, either generic fault-tolerance solutions or algorithm-based solutions. On the other hand we model and theoretically analyze the performance of existing and future solutions, in order to tune their usage and help determine which solution to use in which context.

3.1.2. Scheduling strategies for applications with a probabilistic behavior

Static scheduling algorithms are algorithms where all decisions are taken before the start of the application execution. On the contrary, in non-static algorithms, decisions may depend on events that happen during the execution. Static scheduling algorithms are known to be superior to dynamic and system-oriented approaches in stable frameworks [65], [71], [72], [82], that is, when all characteristics of platforms and applications are perfectly known, known a priori, and do not evolve during the application execution. In practice, the prediction of application characteristics may be approximative or completely infeasible. For instance, the amount of computations and of communications required to solve a given problem in parallel may strongly depend on some input data that are hard to analyze (this is for instance the case when solving linear systems using full pivoting).

We plan to consider applications whose characteristics change dynamically and are subject to uncertainties. In order to benefit nonetheless from the power of static approaches, we plan to model application uncertainties and variations through probabilistic models, and to design for these applications scheduling strategies that are either static, or partially static and partially dynamic.

3.2. Platform-aware scheduling strategies

In this theme, we study and design scheduling strategies, focusing either on energy consumption or on memory behavior. In other words, when designing and evaluating these strategies, we do not limit our view to the most classical platform characteristics, that is, the computing speed of cores and accelerators, and the bandwidth of communication links.

In most existing studies, a single optimization objective is considered, and the target is some sort of absolute performance. For instance, most optimization problems aim at the minimization of the overall execution time of the application considered. Such an approach can lead to a very significant waste of resources, because it does not take into account any notion of efficiency nor of yield. For instance, it may not be meaningful to use twice as many resources just to decrease by 10% the execution time. In all our work, we plan to look only for algorithmic solutions that make a "clever" usage of resources. However, looking for the solution that optimizes a metric such as the efficiency, the energy consumption, or the memory-peak minimization, is doomed for the type of applications we consider. Indeed, in most cases, any optimal solution for such a metric is a sequential solution, and sequential solutions have prohibitive execution times. Therefore, it becomes mandatory to consider multi-criteria approaches where one looks for trade-offs between some user-oriented metrics that are typically related to notions of Quality of Service—execution time, response time, stretch, throughput, latency, reliability, etc.—and some system-oriented metrics that guarantee that resources are not wasted. In general, we will not look for the Pareto curve, that is, the set of all dominating solutions for the considered metrics. Instead, we will rather look for solutions that minimize some given objective while satisfying some bounds, or "budgets", on all the other objectives.

3.2.1. Energy-aware algorithms

Energy-aware scheduling has proven an important issue in the past decade, both for economical and environmental reasons. Energy issues are obvious for battery-powered systems. They are now also important for traditional computer systems. Indeed, the design specifications of any new computing platform now always include an upper bound on energy consumption. Furthermore, the energy bill of a supercomputer may represent a significant share of its cost over its lifespan.

Technically, a processor running at speed s dissipates s^α watts per unit of time with $2 \leq \alpha \leq 3$ [63], [64], [69]; hence, it consumes $s^\alpha \times d$ joules when operated during d units of time. Therefore, energy consumption can be reduced by using speed scaling techniques. However it was shown in [84] that reducing the speed of a processor increases the rate of transient faults in the system. The probability of faults increases exponentially, and this probability cannot be neglected in large-scale computing [80]. In order to make up for the loss in *reliability* due to the energy efficiency, different models have been proposed for fault tolerance: (i) *re-execution* consists in re-executing a task that does not meet the reliability constraint [84]; (ii) *replication* consists in executing the same task on several processors simultaneously, in order to meet the reliability constraints [62]; and (iii) *checkpointing* consists in "saving" the work done at some certain instants, hence reducing the amount of work lost when a failure occurs [79].

Energy issues must be taken into account at all levels, including the algorithm-design level. We plan to both evaluate the energy consumption of existing algorithms and to design new algorithms that minimize energy consumption using tools such as resource selection, dynamic frequency and voltage scaling, or powering-down of hardware components.

3.2.2. Memory-aware algorithms

For many years, the bandwidth between memories and processors has increased more slowly than the computing power of processors, and the latency of memory accesses has been improved at an even slower pace. Therefore, in the time needed for a processor to perform a floating point operation, the amount of data transferred between the memory and the processor has been decreasing with each passing year. The risk is for an application to reach a point where the time needed to solve a problem is no longer dictated by the processor computing power but by the memory characteristics, comparable to the *memory wall* that limits CPU performance. In such a case, processors would be greatly under-utilized, and a large part of the computing power of the platform would be wasted. Moreover, with the advent of multicore processors, the amount of memory per core has started to stagnate, if not to decrease. This is especially harmful to memory intensive applications. The problems related to the sizes and the bandwidths of memories are further exacerbated on modern computing platforms because of their deep and highly heterogeneous hierarchies. Such a hierarchy can extend from core private caches to shared memory within a CPU, to disk storage and even tape-based storage systems, like in the Blue Waters supercomputer [55]. It may also be the case that heterogeneous cores are used (such as hybrid CPU and GPU computing), and that each of them has a limited memory.

Because of these trends, it is becoming more and more important to precisely take memory constraints into account when designing algorithms. One must not only take care of the amount of memory required to run an algorithm, but also of the way this memory is accessed. Indeed, in some cases, rather than to minimize the amount of memory required to solve the given problem, one will have to maximize data reuse and, especially, to minimize the amount of data transferred between the different levels of the memory hierarchy (minimization of the volume of memory inputs-outputs). This is, for instance, the case when a problem cannot be solved by just using the in-core memory and that any solution must be out-of-core, that is, must use disks as storage for temporary data.

It is worth noting that the cost of moving data has lead to the development of so called "communication-avoiding algorithms" [76]. Our approach is orthogonal to these efforts: in communication-avoiding algorithms, the application is modified, in particular some redundant work is done, in order to get rid of some communication operations, whereas in our approach, we do not modify the application, which is provided as a task graph, but we minimize the needed memory peak only by carefully scheduling tasks.

3.3. High-performance computing and linear algebra

Our work on high-performance computing and linear algebra is organized along three research directions. The first direction is devoted to direct solvers of sparse linear systems. The second direction is devoted to combinatorial scientific computing, that is, the design of combinatorial algorithms and tools that solve problems encountered in some of the other research themes, like the problems faced in the preprocessing phases of sparse direct solvers. The last direction deals with the adaptation of classical dense linear algebra kernels to the architecture of future computing platforms.

3.3.1. Direct solvers for sparse linear systems

The solution of sparse systems of linear equations (symmetric or unsymmetric, often with an irregular structure, from a few hundred thousand to a few hundred million equations) is at the heart of many scientific applications arising in domains such as geophysics, structural mechanics, chemistry, electromagnetism, numerical optimization, or computational fluid dynamics, to cite a few. The importance and diversity of applications are a main motivation to pursue research on sparse linear solvers. Because of this wide range of applications, any significant progress on solvers will have a significant impact in the world of simulation. Research on sparse direct solvers in general is very active for the following main reasons:

- many applications fields require large-scale simulations that are still too big or too complicated with respect to today's solution methods;
- the current evolution of architectures with massive, hierarchical, multicore parallelism imposes to overhaul all existing solutions, which represents a major challenge for algorithm and software development;
- the evolution of numerical needs and types of simulations increase the importance, frequency, and size of certain classes of matrices, which may benefit from a specialized processing (rather than resort to a generic one).

Our research in the field is strongly related to the software package MUMPS (see Section 6.1). MUMPS is both an experimental platform for academics in the field of sparse linear algebra, and a software package that is widely used in both academia and industry. The software package MUMPS enables us to (i) confront our research to the real world, (ii) develop contacts and collaborations, and (iii) receive continuous feedback from real-life applications, which is extremely critical to validate our research work. The feedback from a large user community also enables us to direct our long-term objectives towards meaningful directions.

In this context, we aim at designing parallel sparse direct methods that will scale to large modern platforms, and that are able to answer new challenges arising from applications, both efficiently—from a resource consumption point of view—and accurately—from a numerical point of view. For that, and even with increasing parallelism, we do not want to sacrifice in any manner numerical stability, based on threshold partial pivoting, one of the main originalities of our approach (our "trademark") in the context of direct solvers for distributed-memory computers; although this makes the parallelization more complicated, applying the same pivoting strategy as in the serial case ensures numerical robustness of our approach, which we generally measure in terms of sparse backward error. In order to solve the hard problems resulting from the always-increasing demands in simulations, special attention must also necessarily be paid to memory usage (and not only execution time). This requires specific algorithmic choices and scheduling techniques. From a complementary point of view, it is also necessary to be aware of the functionality requirements from the applications and from the users, so that robust solutions can be proposed for a wide range of applications.

Among direct methods, we rely on the multifrontal method [73], [74], [78]. This method usually exhibits a good data locality and hence is efficient in cache-based systems. The task graph associated with the multifrontal method is in the form of a tree whose characteristics should be exploited in a parallel implementation.

Our work is organized along two main research directions. In the first one we aim at efficiently addressing new architectures that include massive, hierarchical parallelism. In the second one, we aim at reducing the running time complexity and the memory requirements of direct solvers, while controlling accuracy.

3.3.2. Combinatorial scientific computing

Combinatorial scientific computing (CSC) is a recently coined term (circa 2002) for interdisciplinary research at the intersection of discrete mathematics, computer science, and scientific computing. In particular, it refers to the development, application, and analysis of combinatorial algorithms to enable scientific computing applications. CSC's deepest roots are in the realm of direct methods for solving sparse linear systems of equations where graph theoretical models have been central to the exploitation of sparsity, since the 1960s. The general approach is to identify performance issues in a scientific computing problem, such as memory use, parallel speed up, and/or the rate of convergence of a method, and to develop combinatorial algorithms and models to tackle those issues.

Our target scientific computing applications are (i) the preprocessing phases of direct methods (in particular MUMPS), iterative methods, and hybrid methods for solving linear systems of equations, and tensor decomposition algorithms; and (ii) the mapping of tasks (mostly the sub-tasks of the mentioned solvers) onto modern computing platforms. We focus on the development and use of graph and hypergraph models, and related tools such as hypergraph partitioning algorithms, to solve problems of load balancing and task mapping. We also focus on bipartite graph matching and vertex ordering methods for reducing the memory overhead and computational requirements of solvers. Although we direct our attention on these models and algorithms through the lens of linear system solvers, our solutions are general enough to be applied to some other resource optimization problems.

3.3.3. Dense linear algebra on post-petascale multicore platforms

The quest for efficient, yet portable, implementations of dense linear algebra kernels (QR, LU, Cholesky) has never stopped, fueled in part by each new technological evolution. First, the LAPACK library [67] relied on BLAS level 3 kernels (Basic Linear Algebra Subroutines) that enable to fully harness the computing power of a single CPU. Then the SCALAPACK library [66] built upon LAPACK to provide a coarse-grain parallel version, where processors operate on large block-column panels. Inter-processor communications occur through highly tuned MPI send and receive primitives. The advent of multi-core processors has led to a major modification in these algorithms [68], [81], [77]. Each processor runs several threads in parallel to keep all cores within that processor busy. Tiled versions of the algorithms have thus been designed: dividing large block-column panels into several tiles allows for a decrease in the granularity down to a level where many smaller-size tasks are spawned. In the current panel, the diagonal tile is used to eliminate all the lower tiles in the panel. Because the factorization of the whole panel is now broken into the elimination of several tiles, the update operations can also be partitioned at the tile level, which generates many tasks to feed all cores.

The number of cores per processor will keep increasing in the following years. It is projected that high-end processors will include at least a few hundreds of cores. This evolution will require to design new versions of libraries. Indeed, existing libraries rely on a static distribution of the work: before the beginning of the execution of a kernel, the location and time of the execution of all of its component is decided. In theory, static solutions enable to precisely optimize executions, by taking parameters like data locality into account. At run time, these solutions proceed at the pace of the slowest of the cores, and they thus require a perfect load-balancing. With a few hundreds, if not a thousand, cores per processor, some tiny differences between the computing times on the different cores ("jitter") are unavoidable and irremediably condemn purely static solutions. Moreover, the increase in the number of cores per processor once again mandates to increase the number of tasks that can be executed in parallel.

We study solutions that are part-static part-dynamic, because such solutions have been shown to outperform purely dynamic ones [70]. On the one hand, the distribution of work among the different nodes will still be statically defined. On the other hand, the mapping and the scheduling of tasks inside a processor will be dynamically defined. The main difficulty when building such a solution will be to design lightweight dynamic schedulers that are able to guarantee both an excellent load-balancing and a very efficient use of data locality.

3.4. Compilers, code optimization and high-level synthesis for FPGA

Christophe Alias and Laure Gonnord asked to join the ROMA team temporarily, starting from September 2015. This was accepted by the team and by Inria. The text below describes their research domain. The results that they have achieved in 2016 are included in this report.

The advent of parallelism in supercomputers, in embedded systems (smartphones, plane controllers), and in more classical end-user computers increases the need for high-level code optimization and improved compilers. Being able to deal with the complexity of the upcoming software and hardware while keeping energy consumption at a reasonnable level is one of the main challenges cited in the Hipeac Roadmap which among others cites the two major issues :

- Enhance the efficiency of the design of embedded systems, and especially the design of optimized specialized hardware.
- Invent techniques to "expose data movement in applications and optimize them at runtime and compile time and to investigate communication-optimized algorithms".

In particular, the rise of embedded systems and high performance computers in the last decade has generated new problems in code optimization, with strong consequences on the research area. The main challenge is to take advantage of the characteristics of the specific hardware (generic hardware, or hardware accelerators). The long-term objective is to provide solutions for the end-user developers to use at their best the huge opportunities of these emerging platforms.

3.4.1. Compiler algorithms for irregular applications

In the last decades, several frameworks has emerged to design efficient compiler algorithms. The efficiency of all the optimizations performed in compilers strongly relies on performant *static analyses* and *intermediate representations*. Among these representations, the polyhedral model [75] focus on regular programs, whose execution trace is predictable statically. The program and the data accessed are represented with a single mathematical object endowed with powerful algorithmic techniques for reasoning about it. Unfortunately, most of the algorithms used in scientific computing do not fit totally in this category.

We plan to explore the extensions of these techniques to handle irregular programs with while loops and complex data structures (such as trees, and lists). This raises many issues. We cannot represent finitely all the possible executions traces. Which approximation/representation to choose? Then, how to adapt existing techniques on approximated traces while preserving the correctness? To address these issues, we plan to incorporate new ideas coming from the abstract interpretation community: control flow, approximations, and also shape analysis; and from the termination community: rewriting is one of the major techniques that are able to handle complex data structures and also recursive programs.

3.4.2. High-level synthesis for FPGA

Energy consumption bounds the performance of supercomputers since the end of Dennard scaling. Hence, reducing the electrical energy spent in a computation is the major challenge raised by Exaflop computing. Novel hardware, software, compilers and operating systems must be designed to increase the energy efficiency (in flops/watt) of data manipulation and computation itself. In the last decade, many specialized hardware accelerators (Xeon Phi, GPGPU) has emerged to overcome the limitations of mainstream processors, by trading the genericity for energy efficiency. However, the best supercomputers can only reach 8 Gflops/watt [61], which is far less than the 50 Gflops/watt required by an Exaflop supercomputer. An extreme solution would be to trade all the genericity by using specialized circuits. However such circuits (application specific integrated circuits, ASIC) are usually too expensive for the HPC market and lacks of flexibility. Once printed, an ASIC cannot be modified. Any algorithm update (or bug fix) would be impossible, which clearly not realistic.

Recently, reconfigurable circuits (Field Programmable Gate Arrays, FPGA) has appeared as a credible alternative for Exaflop computing. Major companies (including Intel, Google, Facebook and Microsoft) show a growing interest to FPGA and promising results has been obtained. For instance, in 2015, Microsoft reaches 40 Gflop/watts on a data-center deep learning algorithm mapped on Intel/Altera Arria 10 FPGAs. We believe that FPGA will become the new building block for HPC and Big Data systems. Unfortunately, programming an FPGA is still a big challenge: the application must be defined at circuit level and use properly the logic cells. Hence, there is a strong need for a compiler technology able to *map complex applications specified in a high-level language*. This compiler technology is usually refered as high-level synthesis (HLS).

We plan to investigate how to extend the models and the algorithms developed by the HPC community to map automatically a complex application to an FPGA. This raises many issues. How to schedule/allocate the computations and the data on the FPGA in order to reduce the data transfers while keeping a high throughput? How to use optimally the resources of the FPGA while keeping a low critical path? To address these issues, we plan to develop novel execution models based on process networks and to extend/cross-fertilize the algorithms developed in both HPC and high-level synthesis communities. The purpose of the XtremLogic start-up company, co-founded by Christophe Alias and Alexandru Plesco is to transfer the results of this research to an industrial level compiler.

4. Application Domains

4.1. Applications of sparse direct solvers

Sparse direct (multifrontal) solvers have a wide range of applications as they are used at the heart of many numerical methods in computational science: whether a model uses finite elements or finite differences, or requires the optimization of a complex linear or nonlinear function, one often ends up solving a linear system of equations involving sparse matrices. There are therefore a number of application fields, among which some of the ones cited by the users of our sparse direct solver MUMPS (see Section 6.1) are: structural mechanics, biomechanics, medical image processing, tomography, geophysics, electromagnetism, fluid dynamics, econometric models, oil reservoir simulation, magneto-hydro-dynamics, chemistry, acoustics, glaciology, astrophysics, circuit simulation, and work on hybrid direct-iterative methods.

5. Highlights of the Year

5.1. Highlights of the Year

- Anne Benoit was the program chair of HiPC 2016 and the Algorithm-track vice-chair for SC'16.

5.1.1. Awards

- Yves Robert was awarded the *2016 Outsanding Service Award* of the *IEEE Technical Committee on Parallel Processing* (TCPP)

6. New Software and Platforms

6.1. MUMPS

A MUltifrontal Massively Parallel Solver
KEYWORDS: High-Performance Computing - Direct solvers - Finite element modelling
FUNCTIONAL DESCRIPTION

MUMPS is a software library to solve large sparse linear systems (AX=B) on sequential and parallel distributed memory computers. It implements a sparse direct method called the multifrontal method. It is used worldwide in academic and industrial codes, in the context numerical modeling of physical phenomena with finite elements. Its main characteristics are its numerical stability, its large number of features, its high performance and its constant evolution through research and feedback from its community of users. Examples of application fields include structural mechanics, electromagnetism, geophysics, acoustics, computational fluid dynamics. MUMPS is developed by INPT(ENSEEIHT)-IRIT, Inria, CERFACS, University of Bordeaux, CNRS and ENS Lyon. In 2014, a consortium of industrial users has been created (http://mumps-consortium.org).

- Participants: Patrick Amestoy, Alfredo Buttari, Jean-Yves L'Excellent, Chiara Puglisi, Mohamed Sid-Lakhdar, Bora Uçar, Marie Durand, Abdou Guermouche, Maurice Bremond, Guillaume Joslin, Stéphane Pralet, Aurélia Fevre, Clément Weisbecker, Theo Mary, Emmanuel Agullo, Jacko Koster, Tzvetomila Slavova, François-Henry Rouet, Philippe Combes and Gilles Moreau
- Partners: CERFACS - CNRS - ENS Lyon - INPT - IRIT - LIP - Université de Bordeaux - Université de Lyon - Université de Toulouse
- Latest public release: MUMPS 5.0.2 (July 2016)
- Contact: Jean-Yves L'Excellent
- URL: http://mumps-solver.org/
- Next MUMPS User Days: we have started organizing the next MUMPS User days, which will be hosted by Inria on June 1 and 2, 2017 near Grenoble, France (see http://mumps.enseeiht.fr/ud_2017.php)

In the context of the MUMPS consortium (see Section 8.1 and http://mumps-consortium.org), we had scientific exchanges and collaborations with industrial members and released two versions in advance for the consortium (in July 2016 and November 2016), containing major improvements for large-scale problems and many other improvements. Much effort was also put on developing features and algorithms to improve the quality and performance of MUMPS, especially in the context of problems offering potential for low-rank compression. This work is done in close collaboration with the partners who co-develop MUMPS, in particular in Toulouse.

6.2. DCC

DPN C Compiler
KEYWORDS: Polyhedral compilation - Automatic parallelization - High-level synthesis
FUNCTIONAL DESCRIPTION

Dcc (Data-aware process network C compiler) analyzes a sequential regular program written in C and generates an equivalent architecture of parallel computer as a communicating process network (Data-aware Process Network, DPN). Internal communications (channels) and external communications (external memory) are automatically handled while fitting optimally the characteristics of the global memory (latency and throughput). The parallelism can be tuned. Dcc has been registered at the APP ("Agence de protection des programmes") and transferred to the XtremLogic start-up under an Inria license.

- Participants: Christophe Alias and Alexandru Plesco (XtremLogic SAS)
- Contact: Christophe Alias

6.3. PoCo

Polyhedral Compilation Library
KEYWORDS: Polyhedral compilation - Automatic parallelization
FUNCTIONAL DESCRIPTION

PoCo (Polyhedral Compilation Library) is a compilation framework allowing to develop parallelizing compilers for regular programs. PoCo features many state-of-the-art polyhedral program analysis and a symbolic calculator on execution traces (represented as convex polyhedra). PoCo has been registered at the APP ("agence de protection des programmes") and transferred to the XtremLogic start-up under an Inria licence.

- Participant: Christophe Alias
- Contact: Christophe Alias

6.4. Aspic

Accelerated Symbolic Polyhedral Invariant Geneneration
KEYWORDS: Abstract Interpretation - Invariant Generation
FUNCTIONAL DESCRIPTION

Aspic is an invariant generator for general counter automata. Used with C2fsm (a tool developed by P. Feautrier in COMPSYS), it can be used to derivate invariants for numerical C programs, and also to prove safety. It is also part of the WTC toolsuite (see http://compsys-tools.ens-lyon.fr/wtc/index.html), a tool chain to compute worse-case time complexity of a given sequential program.

Aspic implements the theoretical results of Laure Gonnord's PhD thesis on acceleration techniques and has been maintained since 2007.

- Participant: Laure Gonnord
- Contact: Laure Gonnord
- URL: http://laure.gonnord.org/pro/aspic/aspic.html

6.5. Termite

Termination of C programs

KEYWORDS: Abstract Interpretation - Termination
FUNCTIONAL DESCRIPTION

TERMITE is the implementation of the algorithm "Counter-example based generation of ranking functions". Based on LLVM and Pagai (a tool that generates invariants), the tool automatically generates a ranking function for each *head of loop*.

TERMITE represents 3000 lines of OCaml and is now available via the opam installer.

- Participants: Laure Gonnord, Gabriel Radanne (PPS, Univ Paris 7), David Monniaux (CNRS/Verimag).
- Contact: Laure Gonnord
- URL: https://termite-analyser.github.io/

6.6. Vaphor

Validation of C programs with arrays with Horn Clauses

KEYWORDS: Abstract Interpretation - Safety - Array Programs
FUNCTIONAL DESCRIPTION

VAPHOR (Validation of Programs with Horn Clauses) is the implementation of the algorithm "An encoding of array verification problems into array-free Horn clauses". The tool implements a traduction from a C-like imperative language into Horn clauses in the SMT-lib Format.

VAPHOR represents 2000 lines of OCaml and its development is under consolidation.

- Participants: Laure Gonnord, David Monniaux (CNRS/Verimag).
- Contact: Laure Gonnord
- Demo page : http://laure.gonnord.org/pro/demopage/vaphor/index.php

7. New Results

7.1. A backward/forward recovery approach for the preconditioned conjugate gradient method

Participants: Massimiliano Fasi [Univ. Mancherster, UK], Julien Langou [UC Denver, USA], Yves Robert, Bora Uçar.

Several recent papers have introduced a periodic verification mechanism to detect silent errors in iterative solvers. Chen [PPoPP'13, pp. 167-176] has shown how to combine such a verification mechanism (a stability test checking the orthogonality of two vectors and recomputing the residual) with checkpointing: the idea is to verify every d iterations, and to checkpoint every $c \times d$ iterations. When a silent error is detected by the verification mechanism, one can rollback to and re-execute from the last checkpoint. In this work, we also propose to combine checkpointing and verification, but we use algorithm-based fault tolerance (ABFT) rather than stability tests. ABFT can be used for error detection, but also for error detection and correction, allowing a forward recovery (and no rollback nor re-execution) when a single error is detected. We introduce an abstract performance model to compute the performance of all schemes, and we instantiate it using the preconditioned conjugate gradient algorithm. Finally, we validate our new approach through a set of simulations.

This work has been accepted for publication in the *Journal of Computational Science* [13].

7.2. High performance parallel algorithms for the tucker decomposition of sparse tensors

Participants: Oguz Kaya, Bora Uçar.

We investigate an efficient parallelization of a class of algorithms for the well-known Tucker decomposition of general N-dimensional sparse tensors. The targeted algorithms are iterative and use the alternating least squares method. At each iteration, for each dimension of an N-dimensional input tensor, the following operations are performed: (i) the tensor is multiplied with $N - 1$ matrices (TTMc step); (ii) the product is then converted to a matrix; and (iii) a few leading left singular vectors of the resulting matrix are computed (TRSVD step) to update one of the matrices for the next TTMc step. We propose an efficient parallelization of these algorithms for the current parallel platforms with multicore nodes. We discuss a set of preprocessing steps which takes all computational decisions out of the main iteration of the algorithm and provides an intuitive shared-memory parallelism for the TTM and TRSVD steps. We propose a coarse and a fine-grain parallel algorithm in a distributed memory environment, investigate data dependencies, and identify efficient communication schemes. We demonstrate how the computation of singular vectors in the TRSVD step can be carried out efficiently following the TTMc step. Finally, we develop a hybrid MPI-OpenMP implementation of the overall algorithm and report scalability results on up to 4096 cores on 256 nodes of an IBM BlueGene/Q supercomputer.

This work has been published at *ICPP'16* [28].

7.3. Preconditioning techniques based on the Birkhoff–von Neumann decomposition

Participants: Michele Benzi [Emory University, Atlanta, USA], Bora Uçar.

We introduce a class of preconditioners for general sparse matrices based on the Birkhoff–von Neumann decomposition of doubly stochastic matrices. These preconditioners are aimed primarily at solving challenging linear systems with highly unstructured and indefinite coefficient matrices. We present some theoretical results and numerical experiments on linear systems from a variety of applications.

This work has been accepted for publication in the journal *Computational Methods in Applied Mathematics* [10].

7.4. Parallel CP decomposition of sparse tensors using dimension trees

Participants: Oguz Kaya, Bora Uçar.

Tensor factorization has been increasingly used to address various problems in many fields such as signal processing, data compression, computer vision, and computational data analysis. CANDECOMP/PARAFAC (CP) decomposition of sparse tensors has successfully been applied to many well-known problems in web search, graph analytics, recommender systems, health care data analytics, and many other domains. In these applications, computing the CP decomposition of sparse tensors efficiently is essential in order to be able to process and analyze data of massive scale. For this purpose, we investigate an efficient computation and parallelization of the CP decomposition for sparse tensors. We provide a novel computational scheme for reducing the cost of a core operation in computing the CP decomposition with the traditional alternating least squares (CP-ALS) based algorithm. We then effectively parallelize this computational scheme in the context of CP-ALS in shared and distributed memory environments, and propose data and task distribution models for better scalability. We implement parallel CP-ALS algorithms and compare our implementations with an efficient tensor factorization library, using tensors formed from real-world and synthetic datasets. With our algorithmic contributions and implementations, we report up to 3.95x, 3.47x, and 3.9x speedups in sequential, shared memory parallel, and distributed memory parallel executions over the state of the art, and up to 1466x overall speedup over the sequential execution using 4096 cores on an IBM BlueGene/Q supercomputer.

This work is described in a technical report [49].

7.5. Scheduling series-parallel task graphs to minimize peak memory

Participants: Enver Kayaaslan, Thomas Lambert, Loris Marchal, Bora Uçar.

We consider a variant of the well-known, NP-complete problem of minimum cut linear arrangement for directed acyclic graphs. In this variant, we are given a directed acyclic graph and asked to find a topological ordering such that the maximum number of cut edges at any point in this ordering is minimum. In our main variant the vertices and edges have weights, and the aim is to minimize the maximum weight of cut edges in addition to the weight of the last vertex before the cut. There is a known, polynomial time algorithm [Liu, SIAM J. Algebra. Discr., 1987] for the cases where the input graph is a rooted tree. We focus on the variant where the input graph is a directed series-parallel graph, and propose a polynomial time algorithm. Directed acyclic graphs are used to model scientific applications where the vertices correspond to the tasks of a given application and the edges represent the dependencies between the tasks. In such models, the problem we address reads as minimizing the peak memory requirement in an execution of the application. Our work, combined with Liu's work on rooted trees addresses this practical problem in two important classes of applications.

This work is described in a technical report [50].

7.6. Matrix symmetrization and sparse direct solvers

Participants: Raluca Portase [Cluj Napoca, Romania], Bora Uçar.

We investigate algorithms for finding column permutations of sparse matrices in order to have large diagonal entries and to have many entries symmetrically positioned around the diagonal. The aim is to improve the memory and running time requirements of a certain class of sparse direct solvers. We propose efficient algorithms for this purpose by combining two existing approaches and demonstrate the effect of our findings in practice using a direct solver. In particular, we show improvements in a number of components of the running time of a sparse direct solver with respect to the state of the art on a diverse set of matrices.

This work is described in a technical report [53].

7.7. Robust Memory-Aware Mapping for Parallel Multifrontal Factorizations

Participants: Emmanuel Agullo [HIEPACS project-team], Patrick Amestoy [INPT-IRIT], Alfredo Buttari [CNRS-IRIT], Abdou Guermouche [HIEPACS project-team], Jean-Yves L'Excellent, François-Henry Rouet [Lawrence Berkeley Laboratory, CA, USA].

In this work, we study the memory scalability of the parallel multifrontal factorization of sparse matrices. In particular, we are interested in controlling the active memory specific to the multifrontal factorization. We illustrate why commonly used mapping strategies (e.g., the proportional mapping) cannot provide a high memory efficiency, which means that they tend to let the memory usage of the factorization grow when the number of processes increases. We propose "memory-aware" algorithms that aim at maximizing the granularity of parallelism while respecting memory constraints. These algorithms provide accurate memory estimates prior to the factorization and can significantly enhance the robustness of a multifrontal code. We illustrate our approach with experiments performed on large matrices.

This work has been published in the *SIAM Journal on Scientific Computing* [1].

7.8. Fast 3D frequency-domain full waveform inversion with a parallel Block Low-Rank multifrontal direct solver: application to OBC data from the North Sea

Participants: Patrick Amestoy [INPT-IRIT], Romain Brossier [ISTerre], Alfredo Buttari [CNRS-IRIT], Jean-Yves L'Excellent, Théo Mary [UPS-IRIT], Ludovic Métivier [CNRS-ISTerre-LJK], Alain Miniussi [Geoazur], Stéphane Operto [Geoazur].

Wide-azimuth long-offset OBC/OBN surveys provide a suitable framework to perform computationally-efficient frequency-domain full waveform inversion (FWI) with a few discrete frequencies. Frequency-domain seismic modeling is performed efficiently with moderate computational resources for a large number of sources with a sparse multifrontal direct solver (Gauss-elimination techniques for sparse matrices). Approximate solutions of the time-harmonic wave equation are computed using a Block Low-Rank (BLR) approximation, leading to a significant reduction in the operation count and in the volume of communication during the LU factorization as well as offering a great potential for reduction in the memory demand. Moreover, the sparsity of the seismic source vectors is exploited to speed up the forward elimination step during the computation of the monochromatic wavefields. The relevance and the computational efficiency of the frequency-domain FWI performed in the visco-acoustic VTI approximation is shown with a real 3D OBC case study from the North Sea. The FWI subsurface models show a dramatic resolution improvement relative to the initial model built by reflection traveltime tomography. The amplitude errors introduced in the modeled wavefields by the BLR approximation for different low-rank thresholds have a negligible footprint in the FWI results. With respect to a standard multifrontal sparse direct factorization, and without compromise on the accuracy of the imaging, the BLR approximation can bring a reduction of the LU factor size by a factor up to three. This reduction is not yet exploited to reduce the effective memory usage (ongoing work). The flop reduction can be larger than a factor of 10 and can bring a factor of time reduction of around three. Moreover, this reduction factor tends to increase with frequency, namely with the matrix size. Frequency-domain visco-acoustic VTI FWI can be viewed as an efficient tool to build an initial model for elastic FWI of 4-C OBC data.

This work has been published in the journal *Geophysics* [2].

7.9. Matching-Based Allocation Strategies for Improving Data Locality of Map Tasks in MapReduce

Participant: Loris Marchal.

MapReduce is a well-know framework for distributing data-processing computations on parallel clusters. In MapReduce, a large computation is broken into small tasks that run in parallel on multiple machines, and scales easily to very large clusters of inexpensive commodity computers. Before the Map phase, the original dataset is first split into chunks, that are replicated (a constant number of times, usually 3) and distributed onto the computing nodes. During the Map phase, nodes request tasks and are allocated first tasks associated to local chunks (if any). Communications take place when requesting nodes do not hold any local chunk anymore. In this work, we provide the first complete theoretical data locality analysis of the Map phase of MapReduce, and more generally, for bag-of-tasks applications that behaves like MapReduce. We show that if tasks are homogeneous (in term of processing time), once the chunks have been replicated randomly on resources with a replication factor larger than 2, it is possible to find a priority mechanism for tasks that achieves a quasi-perfect number of communications using a sophisticated matching algorithm. In the more realistic case of heterogeneous processing times, we prove using an actual trace of a MapReduce server that this priority mechanism enables to complete the Map phase with significantly fewer communications, even on realistic distributions of task durations.

This work is described in a technical report [41].

7.10. Minimizing Rental Cost for Multiple Recipe Applications in the Cloud

Participant: Loris Marchal.

Clouds are more and more becoming a credible alternative to parallel dedicated resources. The pay-per-use pricing policy however highlights the real cost of computing applications. This new criterion, the cost, must then be assessed when scheduling an application in addition to more traditional ones as the completion time or the execution flow. In this work, we tackle the problem of optimizing the cost of renting computing instances to execute an application on the cloud while maintaining a desired performance (throughput). The target application is a stream application based on a DAG pattern, i.e., composed of several tasks with dependencies, and instances of the same execution task graph are continuously executed on the instances. We provide some theoretical results on the problem of optimizing the renting cost for a given throughput then propose some heuristics to solve the more complex parts of the problem, and we compare them to optimal solutions found by linear programming.

This work has been published in *IPDPS Workshops* [27].

7.11. Malleable task-graph scheduling with a practical speed-up model

Participants: Loris Marchal, Bertrand Simon, Oliver Sinnen [Univ. Auckland, New Zealand], Frédéric Vivien.

Scientific workloads are often described by Directed Acyclic task Graphs. Indeed, DAGs represent both a model frequently studied in theoretical literature and the structure employed by dynamic runtime schedulers to handle HPC applications. A natural problem is then to compute a makespan-minimizing schedule of a given graph. In this work, we are motivated by task graphs arising from multifrontal factorizations of sparsematrices and therefore work under the following practical model. We focus on malleable tasks (i.e., a single task can be allotted a time-varying number of processors) and specifically on a simple yet realistic speedup model: each task can be perfectly parallelized, but only up to a limited number of processors. We first prove that the associated decision problem of minimizing the makespan is NP-Complete. Then, we study a widely used algorithm, PropScheduling, under this practical model and propose a new strategy GreedyFilling. Even though both strategies are 2-approximations, experiments on real and synthetic data sets show that GreedyFilling achieves significantly lower makespans.

This work is described in a technical report [52].

7.12. Dynamic memory-aware task-tree scheduling

Participant: Loris Marchal.

Factorizing sparse matrices using direct multifrontal methods generates directed tree-shaped task graphs, where edges represent data dependency between tasks. This work revisits the execution of tree-shaped task graphs using multiple processors that share a bounded memory. A task can only be executed if all its input and output data can fit into the memory. The key difficulty is to manage the order of the task executions so that we can achieve high parallelism while staying below the memory bound. In particular, because input data of unprocessed tasks must be kept in memory, a bad scheduling strategy might compromise the termination of the algorithm. In the single processor case, solutions that are guaranteed to be below a memory bound are known. The multi-processor case (when one tries to minimize the total completion time) has been shown to be NP-complete. We designed in this work a novel heuristic solution that has a low complexity and is guaranteed to complete the tree within a given memory bound. We compared our algorithm to state of the art strategies, and observed that on both actual execution trees and synthetic trees, we always performed better than these solutions, with average speedups between 1.25 and 1.45 on actual assembly trees. Moreover, we showed that the overhead of our algorithm is negligible even on deep trees (10^5), and would allow its runtime execution.

This work is described in a technical report [39].

7.13. Optimal resilience patterns to cope with fail-stop and silent errors

Participants: Anne Benoit, Aurélien Cavelan, Yves Robert, Hongyang Sun.

This work focuses on resilience techniques at extreme scale. Many papers deal with fail-stop errors. Many others deal with silent errors (or silent data corruptions). But very few papers deal with fail-stop and silent errors simultaneously. However, HPC applications will obviously have to cope with both error sources. This work presents a unified framework and optimal algorithmic solutions to this double challenge. Silent errors are handled via verification mechanisms (either partially or fully accurate) and in-memory checkpoints. Fail-stop errors are processed via disk checkpoints. All verification and checkpoint types are combined into computational patterns. We provide a unified model, and a full characterization of the optimal pattern. Our results nicely extend several published solutions and demonstrate how to make use of different techniques to solve the double threat of fail-stop and silent errors. Extensive simulations based on real data confirm the accuracy of the model, and show that patterns that combine all resilience mechanisms are required to provide acceptable overheads.

This work was presented at the *IPDPS'2016* conference [20].

7.14. Two-level checkpointing and partial verifications for linear task graphs

Participants: Anne Benoit, Aurélien Cavelan, Yves Robert, Hongyang Sun.

Fail-stop and silent errors are unavoidable on large-scale platforms. Efficient resilience techniques must accommodate both error sources. A traditional checkpointing and rollback recovery approach can be used, with added verifications to detect silent errors. A fail-stop error leads to the loss of the whole memory content, hence the obligation to checkpoint on a stable storage (e.g., an external disk). On the contrary, it is possible to use in-memory checkpoints for silent errors, which provide a much smaller checkpoint and recovery overhead. Furthermore, recent detectors offer partial verification mechanisms, which are less costly than guaranteed verifications but do not detect all silent errors. In this work, we show how to combine all these techniques for HPC applications whose dependence graph is a chain of tasks, and provide a sophisticated dynamic programming algorithm returning the optimal solution in polynomial time. Simulations demonstrate that the combined use of multi-level checkpointing and partial verifications further improves performance.

This work was presented at the *17th IEEE International Workshop on Parallel and Distributed Scientific and Engineering Computing (PDSEC 2016)* [21].

7.15. Resilient application co-scheduling with processor redistribution

Participants: Anne Benoit, Loïc Pottier, Yves Robert.

Recently, the benefits of co-scheduling several applications have been demonstrated in a fault-free context, both in terms of performance and energy savings. However, large-scale computer systems are confronted to frequent failures, and resilience techniques must be employed to ensure the completion of large applications. Indeed, failures may create severe imbalance between applications, and significantly degrade performance. In this work, we propose to redistribute the resources assigned to each application upon the striking of failures, in order to minimize the expected completion time of a set of co-scheduled applications. First we introduce a formal model and establish complexity results. When no redistribution is allowed, we can minimize the expected completion time in polynomial time, while the problem becomes NP-complete with redistributions, even in a fault-free context. Therefore, we design polynomial-time heuristics that perform redistributions and account for processor failures. A fault simulator is used to perform extensive simulations that demonstrate the usefulness of redistribution and the performance of the proposed heuristics.

This work was presented at the *ICCP'16* conference [22].

7.16. A different re-execution speed can help

Participants: Anne Benoit, Aurélien Cavelan, Valentin Le Fèvre, Yves Robert, Hongyang Sun.

We consider divisible load scientific applications executing on large-scale platforms subject to silent errors. While the goal is usually to complete the execution as fast as possible in expectation, another major concern is energy consumption. The use of dynamic voltage and frequency scaling (DVFS) can help save energy, but at the price of performance degradation. Consider the execution model where a set of K different speeds is given, and whenever a failure occurs, a different re-execution speed may be used. Can this help? We address the following bi-criteria problem: how to compute the optimal checkpointing period to minimize energy consumption while bounding the degradation in performance. We solve this bi-criteria problem by providing a closed-form solution for the checkpointing period, and demonstrate via a comprehensive set of simulations that a different re-execution speed can indeed help.

This work was presented at the *5th International Workshop on Power-aware Algorithms, Systems, and Architectures* [19].

7.17. Coping with recall and precision of soft error detectors

Participants: Anne Benoit, Aurélien Cavelan, Yves Robert, Hongyang Sun.

Many methods are available to detect silent errors in high-performance computing (HPC) applications. Each method comes with a cost, a recall (fraction of all errors that are actually detected, i.e., false negatives), and a precision (fraction of true errors amongst all detected errors, i.e., false positives). The main contribution of this work is to characterize the optimal computing pattern for an application: which detector(s) to use, how many detectors of each type to use, together with the length of the work segment that precedes each of them. We first prove that detectors with imperfect precisions offer limited usefulness. Then we focus on detectors with perfect precision, and we conduct a comprehensive complexity analysis of this optimization problem, showing NP-completeness and designing an FPTAS (Fully Polynomial-Time Approximation Scheme). On the practical side, we provide a greedy algorithm, whose performance is shown to be close to the optimal for a realistic set of evaluation scenarios. Extensive simulations illustrate the usefulness of detectors with false negatives, which are available at a lower cost than the guaranteed detectors.

This work was accepted for publication in the *Journal of Parallel and Distributed Computing* [7].

7.18. Checkpointing strategies for scheduling computational workflows

Participants: Anne Benoit, Yves Robert.

We study the scheduling of computational workflows on compute resources that experience exponentially distributed failures. When a failure occurs, rollback and recovery is used to resume the execution from the last checkpointed state. The scheduling problem is to minimize the expected execution time by deciding in which order to execute the tasks in the workflow and deciding for each task whether to checkpoint it or not after it completes. We give a polynomial-time optimal algorithm for fork DAGs (Directed Acyclic Graphs) and show that the problem is NP-complete with join DAGs. We also investigate the complexity of the simple case in which no task is checkpointed. Our main result is a polynomial-time algorithm to compute the expected execution time of a workflow, with a given task execution order and specified to-be-checkpointed tasks. Using this algorithm as a basis, we propose several heuristics for solving the scheduling problem. We evaluate these heuristics for representative workflow configurations.

This work was published in the *International Journal of Networking and Computing* [4].

7.19. Assessing General-Purpose Algorithms to Cope with Fail-Stop and Silent Errors

Participants: Anne Benoit, Aurélien Cavelan, Yves Robert, Hongyang Sun.

We combine the traditional checkpointing and rollback recovery strategies with verification mechanisms to cope with both fail-stop and silent errors. The objective is to minimize makespan and/or energy consumption. For divisible load applications, we use first-order approximations to find the optimal checkpointing period to minimize execution time, with an additional verification mechanism to detect silent errors before each checkpoint, hence extending the classical formula by Young and Daly for fail-stop errors only. We further extend the approach to include intermediate verifications, and to consider a bi-criteria problem involving both time and energy (linear combination of execution time and energy consumption). Then, we focus on application workflows whose dependence graph is a linear chain of tasks. Here, we determine the optimal checkpointing and verification locations, with or without intermediate verifications, for the bi-criteria problem. Rather than using a single speed during the whole execution, we further introduce a new execution scenario, which allows for changing the execution speed via dynamic voltage and frequency scaling (DVFS). In this latter scenario, we determine the optimal checkpointing and verification locations, as well as the optimal speed pairs for each task segment between any two consecutive checkpoints. Finally, we conduct an extensive set of simulations to support the theoretical study, and to assess the performance of each algorithm, showing that the best overall performance is achieved under the most flexible scenario using intermediate verifications and different speeds.

This work was accepted for publication in the journal *ACM Transactions on Parallel Computing* [8].

7.20. A failure detector for HPC platforms

Participant: Yves Robert.

Building an infrastructure for Exascale applications requires, in addition to many other key components, a stable and efficient failure detector. This work describes the design and evaluation of a robust failure detector, able to maintain and distribute the correct list of alive resources within proven and scalable bounds. The detection and distribution of the fault information follow different overlay topologies that together guarantee minimal disturbance to the applications. A virtual observation ring minimizes the overhead by allowing each node to be observed by another single node, providing an unobtrusive behavior. The propagation stage is using a non-uniform variant of a reliable broadcast over a circulant graph overlay network, and guarantees a logarithmic fault propagation. Extensive simulations, together with experiments on the Titan ORNL supercomputer, show that the algorithm performs extremely well, and exhibits all the desired properties of an Exascale-ready algorithm.

This work was presented at the *SC'16* conference [24].

7.21. Optimal multistage algorithm for adjoint computatio

Participant: Yves Robert.

We reexamine the work of Stumm and Walther on multistage algorithms for adjoint computation. We provide an optimal algorithm for this problem when there are two levels of checkpoints, in memory and on disk. Previously, optimal algorithms for adjoint computations were known only for a single level of checkpoints with no writing and reading costs; a well-known example is the binomial checkpointing algorithm of Griewank and Walther. Stumm and Walther extended that binomial checkpointing algorithm to the case of two levels of checkpoints, but they did not provide any optimality results. We bridge the gap by designing the first optimal algorithm in this context. We experimentally compare our optimal algorithm with that of Stumm and Walther to assess the difference in performance.

This work was accepted for publication in the *SIAM Journal on Scientific Computing* [5].

7.22. Assessing the cost of redistribution followed by a computational kernel: Complexity and performance results

Participant: Yves Robert.

The classical redistribution problem aims at optimally scheduling communications when reshuffling from an initial data distribution to a target data distribution. This target data distribution is usually chosen to optimize some objective for the algorithmic kernel under study (good computational balance or low communication volume or cost), and therefore to provide high efficiency for that kernel. However, the choice of a distribution minimizing the target objective is not unique. This leads to generalizing the redistribution problem as follows: find a re-mapping of data items onto processors such that the data redistribution cost is minimal, and the operation remains as efficient. This work studies the complexity of this generalized problem. We compute optimal solutions and evaluate, through simulations, their gain over classical redistribution. We also show the NP-hardness of the problem to find the optimal data partition and processor permutation (defined by new subsets) that minimize the cost of redistribution followed by a simple computational kernel. Finally, experimental validation of the new redistribution algorithms are conducted on a multicore cluster, for both a 1D-stencil kernel and a more compute-intensive dense linear algebra routine.

This work has been published in the Parallel Computing journal [14].

7.23. When Amdahl Meets Young/Daly

Participants: Aurélien Cavelan, Yves Robert.

This work investigates the optimal number of processors to execute a parallel job, whose speedup profile obeys Amdahl's law, on a large-scale platform subject to fail-stop and silent errors. We combine the traditional checkpointing and rollback recovery strategies with verification mechanisms to cope with both error sources. We provide an exact formula to express the execution overhead incurred by a periodic checkpointing pattern of length T and with P processors, and we give first-order approximations for the optimal values T* and P* as a function of the individual processor MTBF. A striking result is that P* is of the order of the fourth root of the individual MTBF if the checkpointing cost grows linearly with the number of processors, and of the order of its third root if the checkpointing cost stays bounded for any P. We conduct an extensive set of simulations to support the theoretical study. The results confirm the accuracy of first-order approximation under a wide range of parameter settings.

This work was presented at the *Cluster'16* conference [26].

7.24. Computing the expected makespan of task graphs in the presence of silent errors

Participants: Julien Herrmann, Yves Robert.

Applications structured as Directed Acyclic Graphs (DAGs) of tasks correspond to a general model of parallel computation that occurs in many domains, including popular scientific workflows. DAG scheduling has received an enormous amount of attention, and several list-scheduling heuristics have been proposed and shown to be effective in practice. Many of these heuristics make scheduling decisions based on path lengths in the DAG. At large scale, however, compute platforms and thus tasks are subject to various types of failures with no longer negligible probabilities of occurrence. Failures that have recently received increasing attention are silent errors, which cause a task to produce incorrect results even though it ran to completion. Tolerating silent errors is done by checking the validity of the results and re-executing the task from scratch in case of an invalid result. The execution time of a task then becomes a random variable, and so are path lengths. Unfortunately, computing the expected makespan of a DAG (and equivalently computing expected path lengths in a DAG) is a computationally difficult problem. Consequently, designing effective scheduling heuristics is preconditioned on computing accurate approximations of the expected makespan. In this work we propose an algorithm that computes a first order approximation of the expected makespan of a DAG when tasks are subject to silent errors. We compare our proposed approximation to previously proposed such approximations for three classes of application graphs from the field of numerical linear algebra. Our evaluations quantify approximation error with respect to a ground truth computed via a brute-force Monte Carlo method. We find that our proposed approximation outperforms previously proposed approaches, leading to large reductions in approximation error for low (and realistic) failure rates, while executing much faster.

This work was presented at the *Ninth Int. Workshop on Parallel Programming Models and Systems Software for High-End Computing (P2S2)* [25].

7.25. Toward an Optimal Online Checkpoint Solution under a Two-Level HPC Checkpoint Model

Participants: Yves Robert, Frédéric Vivien.

The traditional single-level checkpointing method suffers from significant overhead on large-scale platforms. Hence, multilevel checkpointing protocols have been studied extensively in recent years. The multilevel checkpoint approach allows different levels of checkpoints to be set (each with different checkpoint overheads and recovery abilities), in order to further improve the fault tolerance performance of extreme-scale HPC applications. How to optimize the checkpoint intervals for each level, however, is an extremely difficult problem. In this work, we construct an easy-to-use two-level checkpoint model. Checkpoint level 1 deals with errors with low checkpoint/recovery overheads such as transient memory errors, while checkpoint level 2 deals with hardware crashes such as node failures. Compared with previous optimization work, our new optimal checkpoint solution offers two improvements: (1) it is an online solution without requiring knowledge of the job length in advance, and (2) it shows that periodic patterns are optimal and determines the best pattern. We evaluate the proposed solution and compare it with the most up-to-date related approaches on an extreme-scale simulation testbed constructed based on a real HPC application execution. Simulation results show that our proposed solution outperforms other optimized solutions and can improve the performance significantly in some cases. Specifically, with the new solution the wall-clock time can be reduced by up to 25.3% over that of other state-of-the-art approaches. Finally, a brute-force comparison with all possible patterns shows that our solution is always within 1% of the best pattern in the experiments.

This work has been published in IEEE Transactions on Parallel and Distributed Systems [11].

7.26. Cell morphing: from array programs to array-free Horn clauses

Participants: Laure Gonnord, David Monniaux [(CNRS/Verimag)], Julien Braine [(M2 Student)].

Automatically verifying safety properties of programs is hard. Many approaches exist for verifying programs operating on Boolean and integer values (e.g. abstract interpretation, counterexample-guided abstraction refinement using interpolants), but transposing them to array properties has been fraught with difficulties. Our work addresses that issue with a powerful and flexible abstraction that morphes concrete array cells into a finite set of abstract ones. This abstraction is parametric both in precision and in the back-end analysis used. From our programs with arrays, we generate nonlinear Horn clauses over scalar variables only, in a common format with clear and unambiguous logical semantics, for which there exist several solvers. We thus avoid the use of solvers operating over arrays, which are still very immature. Experiments with our prototype VAPHOR show that this approach can prove automatically and without user annotations the functional correctness of several classical examples, including *selection sort*, *bubble sort*, *insertion sort*, as well as examples from literature on array analysis.

This work has been published in Static Analysis Symposium [30] for the array part. We are currently deseigning an extension to programs with inductive data structures.

7.27. Symbolic Analyses of pointers

Participants: Laure Gonnord, Maroua Maalej, Fernando Pereira [(UFMG, Brasil)], Leonardo Barbosa [(UFMG, Brasil)], Vitor Paisante [(UFMG, Brasil)], Pedro Ramos [(UFMG, Brasil)].

Alias analysis is one of the most fundamental techniques that compilers use to optimize languages with pointers. However, in spite of all the attention that this topic has received, the current state-of-the-art approaches inside compilers still face challenges regarding precision and speed. In particular, pointer arithmetic, a key feature in C and C++, is yet to be handled satisfactorily.

A first work presents a new range-based alias analysis algorithm to solve this problem. The key insight of our approach is to combine alias analysis with symbolic range analysis. This combination lets us disambiguate fields within arrays and structs, effectively achieving more precision than traditional algorithms. To validate our technique, we have implemented it on top of the LLVM compiler. Tests on a vast suite of benchmarks show that we can disambiguate several kinds of C idioms that current state-of-the-art analyses cannot deal with. In particular, we can disambiguate 1.35x more queries than the alias analysis currently available in LLVM. Furthermore, our analysis is very fast: we can go over one million assembly instructions in 10 seconds.

A second work starts from an obvious, yet unexplored, observation: if a pointer is strictly less than another, they cannot alias. Motivated by this remark, we use the abstract interpretation framework to build strict less-than relations between pointers. To this end, we construct a program representation that bestows the Static Single Information (SSI) property onto our dataflow analysis. SSI gives us an efficient sparse algorithm, which, once seen as a form of abstract interpretation, is correct by construction. We have implemented our static analysis in LLVM. It runs in time linear on the number of program variables, and, depending on the benchmark, it can be as much as six times more precise than the pointer disambiguation techniques already in place in that compiler.

This work has been published in the *International Symposium of Code Generation and Optmization* [31] and at CGO'17 [29].

7.28. High-Level Synthesis of Pipelined FSM from Loop Nests

Participants: Christophe Alias, Fabrice Rastello [(Inria/CORSE)], Alexandru Plesco [(XtremLogic SAS, France)].

Embedded systems raise many challenges in power, space and speed efficiency. The current trend is to build heterogeneous systems on a chip with specialized processors and hardware accelerators. Generating an hardware accelerator from a computational kernel requires a deep reorganization of the code and the data. Typically, parallelism and memory bandwidth are met thanks to fine-grain loop transformations. Unfortunately, the resulting control automaton is often very complex and eventually bound the circuit frequency, which limits the benefits of the optimization. This is a major lock, which strongly limits the power of the code optimizations appliable by high-level synthesis tools.

In this work, we propose an architecture of control automaton and an algorithm of high-level synthesis which translates efficiently the control required by fine-grain loop optimizations. Unlike the previous approaches, our control automaton can be pipelined *at will, without any restriction*. Hence, the frequency of the automaton can be as high as possible. Experimental results on FPGA confirms that our control circuit can reach a high frequency with a reasonable resource consumption.

This work is described in a technical report [36].

7.29. Estimation of Parallel Complexity with Rewriting Techniques

Participants: Christophe Alias, Laure Gonnord, Carsten Fuhs [(Birbeck, UK)].

We show how monotone interpretations - a termination analysis technique for term rewriting systems - can be used to assess the inherent parallelism of recursive programs manipulating inductive data structures. As a side effect, we show how monotone interpretations specify a parallel execution order, and how our approach extends naturally affine scheduling - a powerful analysis used in parallelising compilers - to recursive programs. This preliminary work opens new perspectives in automatic parallelisation.

This work has been published in the *Workshop on Termination,* [15].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Mumps Consortium (2014-2019)

In 2016, in the context of the MUMPS consortium (http://mumps-consortium.org):

- We have signed two new membership agreements, with Free Field Technologies and Safran in 2016, on top of the on-going agreements signed in 2014 and 2015 with Altair, EDF, ESI-Group, LSTC, Michelin, Siemens SISW (Belgium) and TOTAL.
- We have organized point-to-point meetings with several members.
- We have provided technical support and scientific advice to members.
- We have provided non-public releases in advance to members, with a specific licence.
- We have organized the second consortium committee meeting, at Michelin (Clermont-Ferrand).
- Two engineers have been funded by the membership fees, for software engineering and software development, performance study and comparisons, business development and management of the consortium.
- 0.5 year of a PhD student were funded by the membership fees (see Section 9.1).

8.2. Technological Transfer: XtremLogic Start-Up

The XTREMLOGIC start-up (former Zettice project) was initiated 5 years ago by Alexandru Plesco and Christophe Alias.

The goal of XTREMLOGIC is to provide energy-efficient circuit blocks for FPGA reconfigurable circuits. These circuits are produced automatically through an high-level synthesis (HLS) tool based on state-of-the-art automatic parallelization technologies, notably from the polyhedral community. The compiler technology transfered to XTREMLOGIC is the result of a tight collaboration between Christophe Alias and Alexandru Plesco. In a way, XTREMLOGIC can be viewed as “applied research” targetting a direct industrial application.

XTREMLOGIC won several awards and grants: Rhône Développement Initiative 2015 (loan), “concours émergence OSEO 2013” at Banque Publique d’Investissement (grant), “most promising start-up award” at SAME 2013 (award), “lean Startup award” at Startup Weekend Lyon 2012 (award), “excel&rate award 2012” from Crealys incubation center (award).

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. PhD grant laboratoire d'excellence MILYON-Mumps consortium

Thanks to the doctoral program from the MILYON labex dedicated to applied research in collaboration with industrial partners, we obtained 50% of a PhD grant, the other 50% being funded by the MUMPS consortium. The PhD student will focus on improvements of the solution phase of the MUMPS solver, in accordance to requirements from industrial members of the consortium.

9.2. National Initiatives

9.2.1. ANR

ANR Project SOLHAR (2013-2017), 4 years. The ANR Project SOLHAR was launched in November 2013, for a duration of 48 months. It gathers five academic partners (the HiePACS, Cepage, ROMA and Runtime Inria project-teams, and CNRS-IRIT) and two industrial partners (CEA/CESTA and EADS-IW). This project aims at studying and designing algorithms and parallel programming models for implementing direct methods for the solution of sparse linear systems on emerging computers equipped with accelerators.

The proposed research is organized along three distinct research thrusts. The first objective deals with linear algebra kernels suitable for heterogeneous computing platforms. The second one focuses on runtime systems to provide efficient and robust implementation of dense linear algebra algorithms. The third one is concerned with scheduling this particular application on a heterogeneous and dynamic environment.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. SCORPIO

Title: Significance-Based Computing for Reliability and Power Optimization

Programm: FP7

Duration: June 2013 - May 2016

Coordinator: Kentro Erevnas Technologias Kai Anaptyxix Thessalias

Partners:

- Ethniko Kentro Erevnas Kai Technologikis Anaptyxis (Greece)
- Ecole Polytechnique Federale de Lausanne (Switzerland)
- The Queen's University of Belfast (United Kingdom)
- Rheinisch-Westfaelische Technische Hochschule Aachen (Germany)
- Interuniversitair Micro-Electronica Centrum Vzw (Belgium)

Inria contact: Frédéric Vivien

Manufacturing process variability at low geometries and power dissipation are the most challenging problems in the design of future computing systems. Currently manufacturers go to great lengths to guarantee fault-free operation of their products by introducing redundancy in voltage margins, conservative layout rules, and extra protection circuitry. However, such design redundancy may result into energy overheads. Energy overheads cannot be alleviated by lowering supply voltage below a nominal value without hardware components experiencing faulty operation due to timing errors. On the other hand, many modern workloads, such as multimedia, machine learning, visualization, etc. are designed to tolerate a degree of imprecision in computations and data. SCoRPiO seeks to exploit this observation and to relax reliability requirements for the hardware layer by allowing a controlled degree of imprecision to be introduced to computations and data. It proposes to introduce methodologies that allow the system- and application-software layers to synergistically characterize the significance of various parts of the program for the quality of the end result, and their tolerance to faults. Based on this information, extracted automatically or semi-automatically, the system software will steer computations and data to either low-power, yet unreliable or higher-power and reliable functional and storage units. In addition, the system will be able to aggressively reduce its power footprint by opportunistically powering hardware modules below nominal values. Significance-based computing lays the foundations for not only approaching the theoretical limits of energy reduction of CMOS technology, but moving beyond those limits by accepting hardware faults in a controlled manner. Significance-based computing promises to be a preferred alternative to dark silicon, which requires that large portions of a chip be powered-off in every cycle to avoid excessive power dissipation.

9.4. International Initiatives

9.4.1. Inria International Labs

9.4.1.1. JLESC — Joint Laboratory on Extreme Scale Computing

The University of Illinois at Urbana-Champaign, Inria, the French national computer science institute, Argonne National Laboratory, Barcelona Supercomputing Center, Jülich Supercomputing Centre and the Riken Advanced Institute for Computational Science formed the Joint Laboratory on Extreme Scale Computing, a follow-up of the Inria-Illinois Joint Laboratory for Petascale Computing. The Joint Laboratory is based at Illinois and includes researchers from Inria, and the National Center for Supercomputing Applications, ANL, BSC and JSC. It focuses on software challenges found in extreme scale high-performance computers.

Research areas include:

- Scientific applications (big compute and big data) that are the drivers of the research in the other topics of the joint-laboratory.
- Modeling and optimizing numerical libraries, which are at the heart of many scientific applications.
- Novel programming models and runtime systems, which allow scientific applications to be updated or reimagined to take full advantage of extreme-scale supercomputers.
- Resilience and Fault-tolerance research, which reduces the negative impact when processors, disk drives, or memory fail in supercomputers that have tens or hundreds of thousands of those components.
- I/O and visualization, which are important part of parallel execution for numerical silulations and data analytics
- HPC Clouds, that may execute a portion of the HPC workload in the near future.

Several members of the ROMA team are involved in the JLESC joint lab through their research on resilience. Yves Robert is the Inria executive director of JLESC.

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

9.4.2.1. Keystone

Title: Scheduling algorithms for sparse linear algebra at extreme scale

International Partner (Institution - Laboratory - Researcher):

Vanderbilt University (United States) - Padma Raghavan

Start year: 2016

See also: http://graal.ens-lyon.fr/~abenoit/Keystone

The Keystone project aims at investigating sparse matrix and graph problems on NUMA multicores and/or CPU-GPU hybrid models. The goal is to improve the performance of the algorithms, while accounting for failures and trying to minimize the energy consumption. The long-term objective is to design robust sparse-linear kernels for computing at extreme scale. In order to optimize the performance of these kernels, we plan to take particular care of locality and data reuse. Finally, there are several real-life applications relying on these kernels, and the Keystone project will assess the performance and robustness of the scheduling algorithms in applicative contexts. We believe that the complementary expertise of the two teams in the area of scheduling HPC applications at scale (ROMA — models and complexity; and SSCL — architecture and applications) is the key to the success of this associate team. We have already successfully collaborated in the past and expect the collaboration to reach another level thanks to Keystone.

9.4.3. Inria International Partners

9.4.3.1. Declared Inria International Partners

- Christophe Alias has a regular collaboration with Sanjay Rajopadhye from Colorado State University (USA) through the advising of the PhD thesis of Guillaume Iooss.
- Anne Benoit, Frédéric Vivien and Yves Robert have a regular collaboration with Henri Casanova from Hawaii University (USA). This is a follow-on of the Inria Associate team that ended in 2014.

9.4.4. Cooperation with ECNU

ENS Lyon has launched a partnership with ECNU, the East China Normal University in Shanghai, China. This partnership includes both teaching and research cooperation.

As for teaching, the PROSFER program includes a joint Master of Computer Science between ENS Rennes, ENS Lyon and ECNU. In addition, PhD students from ECNU are selected to conduct a PhD in one of these ENS. Yves Robert is responsible for this cooperation. He has already given two classes at ECNU, on Algorithm Design and Complexity, and on Parallel Algorithms, together with Patrice Quinton (from ENS Rennes).

As for research, the JORISS program funds collaborative research projects between ENS Lyon and ECNU. Yves Robert and Changbo Wang (ECNU) are leading a JORISS project on resilience in cloud and HPC computing.

In the context of this collaboration two students from ECNU, Li Han and Changjiang Gou, have joined Roma for their PhD.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

- Samuel McCauley visited the team for four months (Oct. 2015 - Feb. 2016) to work with Loris Marchal, Bertrand Simon and Frédéric Vivien on the minimization of I/Os during the out-of-core execution of task trees.

9.5.1.1. Internships

- Laure Gonnord supervised two Master Students in Spring 2016, Vitor Paisante (static analyses for pointers) and Julien Braine (static analyses for data structures).
- Bora Uçar supervised an Raluca Portase, an Erasmus student, for three months (June–September 2016).

9.5.2. Visits to International Teams

9.5.2.1. Research Stays Abroad

- Yves Robert has been appointed as a visiting scientist by the ICL laboratory (headed by Jack Dongarra) at the University of Tennessee Knoxville. He collaborates with several ICL researchers on high-performance linear algebra and resilience methods at scale.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

Laure Gonnord is co-chair of the “Compilation French community”, with Florian Brandner (ENSTA) and Fabrice Rastello (Inria Corse).

Bora Uçar was the workshops chair at IPDPS 2016, local chair of the a topic of Euro-Par 2016, co-chair of PCO 2016 (a workshop of IPDPS 2016), and has organized mini-symposia at SIAM PP16 and PMAA16.

10.1.2. Scientific Events Selection

10.1.2.1. Steering committees

Yves Robert is a member of the steering committee of HCW, Heteropar and IPDPS. He is the chair of the steering committee of Euro-EduPar.

Bora Uçar serves in the steering committee of CSC.

10.1.2.2. Chair of Conference Program Committees

Anne Benoit was the program chair of HiPC 2016, and the program area chair for Algorithms of SC 2016.

Loris Marchal was the program chair of HeteroPar 2016.

10.1.2.3. Member of the Conference Program Committees

Christophe Alias was a member of the program committee of IMPACT’16.

Anne Benoit was a member of the program committee of IPDPS, SC, HCW, and Ena-HPC.

Laure Gonnord was a member of the program committee of VMCAI’17.

Jean-Yves L’Excellent was a member of the program committee of VECPAR’16.

Loris Marchal was a member of the program committee of IPDPS 2016.

Yves Robert was a member of the program committee of FTS, FTXS, ICCS, ISCIS, and SC

Bora Uçar was a member of the program committee of the following conferences and workshops: HiPC 2016, IPDPS 2016, ICCS 2016, HPC4BD 2016, P^3MA, CSE 2016, MPP2016.

Frédéric Vivien was a member of the program committee of IPDPS, SC, HiPC, PDP, EduPar, EuroEduPar and WAPCO.

10.1.2.4. Reviewer

Jean-Yves L’Excellent reviewed papers for VECPAR’16, ADVCOMP’16.

Christophe Alias reviewed papers for IMPACT’16.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

Anne Benoit is Associate Editor of TPDS (IEEE Transactions on Parallel and Distributed Systems), of JPDC (Elsevier Journal of Parallel and Distributed Computing) and SUSCOM (Elsevier Journal of Sustainable Computing).

Loris Marchal is an invited associated Editor of Parallel Computing (Elsevier) for a special issue following HeteroPar 2016.

Yves Robert is Associate Editor f TPDS (IEEE Transactions on Parallel and Distributed Systems), JPDC (Elsevier Journal of Parallel and Distributed Computing), IJHPCA (Sage International Journal of High Performance Computing Applications), and JOCS (Elsevier Journal of Computational Science).

Bora Uçar is Associate Editor of Parallel Computing (Elsevier).

Frédéric Vivien is Associate Editor of Parallel Computing (Elsevier) and of JPDC (Elsevier Journal of Parallel and Distributed Computing).

10.1.3.2. Reviewer - Reviewing Activities

Christophe Alias reviewed papers for TVLSI (IEEE Transactions on Very Large Scale Integration Systems), PARCO (Parallel Computing), MICPRO (Microprocessors and Microsystems).

10.1.4. Invited Talks

Christophe Alias gave a talk at "Journée Calcul" in ENS-Lyon on May 2016 and a talk at "Journée Langage, Compilation et Sémantique" in ENS-Lyon on November 2016.

10.1.5. Tutorials

Yves Robert gave a tutorial on *Fault-tolerance techniques for HPC platforms* at PPoPP'16 (with Thomas Hérault), SC'16 (with Aurélien Bouteiller, George Bosilca, and Thomas Hérault) and Euro-Par'16.

10.1.6. Leadership within the Scientific Community

Christophe Alias, together with Cédric Bastoul (CAMUS), co-founded the Impact workshop (International Workshop on Polyhedral Compilation Techniques) on 2011, which is now the reference international event of the polyhedral compilation community http://impact.gforge.inria.fr/. Since then, Christophe Alias is involved in IMPACT committees.

Laure Gonnord, together with Fabrice Rastello (CORSE) and Florian Brandner (Telecom Paris Tech) animate since 2010 the French Compilation Community (http://compilfr.ens-lyon.fr).

10.1.7. Research Administration

Anne Benoit is a member of the executive committee of the Labex MI-LYON. She is the head of the Master of fundamental computer science at ENS Lyon.

Loris Marchal is a member of the scientific council of the "Ecole Nationale Supe´rieure de Me´canique et des Microtechniques" (ENSMM, Besançon).

Jean-Yves L'Excellent is a member of the direction board of the LIP laboratory.

Yves Robert was a member of the Senior Member election of Institut Universitaire de France. He was a committee member of the IEEE Fellows selection. he is a member of the scientific council of the Maison de la Simulation.

Frédéric Vivien is a member of the scientific council of the École normale supérieure de Lyon and of the academic council of the University of Lyon.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence:

- Anne Benoit : Algorithmique avancée (CM 32h), L3, Ecole Normale Supérieure de Lyon.
- Maroua Maalej : Algorithmique et Programmation Avancée (TD=18, TP=24h), L2, Université Lyon 1 Claude Bernard : Autumn 2016.
- Maroua Maalej : Architecture et système (TP=24h), L2, Université Lyon 1 Claude Bernard : Autumn 2016.
- Maroua Maalej : Gestion de Projet et Génie Logiciel (TD/TP=10h), M1, Université Lyon 1 Claude Bernard : Autumn 2016.
- Christophe Alias : Compilation et outils de développement (CM+TD=18h), L3, INSA Centre-Val-de-Loire : Spring 2016.

- Christophe Alias : Concours E3A – épreuve informatique MPSI (correcteur) : Spring 2016.
- Yves Robert : Algorithmique (CM 32h), L3, Ecole Normale Supérieure de Lyon

Master:

- Anne Benoit, Resilient and energy-aware scheduling algorithms (CM 24h), M2, Ecole Normale Supérieure de Lyon.
- Laure Gonnord : Compilation (CM+TD 76h), M1, Université Claude Bernard Lyon 1, et M1 Ecole Normale Supérieure de Lyon.
- Laure Gonnord : Préparation à l'écrit et à l'oral d'informatique du capès d'informatique, 10h, M1 MEEF Université Claude Bernard Lyon1.
- Laure Gonnord : Program Analysis : (CM+TP 10h, avec D.Monniaux), M2 Ecole Normale Supérieure de Lyon.
- Christophe Alias : Optimisation d'applications embarquées (CM+TD=24h), M1, INSA Centre-Val-de-Loire.
- Christophe Alias: Advanced Compilers: Automatic Parallelization and High-level Synthesis (CM 24h, avec F. Rastello), M2, Ecole Normale Supérieure de Lyon, France.
- Frédéric Vivien, Algorithmique et Programmation Parallèles et Distribuées (CM 36 h), M1, École normale supérieure de Lyon, France.

10.2.2. Supervision

PhD in progress: Aurélien Cavelan, "Resilient and energy-aware scheduling algorithms for large-scale distributed systems", started in September 2014, advisors: Anne Benoit and Yves Robert.

PhD in progress: Changjiang Gou, "Resilient and energy-aware scheduling algorithms for large-scale distributed systems", started in September 2016, funding: China Scholarship Council, advisors: Anne Benoit and Loris Marchal.

PhD in progress: Li Han, "Algorithms for detecting and correcting silent and non-functional errors in scientific workflows", started in September 2016, funding: China Scholarship Council, advisors: Yves Robert and Frédéric Vivien

PhD in progress: Oguz Kaya, "High performance parallel tensor computations", started in September 2014, funding: Inria, advisors: Bora Uçar and Yves Robert.

PhD in progress: Aurélie Kong Win Chang, "Techniques de résilience pour l'ordonnancement de workflows sur plates-formes décentralisées (cloud computing) avec contraintes de sécurité", started in October 2016, funding: ENS Lyon, advisors: Yves Robert, Yves Caniou and Eddy Caron.

PhD in progress: Maroua Maalej, "Low cost static analyses for compilers", started in October 2014, advisors : Laure Gonnord and Frédéric Vivien.

PhD in progress: Gilles Moreau, "High-performance multifrontal solution of sparse linear systems with multiple right-hand sides, application to the MUMPS solver", started in December 2015, funding: MUMPS consortium and Labex MILYON, advisor: Jean-Yves L'Excellent.

PhD in progress: Loic Pottier, "Scheduling concurrent applications in the presence of failures", started in September 2015, advisors: Anne Benoit and Yves Robert.

PhD in progress: Issam Rais, "Multi-criteria scheduling for high-performance computing", started in November 2015, advisors: Anne Benoit, Laurent Lefèvre (LIP, ENS Lyon, Avalon team), and Anne-Cécile Orgerie (IRISA, Myriads team).

PhD in progress: Bertrand Simon, "Task-graph scheduling and memory optimization", started in September 2015, funding: ENS Lyon, advisors: Loris Marchal and Frédéric Vivien.

PhD defended on July 1st: Guillaume Iooss, "Semantic tiling", started in September 2011, joint PhD ENS-Lyon/Colorado State University, advisors: Christophe Alias and Alain Darte (ENS-Lyon) / Sanjay Rajopadhye (Colorado State University).

10.2.3. Juries

- Christophe Alias participated to the PhD jury of Guillaume Iooss (Colorado State University), in July 2016.
- Laure Gonnord participated to the Inria recruting jury for junior research positions (CR2), in Rennes, in Spring 2016.
- Laure Gonnord participated to the PhD jury of Nasrine Damouche (Univ. Perpignan) and Sajith Kalathingal (Univ. Rennes), in December 2016.
- Laure Gonnord is member of the “Comité de Suivi de thèse” de Maurica Fonenantsoa (Univ. Réunion) since 2015.
- Loris Marchal participated to the selection committee recruting an assistant professor (MCF) at University of Bordeaux 1, in Spring 2016.

10.3. Popularization

Frédéric Vivien gave two lectures about “Approximation algorithms” at the CIRM “Algorithmique et programmation” workshop for Maths teachers in *Classes préparatoires aux grandes écoles*. The two lectures were recorded and are available online (http://library.cirm-math.fr/Record.htm?Record=19278406157910966889).

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Publications of the year

Articles in International Peer-Reviewed Journal

[1] E. AGULLO, P. R. AMESTOY, A. BUTTARI, A. GUERMOUCHE, J.-Y. L'EXCELLENT, F.-H. ROUET.*Robust memory-aware mappings for parallel multifrontal factorizations*, in "SIAM Journal on Scientific Computing", July 2016, vol. 38, n^o 3, 23, https://hal.inria.fr/hal-01334113.

[2] P. R. AMESTOY, R. BROSSIER, A. BUTTARI, J.-Y. L'EXCELLENT, T. MARY, L. MÉTIVIER, A. MINIUSSI, S. OPERTO.*Fast 3D frequency-domain full waveform inversion with a parallel Block Low-Rank multifrontal direct solver: application to OBC data from the North Sea*, in "Geophysics", 2016, vol. 81, n^o 6, p. R363-R383, https://hal.inria.fr/hal-01349119.

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Project-Team SOCRATE

Software and Cognitive Radio for Telecommunications

IN COLLABORATION WITH: Centre of Innovation in Telecommunications and Integration of services

IN PARTNERSHIP WITH:
Institut national des sciences appliquées de Lyon

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Networks and Telecommunications

Table of contents

Project-Team SOCRATE

Creation of the Team: 2012 January 01, updated into Project-Team: 2013 July 01

Keywords:

Computer Science and Digital Science:

1.1.2. - Hardware accelerators (GPGPU, FPGA, etc.)
1.1.12. - Non-conventional architectures
1.2.5. - Internet of things
1.2.6. - Sensor networks
1.5.2. - Communicating systems
2.3.1. - Embedded systems
2.6.1. - Operating systems
5.9. - Signal processing
7.8. - Information theory

Other Research Topics and Application Domains:

6.2. - Network technologies
6.2.2. - Radio technology
6.4. - Internet of things
6.6. - Embedded systems

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2. Overall Objectives

2.1. Introduction

The success of radio networking relies on a small set of rules: *i)* protocols are completely defined beforehand, *ii)* resource allocation policies are mainly designed in a static manner and *iii)* access network architectures are planned and controlled. Such a model obviously lacks adaptability and also suffers from a suboptimal behavior and performance.

Because of the growing demand for radio resources, several heterogeneous standards and technologies have been introduced by the standard organizations or industry by different workgroups within the IEEE (802 family), ETSI (GSM), 3GPP (3G, 4G) or the Internet Society (IETF standards) leading to the almost saturated usage of several frequency bands (see Fig. 1).

These two facts, obsolescence of current radio networking rules on one hand, and saturation of the radio frequency band on the other hand, are the main premises for the advent of a new era of radio networking that will be characterized by self-adaptive mechanisms. These mechanisms will rely on software radio technologies, distributed algorithms, end-to-end dynamic routing protocols and therefore require a cross-layer vision of "cognitive wireless networking": *Getting to the meet of Cognition and Cooperation, beyond the inherent communication aspects: cognition is more than cognitive radio and cooperation is not just relaying. Cognition and cooperation have truly the potential to break new ground for mobile communication systems and to offer new business models.* [61]

From a social perspective, pervasive communications and ambient networking are becoming part of more and more facets of our daily life. Probably the most popular usage is mobile Internet access, which is made possible by numerous access technologies, e.g. cellular mobile networks, WiFi, Bluetooth, etc. The access technology itself is becoming *transparent for the end user*, who does not care about how to access the network but is only interested in the services available and in the quality of this service.

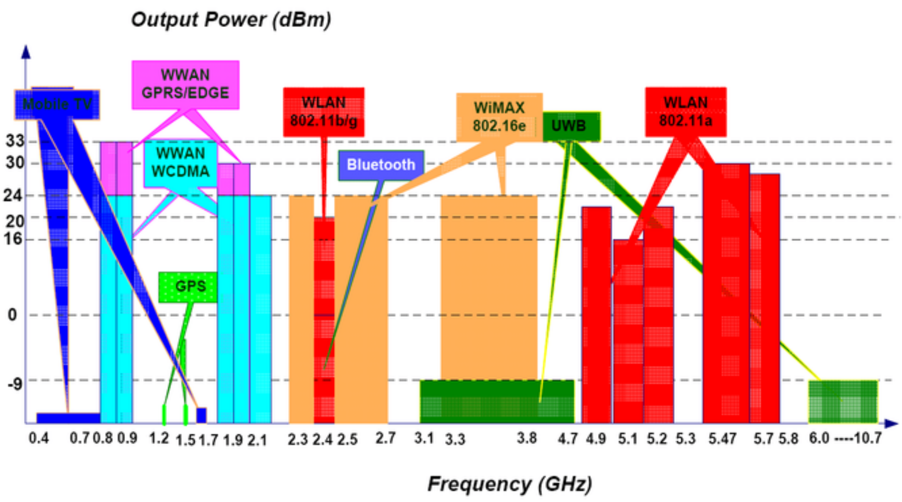

Figure 1. The most recent standards for wireless communications are developed in the UHF and VHF bands. These bands are mostly saturated (source: WPAN/WLAN/WWAN Multi-Radio Coexistence, IEEE 802 Plenary, Atlanta, USA, Nov.2007)

Beyond simple Internet access, many other applications and services are built on the basis of pervasive connectivity, for which the communication is just a mean, and not a finality. Thus, the wireless link is expected to even be *invisible to the end user* and constitutes the first element of the Future Internet of Things [60], to develop a complete twin virtual world fully connected to the real one.

The way radio technologies have been developed until now is far from offering a real wireless convergence [52]. The current development of the wireless industry is surely slowed down by the lack of radio resources and the lack of systems flexibility.

One can get rid of this technological bottleneck by solving three complementary problems: *terminal flexibility, agile radio resource management* and *autonomous networking*. These three objectives are subsumed by the concept of *Software Radio*, a term coined by J. Mitola in his seminal work during the early 90's [57], [58]. While implementing everything in software nodes is still an utopia, many architectures now hitting the market include some degree of programmability; this is called Software-Defined Radio. The word "defined" has been added to distinguish from the ideal software radio. A software *defined* radio is a software radio which is defined for a given frequency range and a maximal bandwidth.

In parallel, the development of new standards is threatened by the radio spectrum scarcity. As illustrated in Fig. 1, the increasing number of standards already causes partial saturation of the UHF band, and will probably lead to its full saturation in the long run. However, this saturation is only "virtual" because all equipments are fortunately not emitting all the time [52]. A good illustration is the so-called "white spaces", i.e. frequency bands that are liberated by analog television disappearing and can be re-used for other purposes, different rules are set up in different countries. In this example, a solution for increasing the real capacity of the band originates from *self-adaptive behavior*. In this case, flexible terminals will have to implement agile algorithms to share the radio spectrum and to avoid interference. In this context, cooperative approaches are even more promising than simple resource sharing algorithms.

With Software-Defined Radio technology, terminal flexibility is at hand, many questions arise that are related to the software layer of a software radio machine: how will this kind of platform be programmed? How can we write programs that are portable from one terminal to another? Autonomous networking will only be reached after a deep understanding of network information theory. Thus, given that there will be many ways for transmitting data from one point to another, what is the most efficient way in terms of throughput? power consumption? etc. Last but not least, agile Radio Resource sharing is addressed by studying MIMO and multi-standard radio front-end. This new technology is offering a wide range of research problems. These three topics: software programming of a software radio machine, distributed algorithms for radio resource management and multi-standard radio front-end constitute the research directions of Socrate.

2.2. Technological State of the Art

A Software-Defined Radio (SDR) system is a radio communication system in which computations that in the past were typically implemented in hardware (e.g. mixers, filters, amplifiers, modulators/demodulators, detectors, etc.) are instead implemented as software programs [57], [53].

2.2.1. SDR Technology

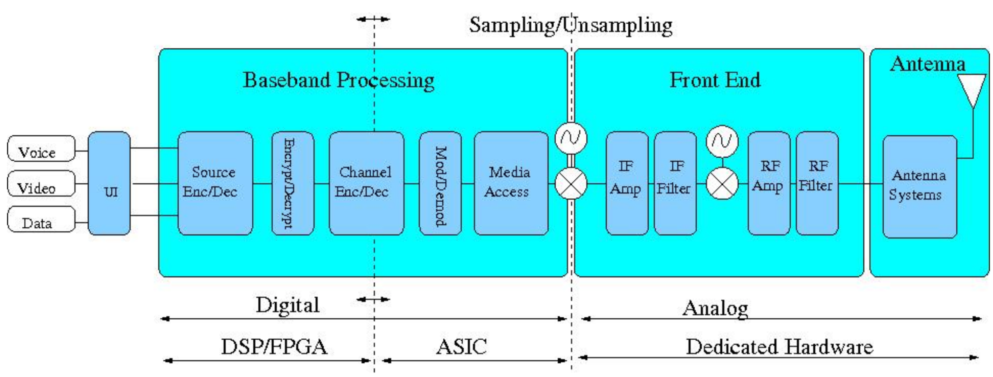

Figure 2. Radio Block Diagram, highlighting separation between digital and analog parts, as well as programmable, configurable and fixed hardware parts.

The different components of a radio system are illustrated in Fig. 2. Of course, all of the digital components may not be programmable, but the bigger the programmable part (DSP/FPGA part on Fig. 2), the more *software* the radio. Dedicated IPs. In this context, IP stand for *Intellectual Properties, this term is widely used to designated dedicated special-purpose circuit blocks implemented in various technologies: Asic,* FPGA*,* DSP*, etc.* are needed, for these IP it is more suitable to use the term *configurable* than programmable. In a typical SDR, the analog part is limited to a frequency translation down to an intermediate band which is sampled and all the signal processing is done digitally.

2.2.2. SDR Forum Classification

To encourage a common meaning for the term "SDR" the SDR Forum (recently renamed *Wireless Innovation Forum* (http://www.wirelessinnovation.org) proposes to distinguish five tiers:

- *Tier 0 – Hardware Radio:* The radio parameters cannot be changed, radio is implemented only with hardware components.
- *Tier 1 – Software Controlled Radio:* A radio where only the control functions are implemented in software, baseband processing is still performed in hardware, the radio is able to switch between different hardware.

- *Tier 2 – Software-Defined Radio:* The most popularly understood definition of SDR: the radio includes software control of modulation, bandwidth, frequency range and frequency bands. Conversion to digital domain still occurs after frequency conversion. It is currently implemented using a wide range of technologies: Asics, FPGAs, DSPs, etc.
- *Tier 3 – Ideal Software Radio:* Digital conversion occurs directly at the antenna, programmability extends to the whole system.
- *Tier 4 – Ultimate Software Radio:* Same reconfigurability capabilities as in Tier 3, but with a switching between two configurations in less than one millisecond.

The main restriction to build an ideal software radio is sampling rate: sampling at a high rate is not an easy task. Following the Shannon-Nyquist theorem, sampling the RF signal at a rate greater than twice the frequency of the signal is sufficient to reconstruct the signal. Sampling can be done at lower rate (decimation), but errors can be introduced (aliasing) that can be corrected by filtering (dirty radio concept). Building an SDR terminal implies a trade-of between sampling frequency and terminal complexity. For instance, sampling at 4.9 GHz would require a 12-bit resolution ADC with at least 10GHz sample rate which is today not available with reasonable power consumption (several hundreds Watt).

2.2.3. Cognitive Radio

SDR technology enables *over the air programming* (Otap) which consists in describing methods for distributing new software updates through the radio interface. However, as SDR architectures are heterogeneous, a standard distribution method has not emerged yet.

Cognitive Radio is a wireless communication system that can sense the air, and decide to configure itself in a given mode, following a local or distributed decision algorithm. Although Tier 3 SDR would be an ideal platform for cognitive radio implementation, cognitive radios do not have to be SDR.

Cognitive Radio is currently a very hot research topic as show the dozens of sessions in research conferences dedicated to it. In 2009, the American National Science Foundation (NSF) held a workshop on “Future Directions in Cognitive Radio Network Research” [59]. The purpose of the workshop was to explore how the transition from cognitive radios to cognitive radio *networks* can be made. The resulting report indicated the following:

- Emerging cognitive radio technology has been identified as a high impact disruptive technology innovation, that could provide solutions to the *radio traffic jam* problem and provide a path to scaling wireless systems for the next 25 years.
- Significant new research is required to address the many technical challenges of cognitive radio networking. These include dynamic spectrum allocation methods, spectrum sensing, cooperative communications, incentive mechanisms, cognitive network architecture and protocol design, cognitive network security, cognitive system adaptation algorithms and emergent system behavior.

The report also mentioned the lack of cognitive radio testbeds and urged *“The development of a set of cognitive networking test-beds that can be used to evaluate cognitive networks at various stages of their development”*, which, in some sense strengthens the creation of the Socrate team and its implication in the FIT project [55].

2.3. Scientific Challenges

Having a clear idea of relevant research areas in SDR is not easy because many parameters are not related to economical cost. For instance, military research has made its own development of SDR for its particular needs: US military SDR follows the SCA communication architecture [56] but this is usually not considered as a realistic choice for a commercial SDR handset. The targeted frequency band has a huge impact as sampling at high rates is very expensive, and trade-offs between flexibility, complexity, cost and power consumption have a big influence on the relative importance of the hot research topics.

Here are the relevant research domains where efforts are needed to help the deployment of SDR:

- *Antennas and RF Front-Ends:* This is a key issue for reducing interference, increasing capacity and reusing frequency. Hot topics such as wake-up radio or multi protocol parallel radio receivers are directly impacted by research on Antennas. Socrate has research work going on in this area.
- *Analog to Digital Converters:* Designing low-power high frequency ADC is still a hot topic rather studied by micro-electronics laboratories (Lip6 for instance in France).
- *Architecture of SDR systems:* The ideal technology for embedded SDR still has to be defined. Hardware prototypes are built using FPGAs, Asics and DSPs, but the real challenge is to handle a Hardware/Software design which includes radio and antennas parts.
- *Middleware for SDR systems:* How to manage, reconfigure, update and debug SDR systems is still an open question which is currently studied for each SDR platform prototype. Having a common programming interface for SDR systems in one research direction of Socrate.
- *Distributed signal processing:* Cognitive, smart or adaptive radios will need complex decision algorithms which, most of the time will need to be solved in a distributed manner. Socrate has clearly a strong research effort in that direction. Distributed information theory is also a hot research topic that Socrate wishes to study.

3. Research Program

3.1. Research Axes

In order to keep young researchers in an environment close to their background, we have structured the team along the three research axes related to the three main scientific domains spanned by Socrate. However, we insist that a *major objective* of the Socrate team is to *motivate the collaborative research between these axes*, this point is specifically detailed in Section 3.5. The first one is entitled "Flexible Radio Front-End" and will study new radio front-end research challenges brought up by the arrival of MIMO technologies, and reconfigurable front-ends. The second one, entitled "Multi-user communication", will study how to couple the self-adaptive and distributed signal processing algorithms to cope with the multi-scale dynamics found in cognitive radio systems. The last research axis, entitled "Software Radio Programming Models" is dedicated to embedded software issues related to programming the physical protocols layer on these software radio machines. Figure 3 illustrates the three regions of a transceiver corresponding to the three Socrate axes.

3.2. Flexible Radio Front-End

Participants: Guillaume Villemaud, Florin Hutu.

This axis mainly deals with the radio front-end of software radio terminals (right of Fig 3). In order to ensure a high flexibility in a global wireless network, each node is expected to offer as many degrees of freedom as possible. For instance, the choice of the most appropriate communication resource (frequency channel, spreading code, time slot,...), the interface standard or the type of antenna are possible degrees of freedom. The *multi-** paradigm denotes a highly flexible terminal composed of several antennas providing MIMO features to enhance the radio link quality, which is able to deal with several radio standards to offer interoperability and efficient relaying, and can provide multi-channel capability to optimize spectral reuse. On the other hand, increasing degrees of freedom can also increase the global energy consumption, therefore for energy-limited terminals a different approach has to be defined.

In this research axis, we expect to demonstrate optimization of flexible radio front-end by fine grain simulations, and also by the design of home made prototypes. Of course, studying all the components deeply would not be possible given the size of the team, we are currently not working in new technologies for DAC/ADC and power amplifiers which are currently studied by hardware oriented teams. The purpose of this axis is to build system level simulation taking into account the state of the art of each key component.

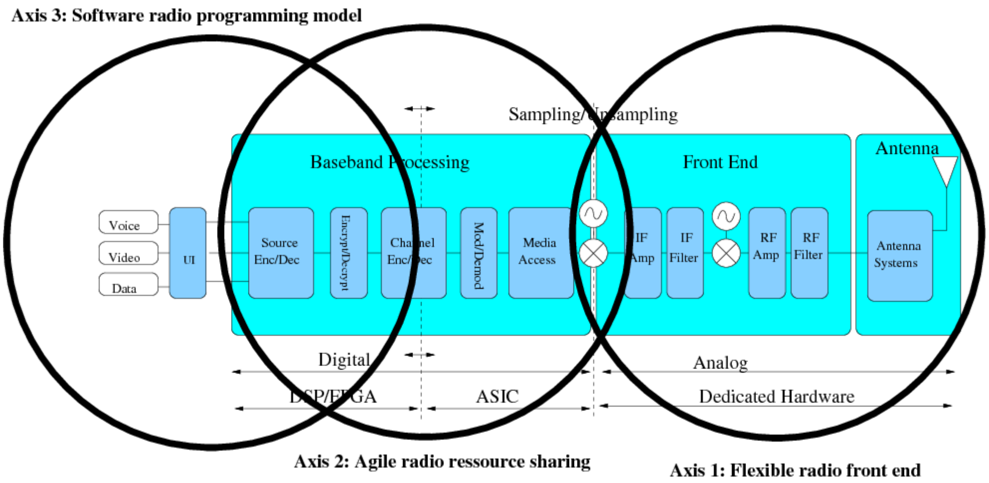

Figure 3. Center of interest for each of the three Socrate research axes with respect to a generic software radio terminal.

3.3. Multi-User Communications

Participants: Jean-Marie Gorce, Claire Goursaud, Nikolai Lebedev, Samir Perlaza, Leonardo Sampaio-Cardoso.

While the first and the third research axes deal with the optimization of the cognitive radio nodes themselves from system and programming point of view, an important complementary objective is to consider the radio nodes in their environments. Indeed, cognitive radio does not target the simple optimization of point to point transmissions, but the optimization of simultaneous concurrent transmissions. The tremendous development of new wireless applications and standards currently observed calls for a better management of the radio spectrum with opportunistic radio access, cooperative transmissions and interference management. This challenge has been identified as one of the most important issue for 5G to guarantee a better exploitation of the spectrum. In addition, mobile internet is going to support a new revolution that is the *tactile internet*, with real time interactions between the virtual and the real worlds, requiring new communication objectives to be met such as low latency end to end communications, distributed learning techniques, in-the-network computation, and many more. The future network will be heterogeneous in terms of technologies, type of data flows and QoS requirements. To address this revolution two work directions have naturally formed within the axis. The first direction concerns the theoretical study of fundamental limits in wireless networks. Introduced by Claude Shannon in the 50s and heavily developed up to today, Information Theory has provided a theoretical foundation to study the performance of wireless communications, not from a practical design view point, but using the statistical properties of wireless channels to establish the fundamental trade-offs in wireless communications. Beyond the classical *energy efficiency - spectral efficiency* tradeoff, information theory and its many derivations, i.e., network information theory, may also help to address additional questions such as determining the optimal rates under decentralized policies, asymptotic behavior when the density of nodes increases, latency controled communication with finite block-length theory, etc... In these cases, information theory is often associated to other theoretical tools such as game theory, stochastic geometry, control theory, graph theory and many others.

Our first research direction consists in evaluating specific mulit-user scenarios from a network information theory perspective, inspired by practical scenarios from various applicative frameworks (e.g. 5G, Wifi, sensor networks, IoT, etc...), and to establish fundamental limits for these scenarios. The second research direction is related to algorithmic and protocol design (PHY/MAC), applied to practical scenarios. Exploiting signal processing, linear algebra inspired models and distributed algorithms, we develop and evaluate various distributed algorithms allowing to improve many QoS metrics such as communication rates, reliability, stability, energy efficiency or computational complexity.

It is clear that both research directions are symbiotic with respect to each other, with the former providing theoretical bounds that serves as a reference to the performance of the algorithms created in the later. In the other way around, the later offers target scenarios for the former, through identifying fundamental problems that are interesting to be studied from the fundamental side. Our contributions of the year in these two directions are summarized further in the document.

3.4. Software Radio Programming Model

Participants: Tanguy Risset, Kevin Marquet, Lionel Morel, Guillaume Salagnac, Florent de Dinechin.

Finally the third research axis is concerned with software aspect of the software radio terminal (left of Fig 3). We have currently two actions in this axis, the first one concerns the programming issues in software defined radio devices, the second one focusses on low power devices: how can they be adapted to integrate some reconfigurability.

The expected contributions of Socrate in this research axis are :

- The design and implementation of a “middleware for SDR”, probably based on a Virtual Machine.
- Prototype implementations of novel software radio systems, using chips from Leti and/or Lyrtech software radio boards.
- Development of a *smart node*: a low-power Software-Defined Radio node adapted to WSN applications.
- Methodology clues and programming tools to program all these prototypes.

3.5. Inter-Axes Collaboration

Innovative results come from collaborations between the three axes. To highlight the fact that this team structure does not limit the ability of inter-axes collaborations between Socrate members, we list below the *on-going* research actions that *already* involve actors from two or more axes, this is also represented on Fig 4.

- *Optimizing network capacity of very large scale networks*. 2 Phds started in October/November 2011 with Guillaume Villemaud (axis 1) and Claire Goursaud (axis 2), respectively.
- *SDR for sensor networks*. A PhD started in 2012 in collaboration with FT R&D, involving people from axis 3 (Guillaume Salagnac, Tanguy Risset) and axis 1 (Guillaume Villemaud).
- *CorteXlab*. The 3 axes also collaborate on the design and the development of CorteXlab.
- *body area networks applications*. Axis 2 and axis 3 collaborate on the development of body area networks applications in the framework of the FUI Smacs project. Jean-Marie Gorce and Tanguy Risset co-advised Matthieu Lauzier.
- *Wiplan and NS3*. The MobiSim ADT involves Guillaume Villemaud (axis 1) and Jean-Marie Gorce (axis 2).
- *Resource allocation and architecture of low power multi-band front-end*. The EconHome project involves people from axis 2 (Jean-Marie Gorce,Nikolai Lebedev) and axis 1 (Florin Hutu). 1 Phd started in 2011.
- *Virtual machine for SDR*. In collaboration with CEA, a PhD started in October 2011, involving people from axis 3 (Tanguy Risset, Kevin Marquet) and Leti’s engineers closer to axis 2.
- *Relay strategy for cognitive radio*. Guillaume Villemaud and Tanguy Risset were together advisers of Cedric Levy-Bencheton PhD Thesis (defense last June).

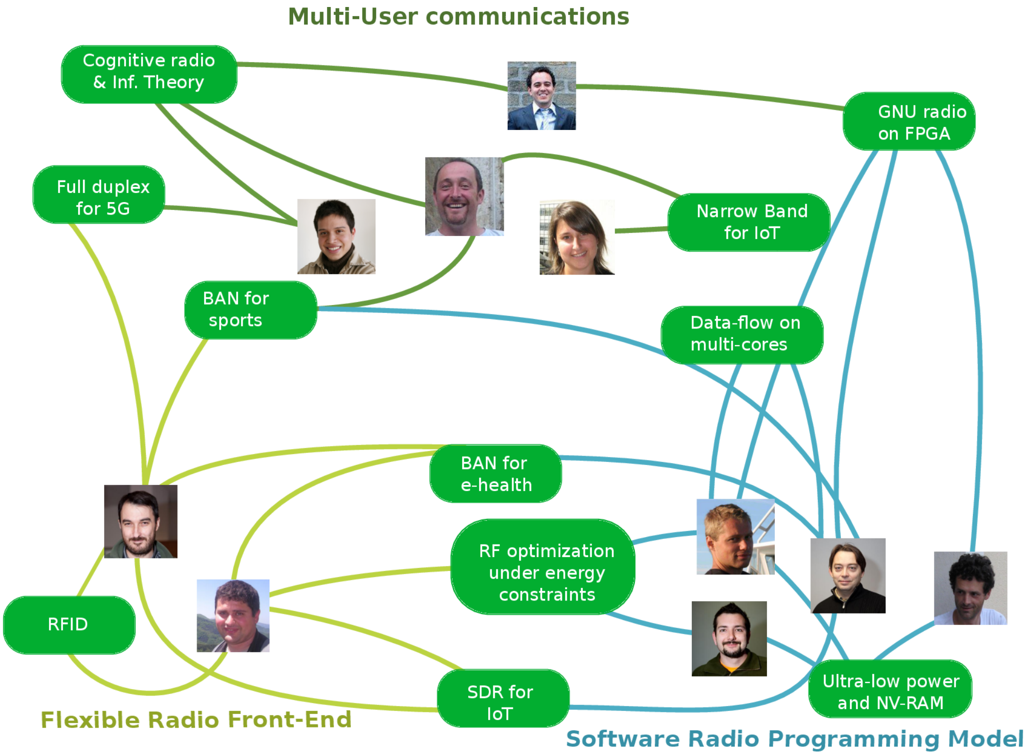

Figure 4. Inter-Axis Collaboration in Socrate: we expect innovative results to come from this pluri-disciplinary research

Finally, we insist on the fact that the *FIT project* will involve each member of Socrate and will provide many more opportunities to perform cross layer SDR experimentations. FIT is already federating all members of the Socrate team.

4. Highlights of the Year

4.1. Highlights of the Year

- The SPIE group's digital services subsidiary, and INSA Lyon announce their joint inauguration of a teaching and research chair in the Internet of Things (IoT). Backed by the CITI laboratory (Centre of Innovation in Telecommunications and Integration of service), this chair is being set up within the context of the future technological and social upheaval entailed by the Internet of Things. It will closely involve the skills of the laboratory within the IoT theme and will aim to develop and promote the know-how of SPIE ICS, the first digital services provider to appoint a chair, and INSA Lyon, through a research program aimed at innovation. Jean-Marie Gorce will be responsible for administration the chair funding within the Citi lab.
- The numap memory profiling library (developped in the team during Manuel Selva's PhD work) has been officially integrated into the Turnus dataflow profiler. Turnus [54] is a profiler dedicated to dynamic dataflow programs.
- Samir M. Perlaza and Selma Belhadj Amor delivered the tutorial **"Simultaneous Energy and Information Transmission"** in: (a)**International Conference on Telecommunications** (ICT), Thessaloniki, Greece, May, 2016; (b)**International Conference on Cognitive Radio Oriented Wireless Networks** (CROWNCOM), Grenoble, France, May, 2016; (c)**European Wireless Conference** (EW), Oulu, Finland, May, 2016, together with Ioannis Kikridis (University of Cyprus, Cyprus).

5. New Software and Platforms

5.1. FloPoCo

Floating-Point Cores, but not only
KEYWORD: Synthesizable VHDL generator
FUNCTIONAL DESCRIPTION

The purpose of the open-source FloPoCo project is to explore the many ways in which the flexibility of the FPGA target can be exploited in the arithmetic realm.

- Participants: Florent Dupont De Dinechin, Nicolas Brunie, Matei Istoan and Antoine Martinet
- Partners: CNRS - ENS Lyon - UCBL Lyon 1 - UPVD
- Contact: Florent Dupont De Dinechin
- URL: http://flopoco.gforge.inria.fr/

5.2. WSNet

KEYWORD: Network simulator
FUNCTIONAL DESCRIPTION

WSNet is a modular event-driven simulator targeted to Wireless Sensor Networks. Its main goals are to offer scalabiliy, extensibility and modularity for the integration of new protocols/hardware models and a precise radio medium simulation. We still hope to find the proper resource to make WSNet evolve into a wireless capillary network simulator suitable for conducting simulations at the urban scale.

- Participants: Rodrigue Domga Komguem, Quentin Lampin, Alexandre Mouradian and Fabrice Valois
- Partner: CEA-LETI
- Contact: Guillaume Chelius
- URL: https://gforge.inria.fr/projects/wsnet-3/

5.3. WiPlan

FUNCTIONAL DESCRIPTION

Wiplan is a software including an Indoor propagation engine and a wireless LAN optimization suite, which has been registered by INSA-Lyon. The heart of this software is the propagation simulation core relying on an original method, MR-FDPF (multi-resolution frequency domain ParFlow), proposed by Jean-Marie Gorce in 2001 and further extended. The discrete ParFlow equations are translated in the Fourier domain providing a large linear system, solved in two steps taking advantage of a multi- resolution approach. The first step computes a cell-based tree structure referred to as the pyramid. In the second phase, a radiating source is simulated, taking advantage of the pre-processed pyramidal structure. Using of a full-space discrete simulator instead of classical ray-tracing techniques is a challenge due to the inherent high computation requests. However, we have shown that the use of a multi-resolution approach allows the main computational load to be restricted to a pre-processing phase. Extensive works have been done to make predictions more realistic.

- Contact: Jean-Marie Gorce
- URL: https://bil.inria.fr

5.4. FFTweb

KEYWORD: Spectrum Analyser , Data visualization , SDR

FUNCTIONAL DESCRIPTION

Visualisation tool use in CorteXlab to visualize the spectrum (or any kind vector signal) occuring in the CorteXlab room. FFTweb is a fundamental debugging and demonstration component for FIT/CorteXlab user.

- Matthieu Imbert
- Partners: Inria
- Contact: Matthieu Imbert
- URL: http://www.cortexlab.fr

5.5. Minus

KEYWORD: Experiment Handler , SDR

FUNCTIONAL DESCRIPTION

Handling and deployement of experiment on the Cognitive radio platform FIT/CorteXlab. On CorteXlab, the user does not have direct access to the SDR nodes, he has access to a server from which Minus deploys the programs on the different SDR nodes.

- Matthieu Imbert, Leonardo Sampaio-Cardoso, Tanguy Risset
- Partners: Inria
- Contact: Matthieu Imbert
- URL: http://www.cortexlab.fr

5.6. Platform - FIT/CortexLab

FIT(Future Internet of Things) is a french Equipex (Équipement d'excellence) which aims to develop an experimental facility, a federated and competitive infrastructure with international visibility and a broad panel of customers. FIT is be composed of four main parts: a Network Operations Center (NOC), a set of IoT test-beds (IoT-Lab), a set of wireless OneLab test-beds, and a cognitive radio test-bed (CorteXlab) deployed by the Socrate team in the Citi lab. In 2014 the construction of the room was finished see Figure 5. SDR nodes have installed in the room, 42 industrial PCs (Aplus Nuvo-3000E/P), 22 NI radio boards (USRP) and 18 Nutaq boards (PicoSDR, 2x2 and 4X4) can be programmed from internet now.

A very successfully inauguration took place int 2014 [0], with the noticable venue of Vincent Poor, Dean of School of Engineering and Applied Science of Princeton University. Since that date, the platform is open to public experiments.

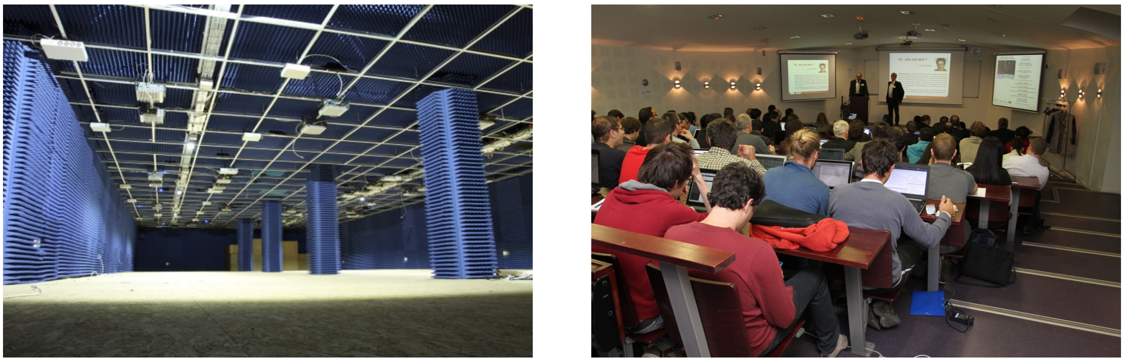

Figure 5. Photo of the FIT/CortexLab experimentation room installed and a snaptshot of the inauguration meeting

6. New Results

6.1. Flexible Radio Front-End

6.1.1. Wake-Up Radio

The last decades have been really hungry in new ways to reduce energy consumption. That is especially true when talking about wireless sensor networks in general and home multimedia networks in particular, since electrical energy consumption is the bottleneck of the network. One of the most energy-consuming functional block of an equipment is the radio front end, and methods to switch it off during the time intervals where it is not active must be implemented. This previous study has proposed a wake-up radio circuit which is capable of both addressing and waking up not only a more efficient but also more energy-consuming radio front end. By using a frequency footprint to differentiate each sensor, awaking all the sensors except for the one of interest is avoided. The particularity of the proposed wake-up receiver [22] is that the decision is taken in the radio-frequency part and no baseband treatment is needed. The global evaluation in theory and in simulation was performed, and a first testbed of this technology was fabricated, demonstrating that this principle actually works in practice [21].

[0] http://www.inria.fr/centre/grenoble/actualites/inauguration-reussie-de-la-plateforme-cortexlab-equipex-fit

6.1.1.1. Full-Duplex

An important work was done in this axis previously around Full-Duplex systems, in order to enhance throughput, flexibility, and, potentially security of wireless links. A PhD thesis grant from DGA and Inria has allowed us to extend this through a collaboration with axis 2, focusing on Physical layer security mechanisms based on Full-Duplex systems. Starting by a theoretical study of the secrecy capacity in the presence of an eavesdropper, this work studies [13] the duality between wiretap channels and state-dependent channels. This represents a basic framework to extend in a near future this study to Full-Duplex scenarios, where the Full-Duplex capability of a node could increase the secrecy of the wireless communication.

6.1.1.2. SDR for SRDs

The technologies employed in urban sensor networks are permanently evolving, and thus the gateways of these networks have to be regularly upgraded. The existing method to do so is to stack-up receivers dedicated to one communication protocol. However, this implies to have to replace the gateway every time a new protocol is added to the network. A more practical way to do this is to perform a digitization of the full band and to perform digitally the signal processing, as done in Software-Defined Radio (SDR). The main hard point in doing this is the dynamic range of the signals: indeed the signals are emitted with very different features because of the various propagation conditions. It has been proved that the difference of power between two signals can be so important that no existing Analog-to-Digital Converter (ADC) is able to properly digitize the signals. We propose a solution to reduce the dynamic range of signals before digital conversion. In this study [9], the assumption is made that there is one strong signal, and several weak signals. This assumption is made from the existing urban sensor networks topology. A receiver architecture with two branches is proposed with a “Coarse Digitization Path” (CDP) and a “Fine Digitization Path” (FDP). The CDP allows to digitize the strong signal and to get data on it that is used to reconfigure the FDP. The FDP then uses a notch filter to attenuate the strong signal (and then to reduce the dynamic range of the signals) and digitizes the rest of the band.

6.2. Multi-User Communications

6.2.1. Fundamental Limits

6.2.1.1. Approximate Capacity Region of the Gaussian Interference Channel with Feedback

An achievability region and a converse region for the two-user Gaussian interference channel with noisy channel-output feedback (G-IC-NOF) are presented [42], [30], [43], [47]. The achievability region is obtained using a random coding argument and three well-known techniques: rate splitting, superposition coding and backward decoding. The converse region is obtained using some of the existing perfect-output feedback outer-bounds as well as a set of new outer-bounds that are obtained by using genie-aided models of the original G-IC-NOF. Finally, it is shown that the achievability region and the converse region approximate the capacity region of the G-IC-NOF to within a constant gap in bits per channel use.

6.2.1.2. Full Characterization of the Capacity Region of the Linear Deterministic Interference Channel with Feedback

The capacity region of the two-user linear deterministic (LD) interference channel with noisy output feedback (IC-NOF) has been fully characterized [29]. This result allows the identification of several asymmetric scenarios in which implementing channel-output feedback in only one of the transmitter-receiver pairs is as beneficial as implementing it in both links, in terms of achievable individual rate and sum-rate improvements w.r.t. the case without feedback. In other scenarios, the use of channel-output feedback in any of the transmitter-receiver pairs benefits only one of the two pairs in terms of achievable individual rate improvements or simply, it turns out to be useless, i.e., the capacity regions with and without feedback turn out to be identical even in the full absence of noise in the feedback links.

6.2.1.3. Full Characterization of the Information Equilibrium Region of the Multiple Access Channel

The fundamental limits of decentralized information transmission in the K-user Gaussian multiple access channel (G-MAC), with $K \geqslant 2$, are fully characterized [38]. Two scenarios are considered. First, a game in which only the transmitters are players is studied. In this game, the transmitters autonomously and independently tune their own transmit configurations seeking to maximize their own information transmission rates, $R_1, R_2, \cdots, R_K$, respectively. On the other hand, the receiver adopts a fixed receive configuration that is known a priori to the transmitters. The main result consists of the full characterization of the set of rate tuples $(R_1, R_2, ..., R_K)$ that are achievable and stable in the G-MAC when stability is considered in the sense of the η-Nash equilibrium (NE), with $\eta > 0$ arbitrarily small. Second, a sequential game in which the two categories of players (the transmitters and the receiver) play in a given order is presented. For this sequential game, the main result consists of the full characterization of the set of rate tuples $(R_1, R_2, ..., R_K)$ that are stable in the sense of an η-sequential equilibrium, with $\eta > 0$.

6.2.1.4. Full Characterization of the Information-Energy Capacity Region of the Multiple Access Channel with Energy Harvester with and without Feedback

The fundamental limits of simultaneous information and energy transmission in the two-user Gaussian multiple access channel (G-MAC) with and without feedback have been fully characterized [10], [15]. More specifically, all the achievable information and energy transmission rates (in bits per channel use and energy-units per channel use, respectively) are identified. In the case without feedback, an achievability scheme based on power-splitting and successive interference cancelation is shown to be optimal. Alternatively, in the case with feedback (G-MAC-F), a simple yet optimal achievability scheme based on power-splitting and Ozarow's capacity achieving scheme is presented. Two of the most important observations in this work are: (a) The information-energy capacity region of the G-MAC without feedback can be a proper subset of the information-energy capacity region of the G-MAC-F and (b) Feedback can at most double the energy rate when the information transmission rate is kept fixed at the sum-capacity of the G-MAC.

6.2.1.5. Full Characterization of the Information-Energy Equilibrium Region of the Multiple Access Channel with Energy Harvester

The fundamental limits of decentralized simultaneous information and energy transmission in the two-user Gaussian multiple access channel (G-MAC) have been fully characterized for the case in which a minimum energy transmission rate b is required for successful decoding [14], [39]. All the achievable and stable information-energy transmission rate triplets (R_1, R_2, B) are identified. R_1 and R_2 are in bits per channel use measured at the receiver and B is in energy units per channel use measured at an energy-harvester (EH). Stability is considered in the sense of an η-Nash equilibrium (NE), with $\eta > 0$ arbitrarily small. The main result consists of the full characterization of the η-NE information-energy region, i.e., the set of information-energy rate triplets (R_1, R_2, B) that are achievable and stable in the G-MAC when: (a) both transmitters autonomously and independently tune their own transmit configurations seeking to maximize their own information transmission rates, R_1 and R_2 respectively; (b) both transmitters jointly guarantee an energy transmission rate B at the EH, such that $B > b$. Therefore, any rate triplet outside the η-NE region is not stable as there always exists one transmitter able to increase by at least η bits per channel use its own information transmission rate by updating its own transmit configuration.

6.2.1.6. Duality Between State-Dependent Channels and Wiretap Channels

A duality between wiretap and state-dependent channels with non-causal channel state information at the transmitter has been established [13]. First, a common achievable scheme is described for a certain class of state-dependent and wiretap channels. Further, state-dependent and wiretap channels for which this scheme is capacity (resp. secrecy capacity) achieving are identified. These channels are said to be dual. This duality is used to establish the secrecy capacity of certain state-dependent wiretap channels with non-causal channel state information at the transmitter. Interestingly, combatting the eavesdropper or combatting the lack of state information at the receiver turn out to be two non-concurrent tasks.

6.2.1.7. Energy efficiency - Spectral Efficiency (EE-SE) Tradeoffs in Wireless RANs

Even for a point-to-point communication, the Shannon capacity can be interpreted for a Gaussian channel as a fundamental spectral and energy efficiency (SE-EE) trade-off. Extending this fundamental trade-off in the context of multi-user communications is not straightforward as it may depend on many parameters. We proposed in [8] a simple and effective method to study this trade-off in cellular networks, an issue that has attracted significant recent interest in the wireless community. The proposed theoretical framework is based on an optimal radio resource allocation of transmit power and bandwidth for the downlink direction, applicable for an orthogonal cellular network. The analysis is initially focused on a single cell scenario, for which in addition to the solution of the main SE-EE optimization problem, it is proved that a traffic repartition scheme can also be adopted as a way to simplify this approach. By exploiting this interesting result along with properties of stochastic geometry, this work is extended to a more challenging multi-cell environment, where interference is shown to play an essential role and for this reason several interference reduction techniques are investigated. Special attention is also given to the case of low signal to noise ratio (SNR) and a way to evaluate the upper bound of EE in this regime is provided. This methodology leads to tractable analytical results under certain common channel properties, and thus allows the study of various models without the need for demanding system level simulations.

6.2.1.8. Spatial Continuum Channel Models

In the context of the deployment of Internet of Things (see next section for more details about our protocol developments), it is expected that a unique cell could serve millions of radio nodes transmitting sporadic short packets. In [18] and [41], our objective is to study this problem from an information theory point of view to derive the fundamental limit in terms of maximal information rates that can be transmitted in such a dense cell. This work proposes a new model called spatial continuum asymmetric channels to study the channel capacity region of asymmetric scenarios in which either one source transmits to a spatial density of receivers or a density of transmitters transmit to a unique receiver. This approach is built upon the classical broadcast channel (BC) and multiple access channel (MAC). For the sake of consistency, the study is limited to Gaussian channels with power constraints and is restricted to the asymptotic regime (zero-error capacity). The reference scenario comprises one base station in Tx or Rx mode, a spatial random distribution of nodes (resp. in Rx or Tx mode) characterized by a probability spatial density of users $u(x)$ where each of them requests a quantity of information with no delay constraint, thus leading to a requested rate spatial density $\rho(x)$. This system is modeled as an ‚àû‚àíuser asymmetric channel (BC or MAC). To derive the fundamental limits of this model, a spatial discretization is first proposed to obtain an equivalent BC or MAC. Then, a specific sequence of discretized spaces is defined to refine infinitely the approximation. Achievability and capacity results are obtained in the limit of this sequence while the access capacity region $\mathcal{C}(Pm)$ is defined as the set of requested rates spatial densities $\rho(x)$ that are achievable with a transmission power Pm. The uniform capacity defined as the maximal symmetric achievable rate is also computed.

6.2.1.9. Finite Block-Length Coding in Wireless Networks

In the context of IoT, the information to be transmitted will be divided in very small packets especially when control and commands will be transmitted over the network. The classical asymptotic information theory relies on the statistic properties of channels and information sources, when the coding block-length tends to infinity. Therefore this framework is not appropriate to study the fundamental limits of short packets transmission over wireless networks. Fortunately, information theory is not only about the asymptotic regime. Shannon himself derived the preliminary foundations of a theory for finite block-length. Later, Gallager extended this framework. Recently this question gained interest after the work of Y. Polyanskiy which extended former results on finite block length to Gaussian channels. This fundamental contribution opens a way for studying wireless networks under finite block-length regime. But this relatively new paradigm suffers from strong problems relative to the compexity of the underlying estimation problem. Starting to work on this topic in the framework of the associated team with Princeton, we exploited in [35] the recent results on the non-asymptotic coding rate for fading channels with no channel state information at the transmitter and we analyzed the goodput in additive white Gaussian noise (AWGN) and the energy-efficiency spectral-efficiency (EE-SE) tradeoff where the fundamental relationship between the codeword length and the EE is given. Finally, the true outage probability in Ricean and Nakagami-m block fading channels is investigated and it is proved that the asymptotic outage capacity is the Laplace approximation of the average error probability in finite blocklength regime. This preliminary work constitutes one of the starting point for our future works in the framework of the ANR project ARBURST.

6.2.2. Algorithm and Protocol Design for Multi-User Communication Scenarios

6.2.2.1. Interference Management in OFDM/MIMO Wireless Networks

Modern cellular networks in traditional frequency bands are notoriously interference-limited especially in urban areas, where base stations are deployed in close proximity to one another. The latest releases of Long Term Evolution (LTE) incorporate features for coordinating downlink transmissions as an efficient means of managing interference. In [4], we review recent field trial results and theoretical studies of the performance of joint transmission (JT) coordinated multi-point (CoMP) schemes. These schemes revealed, however, that their gains are not as high as initially expected, despite the large coordination overhead. These schemes are known to be very sensitive to defects in synchronization or information exchange between coordinating bases stations as well as uncoordinated interference. In this article, we review recent advanced coordinated beamforming (CB) schemes as alternatives, requiring less overhead than JT CoMP while achieving good performance in realistic conditions. By stipulating that, in certain LTE scenarios of increasing interest, uncoordinated interference constitutes a major factor in the performance of CoMP techniques at large, we hereby assess the resilience of the state-of-the-art CB to uncoordinated interference. We also describe how these techniques can leverage the latest specifications of current cellular networks, and how they may perform when we consider standardized feedback and coordination. This allows us to identify some key roadblocks and research directions to address as LTE evolves towards the future of mobile communications.

Among the different techniques described above, we studied in [32] an interference Alignment (IA) technique that, in a large sense, makes use of the increasing signal dimensions available in the system through MIMO and OFDM technologies in order to globally reduce the interference suffered by users in a network. In this paper, we addressed the problem of downlink cellular networks, the so-called interfering broadcast channels, where mobile users at cell edges may suffer from high interference and thus, poor performance. Starting from the downlink IA scheme proposed by Suh et al., a new approach is proposed where each user feeds back multiple selected received signal directions with high signal-to-interference gain. A exhaustive search based scheduler selects a subset of users to be served simultaneously, balancing between sum-rate performance and fairness, but becomes untractable in dense network scenarios where many users send simultaneous requests. Therefore, we develop a sub-optimal scheduler that greatly decreases the complexity while preserving a near-optimal data rate gain. More interestingly, our simulations show that the IA scheme becomes valuable only in correlated channels, whereas the matched filtering based scheme performs the best in the uncorrelated scenarios.

6.2.2.2. Performance of Ultra-NarrowBand Techniques for Internet of Things

This section makes echo to the section entitled Spatial Continuum Channel Models where fundamental limits are studied for a similar scenario. In this section, we investigate the scenario for an existing PHY layer technology, Ultra Narrow Band (UNB) technique, proposer by Sigfox. The ALOHA protocol is regaining interest in the context of the Internet of Things (IoT), especially for UNB signals (dedicated to long range and low power transmission in IoT networks). In this case, the classical assumption of channelization is not verified anymore, modifying the ALOHA performances. Indeed, UNB signals suffer from a lack of precision on the actual transmission carrier frequency, leading to a behavior similar to a frequency unslotted random access. More precisely, the channel access is Random-FTMA, where nodes select their time and frequency in a random and continuous way. The frequency randomness prevents from allocating orthogonal resources for transmission, and induces uncontrolled interference.

In [19], the success probability and throughput of ALOHA is generalized to further describe frequency-unslotted systems such as UNB. The main contribution of this work is the derivation of a generalized expression of the throughput for the random time-frequency ALOHA systems, when neglecting channel attenuation. Besides, this study permits to highlight the duality of ALOHA in time and frequency domain.

Besides, in [26] and [27], to introduce diversity, we propose the use of replication mechanism to enhance the reliability of UNB wireless network. Considering the outage probability, we theoretically evaluate the system performance and show that there exists an optimal number of transmissions. Finally, we highlight that this number of repetitions can be easily optimized by considering a unique global parameter.

Finally, in [28], we also take into consideration the channel effect for such specific network. Indeed, the UNB randomness leads to a new behavior of the interference which has not been theoretically analyzed yet, when considering the pathloss of nodes located randomly in an area. In this work, in order to quantify the system performance, we derive and exploit a theoretical expression of the packet error rate in a UNB based IoT network, when taking into account both interference due to the spectral randomness and path loss due to the propagation.

6.2.2.3. Algorithms and Protocols for BANs

Body Area Networks (BANs) represent a challenging area of research for networking design. Indeed, the topology of these networks differe significantly from classical networks. BANs are dynamic, multi-scale, energy limited and require real time protocols for many applications related to localization. Our work is related to the design of dynamic protocols to gather and exploit localization information in dynamic BANs. Our first contribution is related to the context of group navigation and was developed in the framework of the FUI SMACS project dealing with the localisation of runners during bike races. The problem is to develop fast and reliable protocols to dynamically gather mobility information from moving nodes toward moving sinks.

Our second contribution is relative to the mobility of a single BAN and with the objective of improving localization algorithms based on ranging measures between nodes spread on the body. This work was done in the framework of the ANR CORMORAN project with the PhD of Arturo Gimenez-Guizar who defended his PhD in October 2016 [1].

6.2.2.3.1. Information Gathering in a Group of Mobile Users

In [16], we propose an efficient approach to collect data in mobile wireless sensor networks, with the specific application of sensing in bike races. Recent sensor technology permits to track GPS position of each bike. Because of the inherent correlation between bike positions in a bike race, a simple GPS log is inefficient. The idea presented in this work is to aggregate GPS data at sensors using compressive sensing techniques. We enforce, in addition to signal sparsity, a spatial prior on biker motion because of the group behaviour (peloton) in bike races. The spatial prior is modeled by a graphical model and the data aggregation problem is solved, with both the sparsity and the spatial prior, by belief propagation. We validate our approach on a bike race simulator using trajectories of motorbikes in a real bike race.

6.2.2.3.2. MAC Protocols and Algorithms for Localization at the Body Scale

In this work [20], we have considered the positioning success rate for localization applications deployed in Wireless Body Area Networks (WBAN). Localization is performed with Ultra Wide Band (UWB) pulses, which permits to estimate distances as defined by 3 Way Ranging protocol (3WR). Two channels are considered : the empirical channel CM3, and with our model obtained from our measurement campaign. We first evaluate the positioning loss when considering an aggregation and broadcast scheduling strategy (A&B) upon TDMA MAC. We highlight the channel effects depending on the targeted receiver sensitivity. We then improve the performances by proposing a cooperative algorithm based on conditional permutation of anchors.

6.2.3. Cyber-Physical Systems

6.2.3.1. Attacks in the Electricity Grids

Multiple attacker data injection attack construction in electricity grids with minimum-mean-square-error state estimation has been studied for centralized and decentralized scenarios [6], [11]. A performance analysis of the trade-off between the maximum distortion that an attack can introduce and the probability of the attack being detected by the network operator is considered. In this setting, optimal centralized attack construction strategies are studied. The decentralized case is examined in a game-theoretic setting. A novel utility function is proposed to model this trade-off and it is shown that the resulting game is a potential game. The existence and cardinality of the corresponding set of Nash Equilibria (NEs) of the game is analyzed. Interestingly, the attackers can exploit the correlation among the state variables to facilitate the attack construction. It is shown that attackers can agree on a data injection vector construction that achieves the best trade-off between distortion and detection probability by sharing only a limited number of bits offline. For the particular case of two attackers, numerical results based on IEEE test systems are presented.

6.2.3.2. Recovering Missing Data in Electricity Grids

The performance of matrix completion based recovery of missing data in electricity distribution systems has been analyzed [17]. Under the assumption that the state variables follow a multivariate Gaussian distribution the matrix completion recovery is compared to estimation and information theoretic limits. The assumption about the distribution of the state variables is validated by the data shared by Electricity North West Limited. That being the case, the achievable distortion using minimum mean square error (MMSE) estimation is assessed for both random sampling and optimal linear encoding acquisition schemes. Within this setting, the impact of imperfect second order source statistics is numerically evaluated. The fundamental limit of the recovery process is characterized using Rate-Distortion theory to obtain the optimal performance theoretically attainable. Interestingly, numerical results show that matrix completion based recovery outperforms MMSE estimator when the number of available observations is low and access to perfect source statistics is not available.

6.3. Software Radio Programming Model

6.3.1. Dataflow programming model

The advent of portable software-defined radio (SDR) technology is tightly linked to the resolution of a difficult problem: efficient compilation of signal processing applications on embedded computing devices. Modern wireless communication protocols use packet processing rather than infinite stream processing and also introduce dependencies between data value and computation behavior leading to dynamic dataflow behavior. Recently, parametric dataflow has been proposed to support dynamicity while maintaining the high level of analyzability needed for efficient real-life implementations of signal processing computations. The team developed a new compilation flow [5] that is able to compile parametric dataflow graphs. Built on the LLVM compiler infrastructure, the compiler offers an actor-based C++ programming model to describe parametric graphs, a compilation front end for graph analysis, and a back end that currently matches the Magali platform: a prototype heterogeneous MPSoC dedicated to LTE-Advanced. We also introduce an innovative scheduling technique, called microscheduling, allowing one to adapt the mapping of parametric dataflow programs to the specificities of the different possible MPSoCs targeted. A specific focus on FIFO sizing on the target architecture is presented. The experimental results show compilation of 3GPP LTE-Advanced demodulation on Magali with tight memory size constraints. The compiled programs achieve performance similar to handwritten code.

The memory subsystem of modern multi-core architectures is becoming more and more complex with the increasing number of cores integrated in a single computer system. This complexity leads to profiling needs to let software developers understand how programs use the memory subsystem. Modern processors come with hardware profiling features to help building tools for these profiling needs. Regarding memory profiling, many processors provide means to monitor memory traffic and to sample read and write memory accesses. Unfortunately, these hardware profiling mechanisms are often very complex to use and are specific to each micro-architecture. The numap library [44], [31] is dedicated to the profiling of the memory subsytem of modern multi-core architectures. numap is portable across many micro-architectures and comes with a clean application programming interface allowing to easily build profiling tools on top of it.

This numap library as been officially integrated into Turnus, a profiler dedicated to dynamic dataflow programs.

6.3.2. Implementation of filters and FFTs on FPGAs

In collaboration with two researchers from Inria AriC, we have worked on a digital filter synthesis flow targeting FPGAs [46]. Based on a novel approach to the filter coefficient quantization problem, this approach produces results which are faithful to a high-level frequency-domain specification. An automated design process is also proposed where user intervention is limited to a very small number of relevant input parameters. Computing the optimal value of the other parameters not only simplifies the user interface: the resulting architectures also outperform those generated by mainstream tools in accuracy, performance, and resource consumption.

In collaboration with researchers from Isfahan, Iran, a multi-precision Fast Fourier Transform (FFT) module with dynamic run-time reconfigurability has been proposed [3] to trade off accuracy with energy efficiency in an SDR-based architecture. To support variable-size FFT, a reconfigurable memory-based architecture is investigated. It is revealed that the radix-4 FFT has the minimum computational complexity in this architecture. Regarding implementation constraints such as fixed-width memory, a noise model is exploited to statistically analyze the proposed architecture. The required FFT word-lengths for different criteria, (bit-error rate (BER), modulation scheme, FFT size, and SNR) are computed analytically and confirmed by simulations in AWGN and Rayleigh fading channels. At run-time, the most energy-efficient word-length is chosen and the FFT is reconfigured until the required application-specific BER is met. Evaluations show that the implementation area and the number of memory accesses are reduced. The results obtained from synthesizing basic operators of the proposed design on an FPGA show energy consumption saving of over 80 %.

6.3.3. Tools for FPGA development

The pipeline infrastructure of the FloPoCo arithmetic core generator has been completely overhauled [34], [23]. From a single description of an operator or datapath, optimized implementations are obtained automatically for a wide range of FPGA targets and a wide range of frequency/latency trade-offs. Compared to previous versions of FloPoCo, the level of abstraction has been raised, enabling easier development, shorter generator code, and better pipeline optimization. The proposed approach is also more flexible than fully automatic pipelining approaches based on retiming: In the proposed technique, the incremental construction of the pipeline along with the circuit graph enables architectural design decisions that depend on the pipeline. These allow pipeline-dependent changes to the circuit graph for finer optimization. This is particularly important for the filter structures already mentioned [46].

In parallel, we also started to study the integration of arithmetic optimizations in high-level synthesis (HLS) tools [48]. HLS is a big step forward in terms of design productivity. However, it restricts data-types and operators to those available in the `C` language supported by the compiler, preventing a designer to fully exploit the FPGA flexibility. To lift this restriction, a source-to-source compiler may rewrite, inside critical loop nests of the input `C` code, selected floating-point additions into sequences of simpler operator using non-standard arithmetic formats. This enables hoisting floating-point management out the loop. What remains inside the loop is a sequence of fixed-point additions whose size is computed to enforce a user-specified, application-specific accuracy constraint on the result. Evaluation of this method demonstrates significant improvements in the speed/resource usage/accuracy trade-off.

6.3.4. Computer Arithmetic

In collaboration with researchers from Istanbul, Turkey, operators have also been developed for division by a small positive constant [49]. The first problem studied is the Euclidean division of an unsigned integer by a constant, computing a quotient and a remainder. Several new solutions are proposed and compared against the state of the art. As the proposed solutions use small look-up tables, they match well the hardware resources of an FPGA. The article then studies whether the division by the product of two constants is better implemented as two successive dividers or as one atomic divider. It also considers the case when only a quotient or only a remainder are needed. Finally, it addresses the correct rounding of the division of a floating-point number by a small integer constant. All these solutions, and the previous state of the art, are compared in terms of timing, area, and area-timing product. In general, the relevance domains of the various techniques are very different on FPGA and on ASIC.

On the software side, we have also shown, in collaboration with researchers from LIP and the Kalray company, that correctly rounded elementary functions can be implemented more efficiently using only fixed-point arithmetic than when classically using floating-point arithmetic [24]. A purely integer implementation of the correctly rounded double-precision logarithm outperforms the previous state of the art, with the worst-case execution time reduced by a factor 5. This work also introduces variants of the logarithm that input a floating-point number and output the result in fixed-point. These are shown to be both more accurate and more efficient than the traditional floating-point functions for some applications.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Grants with Industry

7.1.1. Research Contract with Orange Labs (2015-2017)

The goal of this project "PErformances Théoriques des réseaux cellulaires pour la 5G" No. F05151 (50KEuro) is to develop a theoretical approach allowing to study the energy efficiency spectral efficiency tradeoff for 5G networks, by revisiting information theory for dense networks and short packets transmissions.

7.1.2. Research Contract with Bosch (2015-2016)

This contract between Bosch and two project-teams (AriC and Socrate) focusses on the evolution of high-performance embedded controllers.

7.1.3. Research Contract with Sigfox (2015-2016)

A collaboration with Sigfox to work on extension of Sigfox Network to dense cities: 2 years of engineering associated to a Cifre grant

7.1.4. Research Contract with Atlantic

Socrate has a collaborative contract with Atlantic, around wireless communications in HVAC systems.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. Equipex FIT- Future Internet of Things

The FIT projet is a national equipex (*equipement d'excellence*), headed by the Lip6 laboratory. As a member of Inria, Socrate is in charge of the development of an Experimental Cognitive Radio platform that is used as test-bed for SDR terminals and cognitive radio experiments. This has been operational since 2014 and is maintained for a duration of 7 years. To give a quick view, the user will have a way to configure and program through Internet several SDR platforms (MIMO, SISO, and baseband processing nodes).

8.1.2. ANR - MetalibM

The goal of the Metalibm - "Automatic Generation of Function and Filters" (2014-2017, 200 keuros) project is to provide a tool for the automatic implementation of mathematical (libm) functions. A function f is automatically transformed into machine-proven C code implementing an polynomial approximation in a given domain with given accuracy. This project is led by Inria, with researchers from Socrate and AriC; PEQUAN team of Laboratoire d'Informatique de Paris 6 (LIP6) at Université Pierre et Marie Curie, Paris; DALI team from Université de Perpignan Via Domitia and Laboratoire d'Informatique, Robotique et Microélectronique de Montpellier (LIRMM); and SFT group from Centre Européen de Recherche Nucléaire (CERN).

8.1.3. FUI SMACS

The SMACS projet - “SMart And Connected Sensors” (2013-2016, 267 keuros) targets the deployement of an innovating wireless sensor network dedicated to many domains sport, health and digital cities. The projet involves Socrate (Insavalor), HIKOB and wireless broadcasting company Euro Media France. The main goal is to develop a robust technologie enabling real-time localization of mobile targets (like cyclist for instance), at a low energy (more generaly low cost). The technology will be demonstrated at real cycling races (Tour de France 2013 and 2014). One of the goal is to include localisation information with new radio technology. Another subject of study is distributed wireless consensus algorithms for maintaining a neighborhood knowledge with a low energy budget that scales (more than 200 cycles together)

8.1.4. ADT Sytare

The SYTARE project (Développement d’un SYsTème embArqué faible consommation à mémoiRE persistante - ADT Inria 2015-2017) aims to develop and study novel operating system mechanisms for NVRAM-based embedded systems. The term NVRAM collectively describes an emerging generation of memory technologies which are both non-volatile and byte-addressable. These two properties together make the classical RAM+ROM memory architecture obsolete, and enable the design of embedded systems running on intermittent power. This is very attractive in the context of energy-constrained scenarios, for instance systems harvesting their power from the environment. But working with NVRAM also poses novel challenges in terms of software programming. For instance, application state consistency must be guaranteed accross reboots, even though the system includes both NVRAM and volatile elements (e.g. CPU, hardware peripherals). The SYTARE project is funded by Inria via the ADT program.

8.1.5. ADT CorteXlab

The Socrate project-team is in charge of the FIT/CorteXlab platform (section 5.6). This platform (ADT Inria 2015-2017) makes use of many complex technologies from signal processing to computer science through micro-electornics and FPGA. The objectiv of the CorteXlab ADT is to maintain a support to the user of the FPGA-based platform of CorteXlab and to provide tutorial and running experiment that will help them in builing experimentation using the PicoSDR machines.

8.1.6. Taiwan III

In the context of the MoU signed between Inria and The National Science Council of Taiwan. Taiwan’s Institute for Information Industry (III) and Socrate signed a one-year contract on 5G M2M (2015-2016) for a research proposal containing two items: a first to study the OFDMA-based RACH access from theoretical or mathematical models and a second to set up an experiment in CorteXlab that will emulate a given number of M2M device using a narrow band radio protocol and record the resulting radio environment.

8.1.7. ANR - Ephyl

The general objective of the project EPHYL - “Enhanced PHY for Cellular Low Power Communication IoT” (2016-2019, 183 keuros) is to investigate coming and future LPWA technologies with the aim to improve coverage, data rate and connectivity while keeping similar level of complexity and power consumption at the node for the access. New waveforms enablers will be investigated and trialled in order to increase the efficiency of future systems and to provide efficient and fair access to the radio resource. The proposed new waveforms should comply with system constraints and with the coexistence of multiple communications.

8.1.8. ANR - Arburst

In this project Arburst - “Acheivable region of bursty wireless networks” (2016-2020, 195 KEuros), we propose an original approach complementary to other existing projects. Instead of proposing one specific technical solution, our objective is to define a unified theoretical framework devoted to the study of IoT networks fundamental limits. We aim at establishing the fundamental limits for a decentralized system in a bursty regime which includes short packets of information and impulsive interference regime. We are targeting the fundamental limits, their mathematical expression (according to the usual information theory framework capturing the capacity region by establishing a converse and achievability theorems). We will use the recent results relative to finite block-length information theory and we will evaluate the margin for improvement between existing approaches and these limits and we will identify the scientific breakthrough that may bring significant improvements for IoT/M2M communications. This project will contribute to draw the roadmap for the development of IoT/M2M networks and will constitute a unified framework to compare existing techniques, and to identify the breakthrough concepts that may afford the industry the leverage to deploy IoT/M2M technical solutions.

8.2. European Initiatives

8.2.1. FP7 & H2020 Projects

8.2.1.1. CYBERNETS

Title: Cybernetic Communication Networks: Fundamental Limits and Engineering Challenges

Programm: H2020

Duration: June 2015 - June 2017

Coordinator: Inria

Inria contact: Samir M. Perlaza

This Reintegration Panel proposal, CYBERNETS, focuses on the study of Cybernetic Communication Networks (CCN). CCNs are wireless networks that are context-aware, possess learning capabilities and artificial intelligence to guarantee reliability, efficiency and resilience to changes, failures or attacks via autonomous, self-configuring and self-healing individual and network behavior. Typical examples of CCNs are beyond-5G cellular systems and critical communication systems, e.g., law enforcement, disaster relief, body- area, medical instruments, space, and indoor/outdoor commercial applications. A practical implementation of a CCN requires extending classical communication systems to embrace the dynamics of fully decentralized systems whose components might exhibit either cooperative, non-cooperative or even malicious behaviors to improve individual and/or global performance. In this context, CYBERNETS aims to develop a relevant understanding of the interactions between information theory, game theory and signal processing to tackle two particular problems from both theoretical and practical perspectives: (I) use of feedback and (II) behavior adaptation in fully decentralized CCNs. In the former, the main objectives are: (i) to determine the fundamental limits of data transmission rates in CCNs with feedback; and (ii) to develop and test in real-systems, transmit-receive configurations to provide a proof-of-concept of feedback in CCNs. For the achievement of these practical objectives, CYBERNETS relies on the world-class testbed infrastructure of Inria at the CITI Lab for fully closing the gap between theoretical analysis and real-system implementation. In the latter, the main objectives are: (i) to identify and explore alternatives for allowing transmitter-receiver pairs to learn equilibrium strategies in CCNs with and without feedback; (ii) to study the impact of network-state knowledge on scenarios derived from the malicious behavior of network components.

8.2.1.2. COM-MED

Title: COMMunication systems with renewable Energy micro-griD

Programm: H2020

Duration: October 2016 - October 2019

Coordinator: Inria

Inria contact: Samir M. Perlaza

A smart micro-grid is a small-scale power-grid system consisting of a number of distributed energy sources and loads which is responsible to ensure power sufficiency in a small area. The effectiveness of a smart micro-grid depends on the proper implementation of a communications and networking system which monitors, controls and manages the grid's operations. Due to the ever growing worldwide energy consumption, the need of an efficient framework for managing the way power is distributed and utilized has increased. The main objective of the project COM-MED is to study the fundamental interplay between communications and power networks in the context of smart micro-grids and renewable energy sources. On one hand, we study advanced signal processing techniques and communications methods to optimize the operation of smart micro-grid systems. On the other hand, we focus on mobile communications networks with renewable energy base-stations (BSs) and we investigate communications and networking techniques that take into account both data traffic and energy profiles to support high quality-of-service (QoS). The objectives of each technical WP have been assigned in such a way as to ensure that the project's target is realized during the project's time period. The theoretical results derived from the WPs 3, 4 and 5 will be tested using the telecommunication network of MTN in Cyprus but also the state-of-the-art equipment of the CITI/Inria research lab in France. The outcome of this project will provide a theoretical framework for the optimal cooperation between communications networks and power networks in the context of smart micro-grids and renewable energy sources. This is in line with the objectives of the call's theme "Renewable Energy" and is of paramount importance for the Mediterranean area. The consortium of the project has the expertise and the infrastructure to implement the objectives set and to bring the project to a successful end.

8.3. International Initiatives

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

8.3.1.1. CoWIN

Title: Cognitive Wireless Networks from Theory to Implementation

International Partner: Princeton University, School of Engineering and Applied Science. Princeton N.J. USA. Prof. H. Vincent Poor

Start year: 2015

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

The objective of this team is to strengthen the research efforts on emerging software radio and cognitive radio technologies. The team will count on: first, the cognitive radio test-bed CorteXlab recently set up by the Socrate team within the FIT Equipex, second the leading position of Vincent Poor's team in the field of network information theory and third the Orbit Platform of Rutgers university. The goal is to lead research in both the information theory community and the applied research community so as to reinforce the link between both communities. This work will concern architecture and programs of software radio equipments, distributed and cognitive algorithms for radio resource allocation, cognitive radio scenario experimentations, fundamental limits of cooperative wireless channels and the set up of common experimental infrastructure and protocols for research on cognitive wireless networks.

8.3.1.2. Informal International Partners

Socrate has strong collaborations with several international partners.

- **Princeton University**, School of Applied Science, Department of Electrical Engineering, NJ. USA. This cooperation with Prof. H. Vincent Poor is on topics related to decentralized wireless networks. Samir M. Perlaza has been appointed as Visiting Research Collaborator at the EE Department for the academic period 2016-2017. Scientific-Leaders at Inria: Samir M. Perlaza and Jean-Marie Gorce.
- **Technical University of Berlin**, Dept. of Electrical Engineering and Computer Science, Germany. This cooperation with Prof. Rafael Schaffer is on secrecy and covert communications. Scientific-Leaders at Inria: Samir M. Perlaza.

- **National University Singapore (NUS)**, Department of Electrical and Computer Engineering, Singapore. This collaboration with Prof. Vincent Y. F. Tan is on the study of finite block-length transmissions in multi-user channels and the derivation of asymptotic capacity results with non-vanishing error probabilities. Scientific-Leaders at Inria: Samir M. Perlaza
- **University of Sheffield**, Department of Automatic Control and Systems Engineering, Sheffield, UK. This cooperation with Prof. Inaki Esnaola is on topics related to information-driven energy systems and multi-user information theory. Scientific-in-charge at Inria: Samir M. Perlaza.
- **Rutgers University**, Winlab, Orbit testbed. This cooperation with Ivan Seskar is related to experimental wireless testbed. Orbit has been one of the first wireless testbeds of its type. Tanguy Risset and Leonardo Sampaio-Cardoso have visited Winlab and I. Seskar visited the Socrate team for one week. Their collaboration is on the development of tools to ease experiment handling on wireless testbeds: visualisation, synchronization etc. Scientific-Leader at Inria: Tanguy Risset
- **University of Arizona**, Department of Electrical and Computer Engineering, Tucson, AZ, USA. This cooperation with Prof. Ravi Tandon is on topics related to channel-output feedback in wireless networks. Scientific-Leader at Inria: Samir M. Perlaza.
- **University of Cyprus**, Department of Electrical and Computer Engineering, University of Cyprus, Nicosia, Cyprus. This cooperation with Prof. Ioannis Krikidis is on topics related to energy-harvesting and wireless communications systems. Scientific-Leaders at Inria: Guillaume Villemaud and Samir M. Perlaza.
- **Universidade Federal do Ceará**, GTEL, Departamento de Teleinformática, Fortaleza, Brazil. This recently started cooperation with Prof. Tarcisio Ferreira Maciel is on topics related to the optimization of radio ressources for massive MIMO in 5G and 5G-like wireless communications systems. Scientific-in-charge at Inria: Leonardo Sampaio-Cardoso.
- **Universidad Nacional del Sur**, LaPSyC laboratory, Bahía Blanca , Argentina. This cooperation with Prof. Juan Cousseau is on topics related to Full-Duplex communications and Interference Alignment. Scientific-in-charge at Inria: Guillaume Villemaud.
- **Bell Labs New Jersey, USA**, This cooperation with Prof. Antonia Tulino (affiliated to Bell Labs and to University of Napoli, Italy) is on caching in wireless networks. The objective is to demonstrate the efficiency of caching at the edge of wireless networks through experimentations on CorteXlab. This work will be published in 2017 in a special issue of IEEE Communication magazine (Yasser Fadlallah, Antonia M. Tulino, Dario Barone, Giuseppe Vettigli, Jaime Llorca and Jean-Marie Gorce: Coding for caching in 5G networks, IEEE Communication Magazine, 2017, accepted for publication). Scientific leader at Inria : Jean-Marie Gorce.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

Dr. Martin Kumm, from University of Kassel, spent one week at CITI to work on FPGA arithmetic.

8.4.2. Short-Term Visits to International Teams

- Samir M. Perlaza was visiting the Department of Automatic Control and Systems Engineering at the University of Sheffield, UK, hosted by Prof. Iñaki Esnaola.
- Samir M. Perlaza and David Kibloff were visiting the Department of Telecommunication Systems at the Technical University of Berlin, Germany, hosted by Prof. Rafael Schaefer.
- Selma Belhadj Amor was visiting the Center for Wireless Communication and Signal Processing Research (CWCSPR), ECE Department, New Jersey Institute of Technology (NJIT), USA, hosted by Prof. Osvaldo Simeone.
- Florin Hutu was visiting the Department of Electrical and Electronics Engineering", University of Buea, Cameroun, hosted by Pr. Emmanuel Tanyi.

- Lionel Morel was visiting the SCI-STI-MM Multimedia Group at École Polytechnique Fédérale de Lausanne, hosted by Dr Marco Mattavelli.

8.4.2.1. Research Stays Abroad

- Selma Belhadj Amor was hosted by the Electrical Engineering Department at Princeton University, New Jersey, USA, as a Visiting Scholar. Host: Prof. H. Vincent Poor.
- Selma Belhadj Amor hosted by the Electrical and Computer Engineering Department at the National University Of Singapore (NUS), Singapore. Host: Prof. Vincent F. Y. Tan.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. General Chair, Scientific Chair

Jean-Marie Gorce was one of the general chairs in the following conferences:

- GDR-ISIS Meeting: "Wireless networks: decentralized problems and solutions", held in Telecom ParisTech, March, 15, 2016.
- Workshop : "Inclusive Radio Communications for 5G and beyond", held in conjunction with the conference IEEE PIMRC, September 4-7, 2016, Valencia, Spain.

9.1.2. Chair of Conference Program Committees

Florent de Dinechin is a PC chair of the Arith 2017 conference.

9.1.3. Member of the Conference Program Committees

Samir M. Perlaza was a member of the technical program committee of the following conferences:

- IEEE Wireless Communications and Networking Conference (WCNC). 19-22 March 2017, San Francisco, CA. PHY and Fundamentals Track.
- 3rd Workshop on Physical-layer Methods for Wireless Security. Workshop taking place at IEEE CNS 2016 in Philadelphia, PA, USA, Oct 17-19, 2016.
- Workshop on Wireless Energy Harvesting Communication Network. Workshop taking place at IEEE Global Communications Conference (GLOBECOM) in Washington, DC USA, Dec. 8, 2016.
- IEEE WCNC 2016 Workshop on Green and Sustainable 5G Wireless Networks (GRASNET). April 3, 2016, Doha, Qatar
- 6th International Conference on Game Theory for Networks (GameNets). May 10-12, 2016, Kelowna, BC, Canada.

Jean-Marie Gorce was a member of the following technical program committees:

- IEEE APCC(22th Asia-Pacific Communication Conference, Yogyakarta-Indonesia, August 25-27 2016).
- IEEE PIMRC Fundamental & PHY (27th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications , Valencia, Spain, September 4-7, 2016).
- IEEE GLOBECOM Cognitive Radio Networks (Washington, DC, USA, December, 4-8, 2016).
- IEEE ICC Cognitive Radio Networks (IEEE International Conference on Communications, Malaysia, May 23-27 2016).

Guillaume Villemaud was a member of the following technical program committees:

- CROWNCOM2016
- VTC spring 2016
- PIMRC 2016
- EUCAP 2016.

Tanguy Risset was a member of the following technical program committees:

- IEEE Computer Society Annual Symposium on VLSI (ISVLSI) 2016.
- Design Automation and Test in Europe (DATE) 2016.
- International Conference on Cognitive Radio Oriented Wireless Networks (CROWNCOM) 2016 .

Florent de Dinechin was a member of the following technical program committees:

- 12th International Symposium on Applied Reconfigurable Computing (ARC 2016)
- 23rd IEEE Symposium on Computer Arithmetic (Arith)
- 27th Annual IEEE International Conference on Application-specific Systems, Architectures and Processors (ASAP 2016)
- IEEE International Conference on Field Programmable Technologies (FPT 2016)
- Design Automation and Test in Europe (DATE) 2016, track D11.
- 24th IEEE International Symposium on Field-Programmable Custom Computing Machines (FCCM 2016)
- Conférence d'informatique en Parallélisme, Architecture et Système (ComPAS 2016)

9.1.4. Member of the Editorial Boards

Guillaume Villemaud is an associate editor of Annals of Telecommunications (Springer).

Jean-Marie Gorce is an associate editor of Telecommunications Systems (Springer) and Journal of Wireless communications and Networking (Springer).

9.1.5. Invited Talks

S. Perlaza, "On the Benefits of Feedback in Wireless Communications". Invited talk at the Department of Telecommunications, CentraleSupélec, Gif-sur-Yvette, France, December 2, 2016.

G. Salagnac "Peripheral State Persistence For Transiently Powered Systems" at the 3rd edition of the LIP Seminar on Languages Compilation and Semantics. France, November 3 2016.

S. Perlaza, "On the Benefits of Feedback in Wireless Communications". Invited talk at the Department of Electrical Engineering and Computer Science, Technical University of Berlin, Berlin, Germany, November 18, 2016.

J.M. Gorce, "Energy-Capacity Fundamental Limits in a Cell with Dense Users" at Lundis de la radio, Orange Labs, Issy les Moulineaux, France, September 26, 2016.

S. Belhadj Amor, "Simultaneous Energy and Information Transmission". Invited talk at the School of Engineering and Applied Science, Princeton University, Princeton NJ, USA, April 21, 2016.

S. Belhadj Amor, "Simultaneous Energy and Information Transmission". Invited talk at the Center for Wireless Communication and Signal Processing Research (CWCSPR), ECE Department, New Jersey Institute of Technology (NJIT), Newark NJ, USA, April 15, 2016.

S. Perlaza, "Simultaneous Wireless Information and Energy Transmission". Invited talk at the University of Sheffield. Department of Automatic Control and Systems Engineering, Sheffield, UK, April 6, 2016.

T. Risset, "FIT/CorteXlab: A new testbed for cognitive radio experimentation". Invited talk at the Colorado-state University Fort Collins, Computer science departement, Sep. 2016.

T. Risset "Compilation of Parametric Dataflow Applications for Software-Defined-Radio-Dedicated MPSoCs" at the 2rd edition of the LIP Seminar on Languages Compilation and Semantics. Lyon, France, June 24 2016.

T. Risset, "Experimenting Cognitive Radio Communication on FIT/CorteXlab". Invited talk at R2-Lab inauguration, Nice, France, Nov. 2016.

9.1.6. Leadership within the Scientific Community

Guillaume Villemaud is National Delegate (Alt.) for the COST IRACON.

9.1.7. Scientific Expertise

Guillaume Villemaud was reviewer of ANR projects and CIFRE grants.

Jean-Marie Gorce is a member of the following committees:

- Jury prix de thèse 2017 Signal Image et Vision, soutenu par l'association GRETSI, le GDR ISIS et le club EEA.
- Jury for the digital Impulse Innovation price, May, 2016.

Tanguy Risset is member of the Administration council (Conseil d'administration) of the GRAME institute (centre national de création musicale).

9.1.8. Tutorials in International Conferences

- S. Belhadj Amor and S. M. Perlaza, "Simultaneous Energy and Information Transmission". Tutorial at the 11th EAI International Conference on Cognitive Radio Oriented Wireless Networks (Crowncom), Grenoble, France, May 29, 2016.
- S. Belhadj Amor, S. M. Perlaza, and I. Krikidis, "Simultaneous Energy and Information Transmission". Tutorial at the European Wireless (EW) conference, Oulu, Finland, May 18, 2016.
- S. Belhadj Amor and S. M. Perlaza, "Simultaneous Energy and Information Transmission". Tutorial at the 23rd International Conference on Telecommunications, Thessaloniki, Greece, May 16, 2016.
- J.M. Gorce, "Fundamental Limits of Bursty Multi-user Wireless Networks for IoT", at the summer school RESCOM on 5G and Internet of Things, from 13th to 17th June 2016, Guidel Plage, France.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Jean-Marie Gorce is the head ot the Telecommunications department of Insa Lyon.

Tanguy Risset and Jean-Marie Gorce and are professors at the Telecommunications Department of Insa Lyon.

Florent de Dinechin is a professor at the Computer Science Department of Insa Lyon.

Claire Goursaud is an associate professor at the Telecommunications department of Insa Lyon.

Leonardo Sampaio-Cardoso is an associate professor at Insa Lyon (Premier Cycle).

Guillaume Salagnac and Kevin Marquet are associate professors at the Computer Science Department of Insa Lyon.

Guillaume Villemaud and Florin Hutu are associate professor at the Electrical Engineering Department of Insa Lyon.

Samir M. Perlaza and Jean-Marie Gorce teach the course on Network Information Theory at École Normale Supérieure de Lyon.

9.2.2. Supervision

PhD in progress **Tristan Delizy***memory management for normally-of NV-RAM based systems*, Insa-Lyon, (Region ARC6) since 09/2016.

PhD in progress **Yohan Uguen***Synthesis of arithmetic operators*, Insa-Lyon, (Mininstry of research) since 09/2016.

PhD in progress **Yuqi Mo***Scaling of Iot Communication issuers*, Insa-Lyon, since 09/2015.

PhD in progress **David Kibloff***New strategy for Physical Layer Security in wireless networks: self-jamming using Full-Duplex Transceivers*, École Doctorale EEA de Lyon, funded by Inria-DGA grant since 10/2015.

PhD in progress **Victor Quintero***Fundamental Limits of Decentralized Cognitive Radio Networks*, École Doctorale EEA de Lyon, funded by Colciencias since 02/2014.

PhD in progress **Nizar Khalfet***Stochastic Energy Sources to Power Communication Systems*, École Doctorale EEA de Lyon, funded by EU Project COM-MED since 10/2016.

PhD in progress : **Matei Istoan**: *High-performance coarse operators for FPGA-based computing*, ANR Metalibm grant, since 01/2014.

PhD : **Arturo Jimenez Guizar**: *Cooperative communications in Body Area Networks*, ANR Cormoran grant, 27/10/2016.

PhD : **Matthieu Vallerian**: "*Radio Logicielle pour réseau de capteurs*", CIFRE/Orange, 15/06/2016.

9.2.3. Juries

Jean-Marie Gorce was a member of the jury of the following thesis:

- PhD Ehsan Ebrahimi Khaleghi, Advanced techniques of Interference Alignment : Application to Wireless Networks (Telecom ParisTech, January 2016), (as a reviewer).
- PhD Bhanukiran Perabathini, fundamental limits of energy efficiency in wireless networks (CentraleSupélec, January 2016), (as a reviewer).
- PhD Abraham Kaboré, Study of detection-correction error codes for MAC/PHY layers in smart grid networks (University Limoges, March 2016), (as a veviewer).
- PhD Marwa Chami, Optimization of cognitive systems with successive interference cancellation and relaying (CNAM, Paris, May 2016), (as a reviewer).
- PhD Jan Oksanen, Machine learning methods for spectrum exploration and exploitation (University of Aalto, September 2016), (as an opponent).
- PhD Wenjie Li, Robust information gathering and dissemination in wireless sensor networks (CentraleSupélec, November 2016), (as a reviewer).
- PhD Raphael Massin, On the Clustering of Mobile Ad Hoc Networks (Telecom ParisTech, November 2016), (as a reviewer).
- PhD Zheng Chen, User-Centric Content-Aware Communication in Wireless Networks (CentraleSupélec, December 2016), (as a reviewer).
- HdR Frédéric Guilloud, contributions to error correction codes and to digital communications toward communications with short frames (Telecom Brest, December 2016).

Samir M. Perlaza was a member of the jury of the following thesis:

- PhD Chao He, "Broadcasting with delayed CSIT: Finite SNR analysis and heterogeneous feedback". Defended at CentraleSupélec on December 2 2016, Gif-sur-Yvette, France.

Florin Hutu was a member of the jury of the following thesis:

- PhD Jeremy Hyvert, "Techniques de conception d'oscillateurs contrôlés en tension faible bruit de phase en bande Ku intégrés sur silicium en technologie BiCMOS" (Université de Poitiers, September 2016).

Guillaume Villemaud was a member of the jury of the following thesis:

- PhD Roman IGUAL PEREZ, "Platform hardware/software for the energy optimization in a node of wireless sensor networks", Univ. de Lille 1.
- Mohammad ABDI ABYANEH, "Génération des signaux agrégés en fréquences dans le contexte de LTE-A". Telecom Paristech.
- Shiqi CHENG, "Characterization and modeling of the polarimetric MIMO radio channel for highly diffuse scenarios". Univ. de Lille 1.

Tanguy Risset was a member of the jury of the following thesis:

- Marcos Aurelio Pinto Cunha (U. Grenoble, Jan. 2016) as jury president .
- Xiguang Wu (CentraleSupélec, Mar. 2016), as reviewer.
- Shaoyang MEN (U. Nantes, Oct. 2016) jury president.

Florent de Dinechin was a reviewer in the habilitation thesis of Roselyne Chotin-Avot (LIP6, Paris).

10. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] A. GUIZAR.*Cooperative communications with Wireless Body Area Networks for motion capture*, INSA Lyon, September 2016, https://hal.archives-ouvertes.fr/tel-01412953.

[2] M. VALLÉRIAN.*A flexible infrastructure for collecting and processing data from a urban sensor network*, Université de Lyon opérée au sein de l'INSA Lyon, June 2016, https://hal.inria.fr/tel-01416750.

Articles in International Peer-Reviewed Journal

[3] H. ABDOLI, H. NIKMEHR, N. MOVAHEDINIA, F. DE DINECHIN.*Improving Energy Efficiency of OFDM Using Adaptive Precision Reconfigurable FFT*, in "Circuits, Systems, and Signal Processing", October 2016 [*DOI :* 10.1007/s00034-016-0435-z], https://hal.inria.fr/hal-01402231.

[4] G. C. ALEXANDROPOULOS, P. FERRAND, J.-M. GORCE, C. B. PAPADIAS.*Advanced coordinated beam-forming for the downlink of future LTE cellular networks*, in "IEEE Communications Magazine", July 2016, vol. 54, n^o 7, p. 54 - 60, Arxiv: 16 pages, 6 figures, accepted to IEEE Communications Magazine [*DOI :* 10.1109/MCOM.2016.7509379], https://hal.inria.fr/hal-01395615.

[5] M. DARDAILLON, K. MARQUET, T. RISSET, J. MARTIN, H.-P. CHARLES.*A New Compilation Flow for Software-Defined Radio Applications on Heterogeneous MPSoCs*, in "ACM Transactions on Architecture and Code Optimization", 2016, vol. 13 [*DOI :* 10.1145/2910583], https://hal.inria.fr/hal-01396143.

[6] I. ESNAOLA, S. M. PERLAZA, H. V. POOR, O. KOSUT.*Maximum Distortion Attacks in Electricity Grids*, in "IEEE Transactions on Smart Grid", 2016, vol. 7, n^o 4, p. 2007-2015 [*DOI :* 10.1109/TSG.2016.2550420], https://hal.archives-ouvertes.fr/hal-01343248.

[7] A. GUIZAR, C. GOURSAUD, J.-M. GORCE.*Performance of IR-UWB cross-layer ranging protocols under on-body channel models with body area networks*, in "Annals of Telecommunications - annales des télécommunications", March 2016, http://link.springer.com/article/10.1007/s12243-016-0500-4 [*DOI :* 10.1007/s12243-016-0500-4], https://hal.archives-ouvertes.fr/hal-01290211.

[8] D. TSILIMANTOS, J.-M. GORCE, K. JAFFRÈS-RUNSER, H. V. POOR.*Spectral and Energy Efficiency Trade-Offs in Cellular Networks*, in "IEEE Transactions on Wireless Communications", January 2016, vol. 15, n^o 1, p. 54-66 [*DOI :* 10.1109/TWC.2015.2466541], https://hal.inria.fr/hal-01231819.

[9] M. VALLERIAN, F. D. HUTU, G. VILLEMAUD, B. MISCOPEIN, T. RISSET.*A parallel unbalanced digitization architecture to reduce the dynamic range of multiple signals*, in "Radio Science", April 2016 [*DOI :* 10.1002/2015RS005885], https://hal.archives-ouvertes.fr/hal-01312986.

Invited Conferences

[10] S. BELHADJ AMOR, S. M. PERLAZA. *Fundamental Limits of Simultaneous Energy and Information Transmission*, in "23rd International Conference on Telecommunications", Thessaloniki, Greece, Proceedings of the 23rd International Conference on Telecommunications, May 2016, Special Session 3: Exploiting interference towards energy efficient and secure wireless communications, https://hal.archives-ouvertes.fr/hal-01277160.

[11] I. ESNAOLA, S. M. PERLAZA, H. VINCENT POOR, O. KOSUT. *Decentralized MMSE Attacks in Electricity Grids*, in "IEEE Workshop on Statistical Signal Processing (SSP)", Palma de Mallorca, Spain, Proceeding of the 2016 IEEE Workshop on Statistical Signal Processing (SSP), June 2016, https://hal.archives-ouvertes.fr/hal-01312735.

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[13] D. KIBLOFF, S. M. PERLAZA, G. VILLEMAUD, L. S. CARDOSO. *On The Duality Between State-Dependent Channels and Wiretap Channels*, in "IEEE Global Conference on Signal and Information Processing (GlobalSIP)", Greater Washington, D.C., United States, Proceedings of the IEEE Global Conference on Signal and Information Processing, December 2016, https://hal.archives-ouvertes.fr/hal-01374900.

International Conferences with Proceedings

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Project-Team SPADES

Sound Programming of Adaptive Dependable Embedded Systems

IN COLLABORATION WITH: Laboratoire d'Informatique de Grenoble (LIG)

IN PARTNERSHIP WITH:
Institut polytechnique de Grenoble

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Embedded and Real-time Systems

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Creation of the Team: 2013 January 01, updated into Project-Team: 2015 July 01

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6.6. - Embedded systems

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2. Overall Objectives

2.1. Overall Objectives

The SPADES project-team aims at contributing to meet the challenge of designing and programming dependable embedded systems in an increasingly distributed and dynamic context. Specifically, by exploiting formal methods and techniques, SPADES aims to answer three key questions:

1. How to program open networked embedded systems as dynamic adaptive modular structures?
2. How to program reactive systems with real-time and resource constraints on multicore architectures?
3. How to program reliable, fault-tolerant embedded systems with different levels of criticality?

These questions above are not new, but answering them in the context of modern embedded systems, which are increasingly distributed, open and dynamic in nature [31], makes them more pressing and more difficult to address: the targeted system properties – dynamic modularity, time-predictability, energy efficiency, and fault-tolerance – are largely antagonistic (*e.g.*, having a highly dynamic software structure is at variance with ensuring that resource and behavioral constraints are met). Tackling these questions together is crucial to address this antagonism, and constitutes a key point of the SPADES research program.

A few remarks are in order:

- We consider these questions to be central in the construction of future embedded systems, dealing as they are with, roughly, software architecture and the provision of real-time and fault-tolerance guarantees. Building a safety-critical embedded system cannot avoid dealing with these three concerns.
- The three questions above are highly connected. For instance, composability along time, resource consumption and reliability dimensions are key to the success of a component-based approach to embedded systems construction.
- For us, "Programming" means any constructive process to build a running system. It can encompass traditional programming as well as high-level design or "model-based engineering" activities, provided that the latter are supported by effective compiling tools to produce a running system.
- We aim to provide semantically sound programming tools for embedded systems. This translates into an emphasis on formal methods and tools for the development of provably dependable systems.

3. Research Program

3.1. Introduction

The SPADES research program is organized around three main themes, *Components and contracts*, *Real-time multicore programming*, and *Language-based fault tolerance*, that seek to answer the three key questions identified in Section 2.1. We plan to do so by developing and/or building on programming languages and techniques based on formal methods and formal semantics (hence the use of *"sound programming"* in the project-team title). In particular, we seek to support design where correctness is obtained by construction, relying on proven tools and verified constructs, with programming languages and programming abstractions designed with verification in mind.

3.2. Components and Contracts

Component-based construction has long been advocated as a key approach to the "correct-by-construction" design of complex embedded systems [65]. Witness component-based toolsets such as UC Berkeley's PTOLEMY [53], Verimag's BIP [36], or the modular architecture frameworks used, for instance, in the automotive industry (AUTOSAR) [28]. For building large, complex systems, a key feature of component-based construction is the ability to associate with components a set of *contracts*, which can be understood as rich behavioral types that can be composed and verified to guarantee a component assemblage will meet desired properties. The goal in this theme is to study the formal foundations of the component-based construction of embedded systems, to develop component and contract theories dealing with real-time, reliability and fault-tolerance aspects of components, and to develop proof-assistant-based tools for the computer-aided design and verification of component-based systems.

Formal models for component-based design are an active area of research (see *e.g.*, [29], [30]). However, we are still missing a comprehensive formal model and its associated behavioral theory able to deal *at the same time* with different forms of composition, dynamic component structures, and quantitative constraints (such as timing, fault-tolerance, or energy consumption). Notions of contracts and interface theories have been proposed to support modular and compositional design of correct-by-construction embedded systems (see *e.g.*, [40], [41] and the references therein), but having a comprehensive theory of contracts that deals with all the above aspects is still an open question [71]. In particular, it is not clear how to accomodate different forms of composition, reliability and fault-tolerance aspects, or to deal with evolving component structures in a theory of contracts.

Dealing in the same component theory with heterogeneous forms of composition, different quantitative aspects, and dynamic configurations, requires to consider together the three elements that comprise a component model: behavior, structure and types. *Behavior* refers to behavioral (interaction and execution) models that characterize the behavior of components and component assemblages (*e.g.*, transition systems and their multiple variants – timed, stochastic, etc.). *Structure* refers to the organization of component assemblages or configurations, and the composition operators they involve. *Types* refer to properties or contracts that can be attached to components and component interfaces to facilitate separate development and ensure the correctness of component configurations with respect to certain properties. Taking into account dynamicity requires to establish an explicit link between behavior and structure, as well as to consider higher-order systems, both of which have a direct impact on types.

We plan to develop our component theory by progressing on two fronts: component calculi, and semantical framework. The work on typed component calculi aims to elicit process calculi that capture the main insights of component-based design and programming and that can serve as a bridge towards actual architecture description and programming language developments. The work on the semantical framework should, in the longer term, provide abstract mathematical models for the more operational and linguistic analysis afforded by component calculi. Our work on component theory will find its application in the development of a COQ-based toolchain for the certified design and construction of dependable embedded systems, which constitutes our third main objective for this axis.

3.3. Real-Time Multicore Programming

Programming real-time systems (*i.e.*, systems whose correct behavior depends on meeting timing constraints) requires appropriate languages (as exemplified by the family of synchronous languages [39]), but also the support of efficient scheduling policies, execution time and schedulability analyses to guarantee real-time constraints (*e.g.*, deadlines) while making the most effective use of available (processing, memory, or networking) resources. Schedulability analysis involves analyzing the worst-case behavior of real-time tasks under a given scheduling algorithm and is crucial to guarantee that time constraints are met in any possible execution of the system. Reactive programming and real-time scheduling and schedulability for multiprocessor systems are old subjects, but they are nowhere as mature as their uniprocessor counterparts, and still feature a number of open research questions [35], [48], in particular in relation with mixed criticality systems. The main goal in this theme is to address several of these open questions.

We intend to focus on two issues: multicriteria scheduling on multiprocessors, and schedulability analysis for real-time multiprocessor systems. Beyond real-time aspects, multiprocessor environments, and multicore ones in particular, are subject to several constraints *in conjunction*, typically involving real-time, reliability and energy-efficiency constraints, making the scheduling problem more complex for both the offline and the online cases. Schedulability analysis for multiprocessor systems, in particular for systems with mixed criticality tasks, is still very much an open research area.

Distributed reactive programming is rightly singled out as a major open issue in the recent, but heavily biased (it essentially ignores recent research in synchronous and dataflow programming), survey by Bainomugisha et al. [35]. For our part, we intend to focus on two questions: devising synchronous programming languages for distributed systems and precision-timed architectures, and devising dataflow languages for multiprocessors supporting dynamicity and parametricity while enjoying effective analyses for meeting real-time, resource and energy constraints in conjunction.

3.4. Language-Based Fault Tolerance

Tolerating faults is a clear and present necessity in networked embedded systems. At the hardware level, modern multicore architectures are manufactured using inherently unreliable technologies [43], [58]. The evolution of embedded systems towards increasingly distributed architectures highlighted in the introductory section means that dealing with partial failures, as in Web-based distributed systems, becomes an important issue. While fault-tolerance is an old and much researched topic, several important questions remain open: automation of fault-tolerance provision, composable abstractions for fault-tolerance, fault diagnosis, and fault isolation.

The first question is related to the old question of "system structure for fault-tolerance" as originally discussed by Randell for software fault tolerance [77], and concerns in part our ability to clearly separate fault-tolerance aspects from the design and programming of purely "functional" aspects of an application. The classical arguments in favor of a clear separation of fault-tolerance concerns from application code revolve around reduced code and maintenance complexity [49]. The second question concerns the definition of appropriate abstractions for the modular construction of fault-tolerant embedded systems. The current set of techniques available for building such systems spans a wide range, including exception handling facilities, transaction management schemes, rollback/recovery schemes, and replication protocols. Unfortunately, these different techniques do not necessarily compose well – for instance, combining exception handling and transactions is non trivial, witness the flurry of recent work on the topic, see *e.g.*, [64] and the references therein –, they have no common semantical basis, and they suffer from limited programming language support. The third question concerns the identification of causes for faulty behavior in component-based assemblages. It is directly related to the much researched area of fault diagnosis, fault detection and isolation [66].

We intend to address these questions by leveraging programming language techniques (programming constructs, formal semantics, static analyses, program transformations) with the goal to achieve provable fault-tolerance, *i.e.*, the construction of systems whose fault-tolerance can be formally ensured using verification tools and proof assistants. We aim in this axis to address some of the issues raised by the above open questions by using aspect-oriented programming techniques and program transformations to automate the inclusion of fault-tolerance in systems (software as well as hardware), by exploiting reversible programming models to investigate composable recovery abstractions, and by leveraging causality analyses to study fault-ascription in component-based systems. Compared to the huge literature on fault-tolerance in general, in particular in the systems area (see *e.g.*, [59] for an interesting but not so recent survey), we find by comparison much less work exploiting formal language techniques and tools to achieve or support fault-tolerance. The works reported in [42], [44], [47], [54], [67], [76], [81] provide a representative sample of recent such works.

A common theme in this axis is the use and exploitation of causality information. Causality, *i.e.*, the logical dependence of an effect on a cause, has long been studied in disciplines such as philosophy [72], natural sciences, law [73], and statistics [74], but it has only recently emerged as an important focus of research in computer science. The analysis of logical causality has applications in many areas of computer science. For instance, tracking and analyzing logical causality between events in the execution of a concurrent system is required to ensure reversibility [70], to allow the diagnosis of faults in a complex concurrent system [61], or to enforce accountability [69], that is, designing systems in such a way that it can be determined without ambiguity whether a required safety or security property has been violated, and why. More generally, the goal of fault-tolerance can be understood as being to prevent certain causal chains from occurring by designing systems such that each causal chain either has its premises outside of the fault model (*e.g.*, by introducing redundancy [59]), or is broken (*e.g.*, by limiting fault propagation [78]).

4. Application Domains

4.1. Industrial Applications

Our applications are in the embedded system area, typically: transportation, energy production, robotics, telecommunications, systems on chip (SoC). In some areas, safety is critical, and motivates the investment in formal methods and techniques for design. But even in less critical contexts, like telecommunications and multimedia, these techniques can be beneficial in improving the efficiency and the quality of designs, as well as the cost of the programming and the validation processes.

Industrial acceptance of formal techniques, as well as their deployment, goes necessarily through their usability by specialists of the application domain, rather than of the formal techniques themselves. Hence, we are looking to propose domain-specific (but generic) realistic models, validated through experience (*e.g.*, control tasks systems), based on formal techniques with a high degree of automation (*e.g.*, synchronous models), and tailored for concrete functionalities (*e.g.*, code generation).

4.2. Industrial Design Tools

The commercially available design tools (such as UML with real-time extensions, MATLAB/ SIMULINK/ dSPACE[0]) and execution platforms (OS such as VXWORKS, QNX, real-time versions of LINUX ...) start now to provide besides their core functionalities design or verification methods. Some of them, founded on models of reactive systems, come close to tools with a formal basis, such as for example STATEMATE by iLOGIX.

Regarding the synchronous approach, commercial tools are available: SCADE[0] (based on LUSTRE), CONTROLBUILD and RT-BUILDER (based on SIGNAL) from GEENSYS[0] (part of DASSAULTSYSTEMES), specialized environments like CELLCONTROL for industrial automatism (by the INRIA spin-off ATHYS– now part of DASSAULTSYSTEMES). One can observe that behind the variety of actors, there is a real consistency of the synchronous technology, which makes sure that the results of our work related to the synchronous approach are not restricted to some language due to compatibility issues.

4.3. Current Industrial Cooperations

Regarding applications and case studies with industrial end-users of our techniques, we cooperate with Thales on schedulability analysis for evolving or underspecified real-time embedded systems, with Orange Labs on software architecture for cloud services and with Daimler on reduction of nondeterminism and analysis of deadline miss models for the design of automotive systems.

5. New Software and Platforms

5.1. pyCPA_TWCA: A pyCPA plugin for computing deadline miss models

FUNCTIONAL DESCRIPTION

[0]http://www.dspaceinc.com
[0]http://www.esterel-technologies.com
[0]http://www.geensoft.com

We are developing pyCPA_TWCA, a pyCPA plugin for Typical Worst-Case Analysis as described in Section 6.2.5. pyCPA is an open-source Python implementation of Compositional Performance Analysis developed at TU Braunschweig, which allows in particular response-time analysis. pyCPA_TWCA is an extension of this tool that is co-developed by Sophie Quinton, Zain Hammadeh (TU Braunschweig) and Leonie Ahrendts (TU Braunschweig). It allows in particular the computation of weakly-hard guarantees for real-time tasks, *i.e.*, the number of deadline misses out of a sequence of executions. This year, pyCPA_TWCA has been extended to task chains but remains limited to uniprocessor systems, scheduled according to static priority scheduling. A public release is planned but has not yet taken place.

- Authors: Zain Hammadeh and Leonie Ahrendts and Sophie Quinton.
- Contact: Sophie Quinton.

6. New Results

6.1. Components and contracts

Participants: Alain Girault, Christophe Prévot, Sophie Quinton, Jean-Bernard Stefani.

6.1.1. Contracts for the negotiation of embedded software updates

We address the issue of change after deployment in safety-critical embedded system applications in collaboration with Thales and also in the context of the CCC project (http://ccc-project.org/).

The goal of CCC is to substitute lab-based verification with in-field formal analysis to determine whether an update may be safely applied. This is challenging because it requires an automated process able to handle multiple viewpoints such as functional correctness, timing, etc. For this purpose, we propose an original methodology for contract-based negotiation of software updates. The use of contracts allows us to cleanly split the verification effort between the lab and the field. In addition, we show how to rely on existing viewpoint-specific methods for update negotiation. We have validated our approach on a concrete example inspired by the automotive domain in collaboration with our German partners from TU Braunschweig [19].

In collaboration with Thales we mostly focus on timing aspects with the objective to anticipate at design time future software evolutions and identify potential schedulability bottlenecks. This year we have presented an approach to quantify the flexibility of a system with respect to timing. In particular we have shown that it is possible under certain conditions to identify the task that will directly induce the limitations on a possible software update. If performed at design time, such a result can be used to adjust the system design by giving more slack to the limiting task [21].

6.1.2. Location graphs

The design of configurable systems can be streamlined and made more systematic by adopting a component-based structure, as demonstrated with the FRACTAL component model [2]. However, the formal foundations for configurable component-based systems, featuring higher-order capabilities where components can be dynamically instantiated and passivated, and non-hierarchical structures where components can be contained in different composites at the same time, are still an open topic. We have recently introduced the location graph model [79], where components are understood as graphs of locations hosting higher-order processes, and where component structures can be arbitrary graphs.

We have continued the development of location graphs, revisiting the underlying structural model (hypergraphs instead of graphs), and simplifying its operational semantics while preserving the model expressivity. Towards the development of a behavioral theory of location graphs, we have defined different notions of bisimilarity for location graphs and shown them to be congruences, although a fully fledged co-inductive characterization of contextual equivalence for location graphs is still in the works. This work has not yet been published.

6.2. Real-Time multicore programming

Participants: Pascal Fradet, Alain Girault, Gregor Goessler, Xavier Nicollin, Sophie Quinton.

6.2.1. Time predictable programming languages

Time predictability (PRET) is a topic that emerged in 2007 as a solution to the ever increasing unpredictability of today's embedded processors, which results from features such as multi-level caches or deep pipelines [52]. For many real-time systems, it is mandatory to compute a strict bound on the program's execution time. Yet, in general, computing a tight bound is extremely difficult [82]. The rationale of PRET is to simplify both the programming language and the execution platform to allow more precise execution times to be easily computed [34].

Following our past results on the PRET-C programming language [32], we have proposed a time predictable synchronous programming language for multicores, called FOREC. It extends C with a small set of ESTEREL-like synchronous primitives to express concurrency, interaction with the environment, looping, and a synchronization barrier [83] (like the `pause` statement in ESTEREL). FOREC threads communicate with each other via shared variables, the values of which are *combined* at the end of each tick to maintain deterministic execution. We provide several deterministic combine policies for shared variables, in a way similar as concurrent revisions [45]. Thanks to this, it benefits from a deterministic semantics. FOREC is compiled into threads that are then statically scheduled for a target multicore chip. Our WCET analysis takes into account the access to the shared TDMA bus and the necessary administration for the shared variables. We achieve a very precise WCET (the over-approximation being less than 2%) thanks to a reachable space exploration of the threads' states [15]. We have published a research report presenting the complete semantics and the compiler [27], and submitted it to a journal.

Furthermore, we have extended the PRET-C compiler [32] in order to make it energy aware. To achieve this, we use dynamic voltage and frequency scaling (DFVS) and we insert DVFS control points in the control flow graph of the PRET-C program. The difficulty is twofold: first the control flow graph is concurrent, and second resulting optimization problem is in the 2D space (time,energy). Thanks to a novel ILP formulation and to a bicriteria heuristic, we are able to address the two objectives jointly and to compute, for each PRET-C program, the Pareto front of the non-dominated solutions in the 2D space (time, energy) [20].

This is a collaboration with Eugene Yip from Bamberg University, and with Partha Roop and Jiajie Wang from the University of Auckland.

6.2.2. Modular distribution of synchronous programs

Synchronous programming languages describe functionally centralized systems, where every value, input, output, or function is always directly available for every operation. However, most embedded systems are nowadays composed of several computing resources. The aim of this work is to provide a language-oriented solution to describe *functionally distributed reactive systems*. This research started within the Inria large scale action SYNCHRONICS and is a joint work with Marc Pouzet (ENS, PARKAS team from Rocquencourt) and Gwenaël Delaval (UGA, CTRL-A team from Grenoble).

We are working on defining a *fully-conservative* extension of a synchronous data-flow programming language (the HEPTAGON language, inspired from LUCID SYNCHRONE [46]). The extension, by means of *annotations* adds *abstract location parameters* to functions, and *communications* of values between locations. At deployment, every abstract location is assigned an actual one; this yields an executable for each actual computing resource. Compared to the PhD of Gwenaël Delaval [50], [51], the goal here is to achieve *modular* distribution even in the presence of non-static clocks, *i.e.*, clocks defined according to the value of inputs.

By *fully-conservative*, we have three aims in mind:

1. A non-annotated (*i.e.*, centralized) program will be compiled exactly as before;
2. An annotated program eventually deployed onto only one computing location will behave exactly as its centralized couterpart;
3. The input-output semantics of a distributed program is the same as its centralized counterpart.

By *modular*, we mean that we want to compile each function of the program into a single function capable of running on any computing location. At deployment, the program of each location may be optimized (by simple Boolean-constant-propagation, dead-code and unused-variable elimination), yielding different optimized code for each computing location.

We have formalized the type-system for inferring the location of each variable and computation. In the presence of local clocks, added information is computed from the existing clock-calculus and the location-calculus, to infer necessary communication of clocks between location. All pending theorical and technical issues have been answered, and the new compiler is being implemented, with new algorithms for deployment (and code optimization), achieving the three aims detailed above.

6.2.3. Parametric dataflow models

Recent data-flow programming environments support applications whose behavior is characterized by dynamic variations in resource requirements. The high expressive power of the underlying models (*e.g.*, Kahn Process Networks or the CAL actor language) makes it challenging to ensure predictable behavior. In particular, checking *liveness* (*i.e.*, no part of the system will deadlock) and *boundedness* (*i.e.*, the system can be executed in finite memory) is known to be hard or even undecidable for such models. This situation is troublesome for the design of high-quality embedded systems.

Recently, we have introduced the *Schedulable Parametric Data-Flow* (SPDF) MoC for dynamic streaming applications [55], which extends the standard dataflow model by allowing rates to be parametric, and the *Boolean Parametric Data Flow* (BPDF) MoC [38], [37] which combines integer parameters (to express dynamic rates) and boolean parameters (to express the activation and deactivation of communication channels). In the past years, several other parametric dataflow MoCs have been presented. All these models aim at providing an interesting trade-off between analyzability and expressiveness. They offer a controlled form of dynamism under the form of parameters (*e.g.*, parametric rates), along with run-time parameter configuration.

We have written a survey which provides a comprehensive description of the existing parametric dataflow MoCs (constructs, constraints, properties, static analyses) and compares them using a common example [11]. The main objectives are to help designers of streaming applications to choose the most suitable model for their needs and to pave the way for the design of new parametric MoCs.

We have also studied *symbolic* analyses of data-flow graphs [24], [16], [17], [12]. Symbolic analyses express the system performance as a function of parameters (*i.e.*, input and output rates, execution times). Such functions can be quickly evaluated for each different configuration or checked *w.r.t.* different quality-of-service requirements. These analyses are useful for parametric MoCs, partially specified graphs, and even for completely static SDF graphs. We provide symbolic analyses for computing the maximal throughput of acyclic synchronous dataflow graphs, the minimum required buffers for which as soon as possible (asap) scheduling achieves this throughput, and finally the corresponding input-output latency of the graph. We first investigate these problems for a single parametric edge. The results are then extended to general acyclic graphs using linear approximation techniques. We assess the proposed analyses experimentally on both synthetic and real benchmarks.

6.2.4. Synthesis of switching controllers using approximately bisimilar multiscale abstractions

The use of discrete abstractions for continuous dynamics has become standard in hybrid systems design (see *e.g.*, [80] and the references therein). The main advantage of this approach is that it offers the possibility to leverage controller synthesis techniques developed in the areas of supervisory control of discrete-event systems [75]. The first attempts to compute discrete abstractions for hybrid systems were based on traditional systems behavioral relationships such as simulation or bisimulation, initially proposed for discrete systems most notably in the area of formal methods. These notions require inclusion or equivalence of observed behaviors which is often too restrictive when dealing with systems observed over metric spaces. For such systems, a more natural abstraction requirement is to ask for closeness of observed behaviors. This leads to the notions of approximate simulation and bisimulation introduced in [56].

These approaches are based on sampling of time and space where the sampling parameters must satisfy some relation in order to obtain abstractions of a prescribed precision. In particular, the smaller the time sampling parameter, the finer the lattice used for approximating the state-space; this may result in abstractions with a very large number of states when the sampling period is small. However, there are a number of applications where sampling has to be fast; though this is generally necessary only on a small part of the state-space. We have been exploring two approaches to overcome this state-space explosion [5].

We are currently investigating an approach using mode sequences of given length as symbolic states for our abstractions. By using mode sequences of variable length we are able to adapt the granularity of our abstraction to the dynamics of the system, so as to automatically trade off precision against controllability of the abstract states.

6.2.5. Schedulability of weakly-hard real-time systems

We focus on the problem of computing tight deadline miss models for real-time systems, which bound the number of potential deadline misses in a given sequence of activations of a task. In practical applications, such guarantees are often sufficient because many systems are in fact not hard real-time [4].

Our major contribution this year is the extension of our method for computing deadline miss models, called Typical Worst-Case Analysis (TWCA), to systems with task dependencies. This allows us to provide bounds on deadline misses for systems which until now could not be analyzed [18].

In parallel, we have developed an extension of sensitivity analysis for budgeting in the design of weakly-hard real-time systems. During design, it often happens that some parts of a task set are fully specified while other parameters, e.g. regarding recovery or monitoring tasks, will be available only much later. In such cases, sensitivity analysis can help anticipate how these missing parameters can influence the behavior of the whole system so that a resource budget can be allocated to them. We have developed an extension of sensitivity analysis for deriving task budgets for systems with hard and weakly-hard requirements. This approach has been validated on synthetic test cases and a realistic case study given by our partner Thales. This work will be submitted soon.

Finally, in collaboration with TU Braunschweig and Daimler we have investigated the use of TWCA in conjunction with the Logical Execution Time paradigm [68] according to which data are read and written at predefined time instants. In particular, we have extended TWCA to different deadline miss handling strategies. This work has not been published yet.

6.3. Language Based Fault-Tolerance

Participants: Pascal Fradet, Alain Girault, Yoann Geoffroy, Gregor Goessler, Jean-Bernard Stefani, Martin Vassor, Athena Abdi.

6.3.1. Fault Ascription in Concurrent Systems

The failure of one component may entail a cascade of failures in other components; several components may also fail independently. In such cases, elucidating the exact scenario that led to the failure is a complex and tedious task that requires significant expertise.

The notion of causality *(did an event e cause an event e'?)* has been studied in many disciplines, including philosophy, logic, statistics, and law. The definitions of causality studied in these disciplines usually amount to variants of the counterfactual test "e is a cause of e' if both e and e' have occurred, and in a world that is as close as possible to the actual world but where e does not occur, e' does not occur either". In computer science, almost all definitions of logical causality — including the landmark definition of [63] and its derivatives — rely on a causal model that may not be known, for instance in presence of black-box components. For such systems, we have been developing a framework for blaming that helps us establish the causal relationship between component failures and system failures, given an observed system execution trace. The analysis is based on a formalization of counterfactual reasoning [7].

In his PhD thesis, Yoann Geoffroy proposed a generalization of our fault ascription technique to systems composed of black-box and white-box components. For the latter a faithful behavioral model is given but no specification. The approach leverages results from game theory and discrete controller synthesis to define several notions of causality.

We are currently working on an instantiation of our general semantic framework for fault ascription in [60] to acyclic models of computation, in order to compare our approach with the standard definition of *actual causality* proposed by Halpern and Pearl.

6.3.2. Tradeoff exploration between energy consumption and execution time

We have continued our work on multi-criteria scheduling, in two directions. First, in the context of dynamic applications that are launched and terminated on an embedded homogeneous multi-core chip, under execution time and energy consumption constraints, we have proposed a two layer adaptive scheduling method. In the first layer, each application (represented as a DAG of tasks) is scheduled statically on subsets of cores: 2 cores, 3 cores, 4 cores, and so on. For each size of these sets (2, 3, 4, ...), there may be only one topology or several topologies. For instance, for 2 or 3 cores there is only one topology (a "line"), while for 4 cores there are three distinct topologies ("line", "square", and "T shape"). Moreover, for each topology, we generate statically several schedules, each one subject to a different total energy consumption constraint, and consequently with a different Worst-Case Reaction Time (WCRT). Coping with the energy consumption constraints is achieved thanks to Dynamic Frequency and Voltage Scaling (DVFS). In the second layer, we use these pre-generated static schedules to reconfigure dynamically the applications running on the multi-core each time a new application is launched or an existing one is stopped. The goal of the second layer is to perform a dynamic global optimization of the configuration, such that each running application meets a pre-defined quality-of-service constraint (translated into an upper bound on its WCRT) and such that the total energy consumption be minimized. For this, we *(i)* allocate a sufficient number of cores to each active application, *(ii)* allocate the unassigned cores to the applications yielding the largest gain in energy, and *(iii)* choose for each application the best topology for its subset of cores (*i.e.*, better than the by default "line" topology). This is a joint work with Ismail Assayad (U. Casablanca, Morocco) who visited the team in September 2015.

Second, in the context of a static application (again represented a DAG of tasks) running on an homogeneous multi-core chip, we have worked on the static scheduling minimizing the WCRT of the application under the multiple constraints that the reliability, the power consumption, and the temperature remain below some given thresholds. There are multiple difficulties: *(i)* the reliability is not an invariant measure w.r.t. time, which makes it impossible to use backtrack-free scheduling algorithms such as list scheduling [33]; to overcome this, we adopt instead the Global System Failure Rate (GSFR) as a measure of the system's reliability, which is invariant with time [57]; *(ii)* keeping the power consumption under a given threshold requires to lower the voltage and frequency, but this has a negative impact both on the WCRT and on the GSFR; keeping the GSFR below a given threshold requires to replicate the tasks on multiple cores, but this has a negative impact both on the WCRT, on the power consumption, and on the temperature; *(iii)* keeping the temperature below a given threshold is even more difficult because the temperature continues to increase even after the activity stops, so each scheduling decision must be assessed not based on the current state of the chip (*i.e.*, the temperature of each core) but on the state of the chip at the end of the candidate task, and cooling slacks must be inserted. We have proposed a multi-criteria scheduling heuristics to address these challenges. It produces a static schedule of the given application graph and the given architecture description, such that the GSFR, power, and temperature thresholds are satisfied, and such that the execution time is minimized. We then combine our heuristic with a variant of the ε-constraint method [62] in order to produce, for a given application graph and a given architecture description, its entire Pareto front in the 4D space (exec. time, GSFR, power, temp.). This is a joint work with Athena Abdi and Hamid Zarandi from Amirkabir U., Iran, who have visited the team in 2016.

6.3.3. Automatic transformations for fault tolerant circuits

In the past years, we have studied the implementation of specific fault tolerance techniques in real-time embedded systems using program transformation [1]. We are now investigating the use of automatic transformations to ensure fault-tolerance properties in digital circuits. To this aim, we consider program transformations for hardware description languages (HDL). We consider both single-event upsets (SEU) and single-event transients (SET) and fault models of the form *"at most 1 SEU or SET within n clock cycles"*.

We have expressed several variants of triple modular redundancy (TMR) as program transformations. We have proposed a verification-based approach to minimize the number of voters in TMR [25]. Our technique guarantees that the resulting circuit *(i)* is fault tolerant to the soft-errors defined by the fault model and *(ii)* is functionally equivalent to the initial one. Our approach operates at the logic level and takes into account the input and output interface specifications of the circuit. Its implementation makes use of graph traversal algorithms, fixed-point iterations, and BDDs. Experimental results on the ITC'99 benchmark suite indicate that our method significantly decreases the number of inserted voters which entails a hardware reduction of up to 55% and a clock frequency increase of up to 35% compared to full TMR. We address scalability issues arising from formal verification with approximations and assess their efficiency and precision. As our experiments show, if the SEU fault-model is replaced with the stricter fault-model of SET, it has a minor impact on the number of removed voters. On the other hand, BDD-based modeling of SET effects represents a more complex task than the modeling of an SEU as a bit-flip. We propose solutions for this task and explain the nature of encountered problems. We discuss scalability issues arising from formal verification with approximations and assess their efficiency and precision.

6.3.4. Concurrent flexible reversibility

Reversible concurrent models of computation provide natively what appears to be very fine-grained checkpoint and recovery capabilities. We have made this intuition clear by formally comparing a distributed algorithm for checkpointing and recovery based on causal information, and the distributed backtracking algorithm that lies at the heart of our reversible higher-order pi-calculus. We have shown that (a variant of) the reversible higher-order calculus with explicit rollback can faithfully encode a distributed causal checkpoint and recovery algorithm. The reverse is also true but under precise conditions, which restrict the ability to rollback a computation to an identified checkpoint. This work has currently not been published.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- INRIA and Orange Labs have established this year a joint virtual research laboratory, called I/O LAB. We have been heavily involved in the creation of the laboratory and are actively involved in its operation (Jean-Bernard Stefani is one of the two co-directors of the lab). I/O LAB focuses on the network virtualization and cloudification. As part of the work of I/O LAB, we have cooperated with Orange Lab, as part of a cooperative research contract funded by Orange, on defining architectural principles and frameworks for network cloud infrastructures encompassing control and management of computing, storage and network resources.
- With Daimler (subcontracting via iUTBS): We have shown how to extend our current method for computing deadline miss models to real-time systems designed according to the Logical Execution Time paradigm.

7.2. Bilateral Grants with Industry

With Thales: Early Performance assessment for evolving and variable Cyber-Physical Systems. This CIFRE grant funds the PhD of Christophe Prévot.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. CASERM (PERSYVAL-Lab project)

Participants: Pascal Fradet, Alain Girault, Gregor Goessler, Xiaojie Guo, Xavier Nicollin, Stephan Plassart, Sophie Quinton, Jean-Bernard Stefani.

Despite recent advances, there exist currently no integrated formal methods and tools for the design and analysis of reconfigurable multi-view embedded systems. This is the goal of the CASERM project.

The CASERM project represents a significant effort towards a COQ-based design method for reconfigurable multi-view embedded systems, in order to formalize the structure and behavior of systems and to prove their main properties. The use of a proof assistant to support such a framework is motivated by the fact that the targeted systems are both extremely complex and critical. The challenges addressed are threefold:

1. to model software architectures for embedded systems taking into account their dynamicity and multiple constraints (functional as well as non functional);
2. to propose novel scheduling techniques for dynamically reconfiguring embedded systems; and
3. to advance the state of the art in automated proving for such systems.

The objectives of CASERM that address these challenges are organized in three tasks. They consist respectively in designing an architecture description framework based on a process calculus, in proposing online optimization methods for dynamic reconfiguration systems (this is the topic of Stephan Plassart's PhD), and in developing a formal framework for real-time analysis in the COQ proof assistant (this is the topic of Xiaojie Guo's PhD). A fourth task focuses on common case studies for the evaluation of the obtained results.

The CASERM consortium gathers researchers from the G-SCOP, LIG and VERIMAG laboratories who are reknown specialists in these fields. The project started in November 2016 and will last three years.

8.2. European Initiatives

8.2.1. Collaborations with Major European Organizations

We have a strong collaboration with the Technische Universität Braunschweig in Germany. In particular, Sophie Quinton is involved in the CCC project (http://ccc-project.org/) to provide methods and mechanisms for the verification of software updates after deployment in safety-critical systems and in the TypicalCPA project which aims at computing deadline miss models for distributed systems.

We also a recent collaboration with the MPI-SWS in Kaiserslautern (Germany) on formal proofs for real-time systems.

8.3. International Initiatives

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

8.3.1.1. Causalysis

Title: Causality Analysis for Safety-Critical Embedded Systems

International Partner (Institution - Laboratory - Researcher):

University of Pennsylvania (United States) - PRECISE center - Oleg Sokolsky

Start year: 2015

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

Today's embedded systems become more and more complex, while an increasing number of safety-critical functions rely on them. Determining the cause(s) of a system-level failure and elucidating the exact scenario that led to the failure is today a complex and tedious task that requires significant expertise. The CAUSALYSIS project will develop automated approaches to causality analysis on execution logs.

8.4. International Research Visitors

8.4.1. Visits of International Scientists

8.4.1.1. Internships

- Athena Abdi has been a visitor in the team from October 2015 to June 2016. She is doing her PhD at the Amirkabir University of Technology in Teheran, Iran. In the SPADES team, she is working on multi-criteria scheduling for real-time embedded systems, addressing the complex interplay between reliability, power consumption, temperature, and execution time (see 6.3.2).
- Ismail Assayad has been a visitor in the team in September 2015. He is assistant professor at the University of Casablanca, Morocco. In the SPADES team, he is working on adaptive scheduling methods and admission control for dynamic embedded applications (see 6.3.2).

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific events organisation

9.1.1.1. Member of organizing committees

- Sophie Quinton was artifact evaluation chair of the 24th International Conference on Real-Time Networks and Systems (RTNS'16).
- Sophie Quinton was demo chair of the 22nd IEEE Real-Time Embedded Technology & Applications Symposium (RTAS'16)
- Sophie Quinton was co-chair of the 1st Tutorial on Tools for Real-Time Systems (TuToR'16), held as a satellite event of CPSWeek'16. http://tutor2016.inria.fr/
- Sophie Quinton was co-organizer of the 1st Workshop on Collaboration of Academia and Industry for Real World Embedded Systems (CAIRES'16), held as a satellite event of ESWeek'16. http://caires2016.inria.fr/

9.1.2. Scientific events selection

9.1.2.1. Chair of conference program committees

- Gregor Gössler was co-chair of the 1st international Workshop on Causal Reasoning for Embedded and safety-critical Systems Technologies (CREST'16) [22], held as a satellite event of ETAPS'16. http://crest2016.inria.fr
- Sophie Quinton was co-chair of the 7th International Workshop on Analysis Tools and Methodologies for Embedded and Real-time Systems (WATERS'16), held as a satellite event of ECRTS'16. http://waters2016.inria.fr

9.1.2.2. Member of conference program committees

- Pascal Fradet served in the program committee of the 15th International Conference on Modularity (MODULARITY'16).
- Alain Girault served in the program committees of the International Conference on Design and Test in Europe (DATE'16), the Embedded Software conference (EMSOFT'16), and the International Symposium on Industrial Embedded Systems (SIES'16).

- Sophie Quinton served in the program committees of the 28th Euromicro Conference on Real-Time Systems (ECRTS'16), the 24th International Conference on Real-Time Networks and Systems (RTNS'16), the 4th International Workshop on Mixed Criticality Systems (WMC'16), the 10th Junior Researcher Workshop on Real-Time Computing (JRWRTC'16), and in the artifact evaluation committees of ECRTS'16 and the IEEE Real-Time Systems Symposium (RTSS'16).
- Jean-Bernard Stefani served on the program committees of the 36th IFIP International Conference on Formal Techniques for Distributed Objects, Components and Systems (FORTE) and the 8th Conference on Reversible Computation.

9.1.2.3. Reviewer

- Alain Girault reviewed an article for ECRTS'16.
- Gregor Gössler reviewed articles for EMSOFT'16, FACS'16, and RTNS'16.
- Xavier Nicollin reviewed an article for SIES'16.
- Sophie Quinton reviewed articles for EMSOFT'16 and DATE'17.

9.1.3. Journal

9.1.3.1. Member of the editorial boards

- Alain Girault is a member of the editorial board of the EURASIP Journal on Embedded Systems.
- Jean-Bernard Stefani is a member of the editorial board of Annals of Telecommunications.

9.1.3.2. Reviewer - Reviewing activities

- Alain Girault reviewed articles for ACM TECS, Parallel Computing, Embedded Systems Letters, and Microprocessors and Microsystems.
- Gregor Gössler reviewed articles for Formal Methods in System Design (FMSD) and IEEE Transactions on Automatic Control (TAC).
- Jean-Bernard Stefani reviewed articles for Theoretical Computer Science (TCS) and Science of Computer Programming (SCP).

9.1.4. Research administration

- Pascal Fradet is head of the committee for doctoral studies ("Responsable du comité des études doctorales") of the INRIA Grenoble – Rhône-Alpes research center and local correspondent for the young researchers INRIA mission (mission jeunes chercheurs).
- Alain Girault is Vice Chair of the INRIA Evaluation Committee. As such, he co-organizes in particular the evaluation seminars of the INRIA teams (twice a year) and all the juries for the hiring and promotion of INRIA's researchers (CR2, CR1, DR2, DR1, and DR0).
- Jean-Bernard Stefani is Head of science of the INRIA Grenoble – Rhône-Alpes research center. As such, he manages with the research center director all aspects of the scientific life of the research center (creation of the research teams and their evaluation by international panels, scientific relationships with our academic and industrial partners, hiring of the new junior researchers, ...).
- Jean-Bernard Stefani is co-director of I/O LAB, the joint research laboratory with Orange Lab.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence : Pascal Fradet, Théorie des Langages 1 & 2, 36 HeqTD, niveau L3, Grenoble INP (Ensimag), France

Licence : Gregor Gössler, Théorie des Langages 2, 36 HeqTD, niveau L3, Grenoble INP (Ensimag), France

Master : Xavier Nicollin, Sémantique et Analyse des Programmes, 11,25 HeqTD, niveau M1, Grenoble INP (Ensimag), France

Licence : Xavier Nicollin, Théorie des Langages 2, 36 HeqTD, niveau L3, Grenoble INP (Ensimag), France

Licence : Xavier Nicollin, Bases de la Programmation Impérative, 66 HeqTD, niveau L3, Grenoble INP (Ensimag), France

Licence : Sophie Quinton, Théorie des Langages 2, 18 HeqTD, niveau L3, Grenoble INP (Ensimag), France

Master : Jean-Bernard Stefani, Formal Aspects of Component Software, 9h, MOSIG, Univ. Grenoble Alpes, France

Master : Sophie Quinton, Performance and Quantitative Properties, 6h, MOSIG, Univ. Grenoble Alpes, France

9.2.2. Supervision

- PhD: Yoann Geoffroy, "A general trace-based causality framework for component-based systems", Univ. Grenoble Alpes, defended on December 7th 2016, advised by Gregor Gössler.
- PhD in progress: Sihem Cherrared, "Fault Management in Multi-Tenant Programmable Networks", Univ. Rennes 1, since October 2016, co-advised by Eric Fabre and Gregor Gössler.
- PhD in progress: Christophe Prévot, "Early Performance assessment for evolving and variable Cyber-Physical Systems", Univ. Grenoble Alpes, since November 2015, co-advised by Alain Girault and Sophie Quinton.
- PhD in progress: Xiaojie Guo, "Formal Proofs for the Analysis of Real-Time Systems in COQ", Univ. Grenoble Alpes, since December 2016, co-advised by Pascal Fradet, Jean-François Monin, and Sophie Quinton.
- PhD in progress: Stephan Plassart, "On-line optimization in dynamic real-time systems", Univ. Grenoble Alpes, since September 2016, co-advised by Alain Girault and Bruno Gaujal.

9.2.3. Juries

- Alain Girault was president of the HDR jury of Goran Frehse (Univ. Grenoble Alpes).
- Sophie Quinton was member of the PhD jury of Houssam Zahaf (U. Lille).
- Jean-Bernard Stefani was president of the HDR jury of Tom Hirschowitz (U. Savoie).

9.3. Popularization

Alain Girault gave a lecture to high school math professors, titled "Multi-core architectures, reliability, and optimization" (ISN conference cycle, Grenoble, February 2016). http://www.canal-u.tv/video/inria/architectures_multi_coeurs_ fiabilite_et_optimisation.20829

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Articles in International Peer-Reviewed Journal

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Project-Team STEEP

Sustainability transition, environment, economy and local policy

IN COLLABORATION WITH: Laboratoire Jean Kuntzmann (LJK)

IN PARTNERSHIP WITH:
CNRS

Université Grenoble Alpes

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Earth, Environmental and Energy Sciences

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Project-Team STEEP

Creation of the Team: 2010 January 01, updated into Project-Team: 2015 December 01

Keywords:

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6.1. - Mathematical Modeling
8.6. - Decision support

Other Research Topics and Application Domains:

1.2. - Ecology
1.2.1. - Biodiversity
3.1. - Sustainable development
3.1.1. - Resource management
3.4.3. - Pollution
7. - Transport and logistics
8.3. - Urbanism and urban planning
8.5.1. - Participative democracy
8.5.3. - Collaborative economy
9.10. - Ethics

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Corentin Deleau [Inria, High school student, until Mar 2016]
Huu Phuoc Nguyen [Inria, Master student, from Feb 2016 until Jun 2016]
Songyou Peng [Inria, Master student, from Jul 2016 until Aug 2016]

2. Overall Objectives

2.1. Overview

STEEP started in January 2010, initially as an Inria “Action Exploratoire” (2010+2011). It is now an “Équipe Projet Inria” of Inria Grenoble - Rhône-Alpes and is also affiliated with the Jean Kuntzmann laboratory (LJK [0]).

STEEP is an interdisciplinary research team devoted to systemic modelling and simulation of the interactions between the environmental, economic and social factors in the context of a transition to sustainability at local (sub-national) scales. Our goal is to develop decision-making tools to support decision makers in the implementation of this transition by developing simulation and optimization programs. In other words, our objective is to set up some mathematical and computational tools which enable us to provide some parts of the answer to the challenges *how to operate the sustainable development at local scales? and which local governance for environmental public policies?*.

The work of STEEP follows several research directions, covering different application domains; these are described in “Scientific Foundations” and “Application Domains” respectively.

2.2. Sustainable development: issues and research opportunities

Environmental issues now pose a threat to human civilization worldwide. They range from falling water tables to eroding soils, expanding deserts, biodiversity loss, rising temperatures, *etc*. For example, half the world’s population lives in countries where water tables are falling as aquifers are being depleted. Roughly a third of the world’s cropland is losing topsoil at an excessive rate. Glaciers are melting in all of the world’s major mountains. The consequences on the present human societies are critical; they comprise for example a decreasing food security, important population movements (such as climate refugees) and explosive geopolitical tensions.

Sustainable development is often formulated in terms of a required balance between its environmental, economic and social dimensions, but in practice public policies addressing sustainability issues are dominantly oriented towards environment management in Western countries. This approach is problematic to some extent as environmental problems and sustainability issues result from socio-economic phenomena (for example the economic growth model which is strengthened by powerful and polluting technologies). Environmental problems have only recently been the object of media attention and public awareness. Most efforts bear on developing technological solutions. However, it is now clear that this will not be sufficient. We need to rethink our socio-economic and institutional models in order to leave room for a possible paradigm shift. In this perspective, we believe that crucial steps should be taken in research to help elaborating and implementing socio-economic alternatives.

The risks associated with delayed reaction and adaptation times make the situation urgent. Delayed reactions significantly increase the probability of overshoot of the planet carrying capacity followed by uncontrolled and irreversible evolution on a number of fronts . This systemic problem is amplified by two facts: the environment is degrading on all fronts at the same time, and at the global planetary scale, a first in human history.

[0] http://ljk.imag.fr/

Although environmental challenges are monitored worldwide, the search for appropriate lines of actions must nevertheless take place at all institutional levels, in particular at local scales.At such scales, the proximity and smaller number of stakeholders allows decision makers to reach a consensus much more easily than at national or international scales. The failure of the recent Copenhagen summit (and for that matter of all climate summits since the adoption of the Kyoto protocol in 1997) is a good illustration of the difficulties encountered in international negotiations. There are significant possibilities for operations at local scales, and the emergency of the situation gives the "think locally to act globally" logic an essential opportunity.

As of now, local decision levels have real political and economic leverage, and are more and more proactive on sustainability issues, either independently or in coordination through nationwide or European networks (we can refer for example to the European GMO-free Regions Network [0] or to the Network of European Regions for a Competitive and Sustainable TouRism [0]). Also, we think that two local scales are going to be increasingly dominant in the near future: urban areas (more exactly the employment areas of main cities) and "regions" (such as régions in France, Lander in Germany or Cantons in Switzerland). In particular, the sustainability of urban areas is one of the key issues of this century. As focal points of human activity, urban areas concentrate and amplify environmental pressures in a direct or indirect way.

Urbanization is a global and an ever-increasing trend process, with more than half the human population living in cities. Although urbanized areas still represent a very small fraction of the total terrestrial surface, urban resource consumption amounts to three-fourths of the annual total in energy, water, building materials, agricultural products etc., and pollution and waste management is a growing concern for urban planners worldwide. In France, for example, even if resource intensity (materials use divided by GDP [0]) has been reduced by half since the 70s, the actual material use (total and per inhabitant) has remained essentially constant, and household wastes have grown by 20% since 1995. Greenhouse gas (GHG) emissions have been reduced by a few percent since 1990, but the transportation share (a major issue on this front) has been steadily growing over the same period.

Furthermore, urban sprawl is a ubiquitous phenomenon showing no sign of slackening yet, even in countries where rural depopulation has long been stabilized. Urban sprawl in industrialized countries is largely driven by residential suburban growth. This phenomenon has both social and environmental consequences. First it implies an increase of daily mobility. In a context of high dependency on private cars and uncertainty on energy prices, this translates into an increased vulnerability of some population categories. It also induces an increase in greenhouse gas emissions, as well as an irreversible loss of cropland and a fragmentation of ecological habitat, with negative effects on biodiversity. The increasing concerns about climate change and upheaval in the market price of fossil fuels raise many questions about urban energy consumption while reviving the debate on the desirable urban structures and their determinants. Controlling urban sprawl is therefore a key sustainability issue.

Let us mention here that cities cannot be sustainable by themselves and that from this point of view, it does not make sense to focus on the municipality scale ("*communes*"). We think that it is very important to work at larger scales, typically, at employment catchment areas complemented by the adjacent agricultural and natural zones they are dependent on (that would correspond to the smallest scale for which a systemic analysis could make sense). Nevertheless, let us emphasize that because of resource imports and waste exports (e.g. GHG emissions), for any limited territory, the considered area will always depend on and impact other more or less distant territories. This is one of the key issues when trying to assess local sustainability.

Finally, let us note that the numerous and interrelated pressures exerted by human activities on the environment make the identification of sustainable development pathways arduous in a context of complex and sometimes conflicting stakeholders and socio-ecological interactions. This is why we also think that it is crucial to develop interdisciplinary and integrated approaches; consequently, our proposal tries to address the entire spectrum from scientific expertise to stakeholder decision-help.

[0] http://www.gmo-free-regions.org
[0] http://www.necstour.eu
[0] Gross Domestic Product (GDP) is defined as an aggregate measure of production equal to the sum of the gross values added of all resident institutional units engaged in production.

STEEP, with its strong background in various areas of applied mathematics and modeling, can be a game changer in three connected key domains: urban economy, and related transportation and land use issues; material flow analysis and ecological accounting; and ecosystem services modeling. The group potential on these fronts relies on its capabilities to strongly improve existing integrated activity / land use / transportation models at the urban level on the one hand, and on the other, to build new and comprehensive decision-help tools for sustainability policies at the local and regional levels, in particular through the analysis of strategic social–environmental trade-offs between various policy options.

3. Research Program

3.1. Development of numerical systemic models (economy / society /environment) at local scales

The problem we consider is intrinsically interdisciplinary: it draws on social sciences, ecology or science of the planet. The modeling of the considered phenomena must take into account many factors of different nature which interact with varied functional relationships. These heterogeneous dynamics are *a priori* nonlinear and complex: they may have saturation mechanisms, threshold effects, and may be density dependent. The difficulties are compounded by the strong interconnections of the system (presence of important feedback loops) and multi-scale spatial interactions. Environmental and social phenomena are indeed constrained by the geometry of the area in which they occur. Climate and urbanization are typical examples. These spatial processes involve proximity relationships and neighborhoods, like for example, between two adjacent parcels of land, or between several macroscopic levels of a social organization. The multi-scale issues are due to the simultaneous consideration in the modeling of actors of different types and that operate at specific scales (spatial and temporal). For example, to properly address biodiversity issues, the scale at which we must consider the evolution of rurality is probably very different from the one at which we model the biological phenomena.

In this context, to develop flexible integrated systemic models (upgradable, modular, ...) which are efficient, realistic and easy to use (for developers, modelers and end users) is a challenge in itself. What mathematical representations and what computational tools to use? Nowadays many tools are used: for example, cellular automata (e.g. in the LEAM model), agent models (e.g. URBANSIM), system dynamics (e.g. World3), large systems of ordinary equations (e.g. equilibrium models such as TRANUS), and so on. Each of these tools has strengths and weaknesses. Is it necessary to invent other representations? What is the relevant level of modularity? How to get very modular models while keeping them very coherent and easy to calibrate? Is it preferable to use the same modeling tools for the whole system, or can we freely change the representation for each considered subsystem? How to easily and effectively manage different scales? (difficulty appearing in particular during the calibration process). How to get models which automatically adapt to the granularity of the data and which are always numerically stable? (this has also a direct link with the calibration processes and the propagation of uncertainties). How to develop models that can be calibrated with reasonable efforts, consistent with the (human and material) resources of the agencies and consulting firms that use them?

Before describing our research axes, we provide a brief overview of the types of models that we are or will be working with. As for LUTI (Land Use and Transportation Integrated) modeling, we have been using the TRANUS model since the start of our group. It is the most widely used LUTI model, has been developed since 1982 by the company Modelistica, and is distributed *via* Open Source software. TRANUS proceeds by solving a system of deterministic nonlinear equations and inequalities containing a number of economic parameters (e.g. demand elasticity parameters, location dispersion parameters, etc.). The solution of such a system represents an economic equilibrium between supply and demand. A second LUTI model that will be considered in the near future, within the CITiES project, is UrbanSim [0]. Whereas TRANUS aggregates over e.g. entire population or housing categories, UrbanSim takes a micro-simulation approach, modeling and simulating choices made at the level of individual households, businesses, and jobs, for instance, and it operates on a finer geographic scale than TRANUS.

[0] http://www.urbansim.org

On the other hand, the scientific domains related to ecosystem services and ecological accounting are much less mature than the one of urban economy from a modelling point of view (as a consequence of our more limited knowledge of the relevant complex processes and/or more limited available data). Nowadays, the community working on ecological accounting develops statistical models based on the enforcement of the mass conservation constraint for accounting for material fluxes through a territorial unit or a supply chain, relying on more or less simple data correlations when the relevant data is missing; the overall modelling makes heavy use of more or less sophisticated linear algebra and constrained optimization techniques. The ecosystem service community has been using statical models too, but is also developing more sophisticated models based for example on system dynamics, multi-agent type simulations or cellular models. In the ESNET project, STEEP will work in particular on a land use/ land cover change (LUCC) modelling environments (Dinamica [0]) which belongs to the category of spatially explicit statistical models.

In the following, our two main research axes are described, from the point of view of applied mathematical development. The domains of application of this research effort is described in the application section, where some details about the context of each field is given.

3.2. Model calibration and validation

The overall calibration of the parameters that drive the equations implemented in the above models is a vital step. Theoretically, as the implemented equations describe e.g. socio-economic phenomena, some of these parameters should in principle be accurately estimated from past data using econometrics and statistical methods like regressions or maximum likelihood estimates, e.g. for the parameters of logit models describing the residential choices of households. However, this theoretical consideration is often not efficient in practice for at least two main reasons. First, the above models consist of several interacting modules. Currently, these modules are typically calibrated independently; this is clearly sub-optimal as results will differ from those obtained after a global calibration of the interaction system, which is the actual final objective of a calibration procedure. Second, the lack of data is an inherent problem.

As a consequence, models are usually calibrated by hand. The calibration can typically take up to 6 months for a medium size LUTI model (about 100 geographic zones, about 10 sectors including economic sectors, population and employment categories). This clearly emphasizes the need to further investigate and at least semi-automate the calibration process. Yet, in all domains STEEP considers, very few studies have addressed this central issue, not to mention calibration under uncertainty which has largely been ignored (with the exception of a few uncertainty propagation analyses reported in the literature).

Besides uncertainty analysis, another main aspect of calibration is numerical optimization. The general state-of-the-art on optimization procedures is extremely large and mature, covering many different types of optimization problems, in terms of size (number of parameters and data) and type of cost function(s) and constraints. Depending on the characteristics of the considered models in terms of dimension, data availability and quality, deterministic or stochastic methods will be implemented. For the former, due to the presence of non-differentiability, it is likely, depending on their severity, that derivative free control methods will have to be preferred. For the latter, particle-based filtering techniques and/or metamodel-based optimization techniques (also called response surfaces or surrogate models) are good candidates.

These methods will be validated, by performing a series of tests to verify that the optimization algorithms are efficient in the sense that 1) they converge after an acceptable computing time, 2) they are robust and 3) that the algorithms do what they are actually meant to. For the latter, the procedure for this algorithmic validation phase will be to measure the quality of the results obtained after the calibration, i.e. we have to analyze if the calibrated model fits sufficiently well the data according to predetermined criteria.

To summarize, the overall goal of this research axis is to address two major issues related to calibration and validation of models: (a) defining a calibration methodology and developing relevant and efficient algorithms to facilitate the parameter estimation of considered models; (b) defining a validation methodology and developing the related algorithms (this is complemented by sensitivity analysis, see the following section).

[0] http://www.csr.ufmg.br/dinamica/

In both cases, analyzing the uncertainty that may arise either from the data or the underlying equations, and quantifying how these uncertainties propagate in the model, are of major importance. We will work on all those issues for the models of all the applied domains covered by STEEP.

3.3. Sensitivity analysis

A sensitivity analysis (SA) consists, in a nutshell, in studying how the uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model inputs. It is complementary to an uncertainty analysis, which focuses on quantifying uncertainty in model output. SA's can be useful for several purposes, such as guiding model development and identifying the most influential model parameters and critical data items. Identifying influential model parameters may help in divising metamodels (or, surrogate models) that approximate an original model and may be simulated, calibrated, or analyzed more efficiently. As for detecting critical data items, this may indicate for which type of data more effort must be spent in the data collection process in order to eventually improve the model's reliability. Finally, SA can be used as one means for validating models, together with validation based on historical data (or, put simply, using training and test data) and validation of model parameters and outputs by experts in the respective application area. All these uses of SA will be considered in our research.

The first two applications of SA are linked to model calibration, discussed in the previous section. Indeed, prior to the development of the calibration tools, one important step is to select the significant or sensitive parameters and to evaluate the robustness of the calibration results with respect to data noise (stability studies). This may be performed through a global sensitivity analysis, e.g. by computation of Sobol's indices. Many problems will have to be circumvented e.g. difficulties arising from dependencies of input variables, variables that obey a spatial organization, or switch inputs. We will take up on current work in the statistics community on SA for these difficult cases.

As for the third application of SA, model validation, a preliminary task bears on the propagation of uncertainties. Identifying the sources of uncertainties and their nature is crucial to propagate them via Monte Carlo techniques. To make a Monte Carlo approach computationally feasible, it is necessary to develop specific metamodels. Both the identification of the uncertainties and their propagation require a detailed knowledge of the data collection process; these are mandatory steps before a validation procedure based on SA can be implemented. First, we will focus on validating LUTI models, starting with the CITiES ANR project: here, an SA consists in defining various land use policies and transportation scenarios and in using these scenarios to test the integrated land use and transportation model. Current approaches for validation by SA consider several scenarios and propose various indicators to measure the simulated changes. We will work towards using sensitivity indices based on functional analysis of variance, which will allow us to compare the influence of various inputs on the indicators. For example it will allow the comparison of the influences of transportation and land use policies on several indicators.

4. Application Domains

4.1. Introduction

In the context described in the previous sections, we can distinguish two connected and complementary strategies for analyzing environmental pressures: a sectorial approach and a spatial one. The first one is more directly connected to ecological accounting, the second one has more direct relations to urban economy and land cover modelling. Let us start by describing the former.

4.2. Ecological accounting for sectorial pressure assessment

One of the major issues in the assessment of the long-term sustainability of urban areas is related to the concept of "imported sustainability". Cities bring in from the outside most of their material and energy resources, and reject to the outside the waste produced by their activity. The modern era has seen a dramatic increase in both volume and variety of these material flows and consumption as well as in distance of origin and destination of these flows, usually accompanied by a spectacular increase in the associated environmental impacts. A realistic assessment of the sustainability of urban areas requires to quantify both local and distant environmental impacts; greenhouse gas emissions are only one aspect of this question. Such an assessment brings to light the most relevant direct and indirect lines of action on these issues. In this respect, it is useful to introduce the alternative concepts of consumer versus producer responsibility (or point of view).

The producer point of view is the most useful to pinpoint relevant direct lines of actions on environmental pressures due to production. In other respects, any territory imports and exports goods and services from and to the rest of the world. The consumer point of view provides information on the indirect pressures associated with these exchanges, as production responds to a final demand. Tracking the various supply chains through the analysis of the structure of the local economy and its relations and dependencies to the external world allows us to identify critically important contributions to environmental pressures; this also enables us to define fair environmental indicators in order not to attribute environmental pressures to producers only (whose responsibility is the easier to quantify of the two). In this approach, the producer responsibility follows directly from the measurement of its energy and material uses, while the consumer responsibility is established indirectly through an allocation of the impacts of production to the final consumers, but this second mode of allocation is to some extent virtual and partly subjective. Four methods stand out:

- Material Flow Analysis (MFA)
- Input-Output Analysis (IOA)
- Life-Cycle Analysis (LCA)
- Ecological Footprint (EF)

Each of these is based on a well-defined structuring element: mass conservation for MFA, measure of industrial inter-dependencies for IOA, identification of all the steps from cradle to grave for LCA, measure of biocapacity demand for EF. The different methods have preferred areas of application. For example, EF is more relevant for analyzing primary production such as agricultural staples, wood, etc. IOA is more focused on whole industrial sectors, while LCA is geared towards end-user products, taken as functional units; finally, primary materials (such as metals), waste and emissions are more easily characterized through MFA. Methodological choices are driven by the type of question one needs to address, data availability and collection method and the spatial scales under consideration. Indeed, data can be used in two different ways: bottom-up or top-down. The bottom-up data is more precise, but in general precludes comprehensiveness; on the contrary, the top-down data is by nature more comprehensive, but is not suited for a detailed, fine-scale analysis of the results.

STEEP is pursuing its research program on this theme with three major goals: 1) Creating a comprehensive database enabling pressure analyses; 2) Developing methodologies and models resolving scaling issues, and developing algorithms allowing us to rigorously and automatically obtain adequate assessments; 3) Providing a synthetic analysis of environmental pressures associated to the major material flows, at various geographic levels (employment catchment area, *département* and *région*, for France), with the explicit aim of incorporating this type of information in the public decision process on environmental issues, via specifically designed decision-help procedures.

4.3. Urban economy and land use/land cover changes: assessment of spatial distributions of the pressures

The preceding section was focused on territorial metabolism, in particular on the analysis of supply chains. Here territories are examined with a more prominent emphasis on their spatial dimension, with attention to: the spatial distribution of local pressures previously identified (from a land use point of view), and the modeling of future land use and activity location (from an economic point of view). These two questions correspond to very different modeling strategies: the first one is more statistical in nature, extrapolating future land use from past evolution combined with global territory scenarios; the other one has a more fundamental flavor and focuses on an understanding of the processes driving urbanization. For this, we focus more precisely on the question of household and businesses choices of localization, as well as on spatial fluxes within the territory (transportation of goods and persons). The critical point here is to understand and manage urban sprawl and its environmental effects (GHG emission, loss of arable land, ecosystem fragmentation, and so on).

4.3.1. Land Use/Land Cover Change models (LUCC)

LUCC models are mostly used in environmental sciences, e.g. to evaluate the impact of climate change on agriculture, but they can also be used to analyze urban sprawl. There is a variety of models, static or dynamic, grid- or agent- based, local or global, etc., and with varying degrees of sophistication concerning spatio-temporal analysis or decision structures incorporated in the model.

The models of interest here are statistical in nature but spatially explicit. Following decades of development, they are robust, versatile and mature. In principle, agent-models have a larger potential for representing decision processes, but in practice this advantage results in a loss of universality of the models. Among the most well-known and most mature models, one can mention the CLUE family of models, DINAMIC, or LCM (Land Change Modeler. These models are well described in the literature, and will only be briefly presented here.

These models analyze change in land use in a statistical way; they are structured around three different modules:

- The first module determines the probability of change of pixels of the territory (pixels are typically tens to hundreds of meters in size).
- The second module defines the global changes between the various land uses of interest per time step (usually, a few years), based on global scenarios of evolution of the territory under study. These first two modules are independent of one another.
- The last module distributes changes of land use in an explicit manner, pixel per pixel, at each time step, on the basis of the information provided by the first two modules.

Probabilities of change are calibrated on past evolution, from the differences between two past maps of land use in the more favorable cases, or from a single map otherwise (under the assumption that the logic of occupation changes is the same as the logic of land use at this single date). Such changes are then characterized in a statistical way with the help of modeling variables identified by the modeler as having potential explaining or structuring power (typically, a few to a dozen variables are used for one type of land use change). For example, in the case of urban sprawl, typical explaining factors are the distance to existing urbanized zones or distances to roads and other means of transportation, elements of real estate costs, etc. Global scenarios are quantified in terms of global changes in land use over the whole studied area (e.g., how many hectares are transformed from agricultural to urban uses in a given number of years, how does this evolve over time...); this is done either from academic expert knowledge, or from information provided by local planning agencies. Whenever feasible, models are validated by comparing the model predictions with actual evolution at a later date. Therefore, such models need from one to three land use maps at different dates for calibration and validation purposes (the larger the number of maps, the more robust and accurate the model). A large array of statistical tools is available in the literature to perform the calibration and validation of the model.

The horizon of projections of such models is limited in time, typically 20-30 years, due to the inherent uncertainty in such models, although they are occasionally used on longer time-scales. Climate change constraints are included, when needed, through scenarios, as it is not in the scope of such models to incorporate ecological processes that may translate climate change constraints into land cover change dynamics. Note that on such short time-scales, climate change is not dominated by the mean climate evolution but by decade variations which average out on longer time-scales and are not modeled in the global climate models used e.g. for IPCC projections for the end of the century; as a consequence, the various IPCC climate scenarios cannot be distinguished on such a short time horizon.

With regard to LUCC, the STEEP team has been involved for four years in the ESNET project whose funding came to a close in July of 2016, but the scientific production of the project is still underway. This project bears on the characterization of local Ecosystem Services networks; the project has been coordinated by LECA (*Laboratoire d'Ecologie Alpine*), in collaboration with a number of other research laboratories (most notably, IRSTEA Grenoble, besides our team), and in close interaction with a panel of local stakeholders; the scale of interest is typically a landscape (in the ecologic/geographic sense, i.e., a zone a few kilometers to a few tens of kilometers wide). The project aims at developing a generic modelling framework of ecosystem services, and studying their behavior under various scenarios of coupled urban/environment evolution, at the 2030/2040 horizon, under constraints of climate change. The contribution of the STEEP team is centered on the Land Use/Land Cover Change (LUCC) model that will be one of the major building blocks of the whole project modelling effort, with the help of an ESNET funded post-doctoral researcher. In the process, areas of conceptual and methodological improvements of statistical LUCC models have been identified; implementing these improvements will be useful for the LUCC community at large, independently of the ESNET project needs.

4.3.2. Models for Land-Use and Transportation Interactions (LUTI)

Urban transport systems are intricately linked to urban structure and activities, i.e., to land use. Urbanization generally implies an increased travel demand. Cities have traditionally met this additional demand by extending transportation supply, through new highways and transit lines. In turn, an improvement of the accessibility of ever-farther land leads to an expansion of urban development, resulting in a significant feedback loop between transportation infrastructure and land use, one of the main causes of urban sprawl. Transportation models allow us to address questions generally limited to the impacts of new infrastructures, tolls and other legislation on traffic regulation [0], on user behavior [0], or on the environment [0]. LUTI models (Land-Use and Transport Integrated models) can answer a much broader spectrum of issues. For example, they allow us to understand how the localization of households and of economic activities (which generate transportation demand) adapt to changes of transportation supply. They also allow us to assess the impacts of such changes on the increase in real estate value, or more generally on their effects on the economic development of a specific sector or neighborhood. An economic vision interprets all these interactions in terms of equilibrium between demand and supply. Modelling the localization of households and employments (companies) relies on capturing the way stakeholders arbitrate between accessibility, real estate prices, and attractiveness of different areas.

State of the art and operability of LUTI models. The first model that proved able to analyze the interactions between transport and urbanization was developed by Lowry. Since then theories and models have become increasingly complex over time. They can be classified according to different criteria. A first classification retraces the historic path of these theories and models. They can be associated with one or several of the approaches underlying all present theories: economic base theory and gravity models, Input/Output models and theory of urban rent, and micro-simulations. A second possibility consists in classifying the models according to their aims and means.

Significant scientific progress has been made over the last thirty years. Nevertheless, modelling tools remain largely restricted to the academic world. Today, only seven models have at least had one recent application outside academia or are commercialized or potentially marketable, in spite of the important needs expressed by the urban planning agencies: Cube Land, DELTA, MARS, OPUS/UrbanSim, PECAS, TRANUS and Pirandello.

To guide their choice of a modelling framework, users can rely on various criteria such as the strength of the theoretical framework, the quality and the diversity of the available documentation, the accessibility of the models (is the model freely available? is the code open source? is the software regularly updated and compatible with the recent operating systems?), the functionality and friendliness of user interfaces (existence of graphic user interface, possibility of interfacing with Geographic Information Systems), existence of technical assistance, volume and availability of the data required to implement the model, etc. For example, among the seven models mentioned above, only two are open source and mature enough to meet professional

[0]Congestion, cost and time spent for the transport, etc.
[0]Changes in modality choice.
[0]CO2 emissions, air pollution, noise nuisance, etc.

standards: TRANUS and UrbanSim [0]. These two models are very different but particularly representative of the main current philosophies and trends in this scientific domain. Their comparison is informative.

STEEP implication in LUTI modelling. As yet, very few local planning authorities make use of these strategic models, mostly because they are difficult to calibrate and validate. Systematic improvement on these two critical steps would clearly increase the level of confidence in their results; these limitations hinder their dissemination in local agencies. One of the major goals of STEEP is therefore to meet the need for better calibration and validation strategies and algorithms. This research agenda lies at the core of our project CITiES (*ANR Modèles Numériques*). As for LUTI modeling, we have been using the TRANUS model since the creation of our team. We have also been working on UrbanSim from the beginning of the CITiES project. In this framework we work in close collaboration with AURG [0], the local urban planning agency of Grenoble (*Agence d'Urbanisme de la Région Grenobloise*) in order to better understand and to improve the relevance of these tools for such territorial agencies.

5. Highlights of the Year

5.1. Highlights of the Year

This year represents an important landmark in the life of the team, who witnessed the first PhD defense since it has been formed.

The thesis of Jean-Yves Courtonne beared on ecological accounting, with the inception and implementation of a new downscaling method allowing us to track material flow through supply chains at various nested geographical scales; the method also provides an assessment of the associated environmental pressures and an analysis of the errors of the process. This thesis has been recognized by the two referees as a major step forward in France in this field. Four articles have come out of this work; they are published or considered for publication in the leading journals in the field.

A second PhD defense took place this year, by Laurent Gilquin who did most of his PhD studies in STEEP before he followed his supervisor (E. Arnaud) to the AIRSEA project-team.

6. New Software and Platforms

6.1. Comptabilité Ecologique

FUNCTIONAL DESCRIPTION

Databases, database handling tools and data visualization tools (on the website). Databases include socio-economic and environmental datasets. Visualization tools include interactive piecharts, maps and Sankey diagrams.

- Participants: Jean-Yves Courtonne and Pierre-Yves Longaretti
- Contact: Jean-Yves Courtonne
- URL: http://www.eco-data.fr

6.2. InterfacesTRANUS

FUNCTIONAL DESCRIPTION

[0] http://www.urbansim.org
[0] http://www.aurg.org/

This software contains two interfaces dedicated to facilitating the usage of the TRANUS integrated land use and transport model+software. The first interface is dedicated to enabling the execution of the TRANUS binary programs without the need to use the console or the TRANUS GUI. The second interface provides an aid for calibrating a TRANUS model, by interactively exploring ranges of different parameters of a TRANUS model and visualising model outputs across these ranges.

- Participants: Peter Sturm, Julien Armand and Thomas Capelle
- Contact: Peter Sturm
- URL: http://gitlab.inria.fr/tranus/TRANUS_Interfaces

6.3. LUM_OSM

Land Use Mix calculation from OpenStreepMap data

FUNCTIONAL DESCRIPTION

The software uses Mapzen Metro Extracts to retrieve the OpenStreetMap data of a given region in the PostgreSQL format. Afterwards, a continuous representation of residential and activity land uses is created. Finally, a GIS output containing the degree of land use mixture is calculated by means of using the land uses maps. The implemented approach is documented in [9].

- Participants: Martís Bosch Padros, Luciano Gervasoni, Serge Fenet and Peter Sturm
- Partners: EPFL - Ecole Polytechnique Fédérale de Lausanne - LIRIS
- Contact: Peter Sturm
- URL: http://github.com/martibosch/landusemix

6.4. QGIS_Tranus_Reports

FUNCTIONAL DESCRIPTION

This software allows to graphically visualise data output by the TRANUS LUTI model (and possibly, of any other data of the same structure). In particular, this concerns any data items defined per zone of a modelled territory (productions, indicators, etc.). The software is designed as a plugin for the geographical information system platform QGIS and can be run interactively as well as by the command line or by a call from within another software. The interactive mode (within QGIS) allows the user to define graphical outputs to be generated from TRANUS output files (type of graphs to be generated – 2D or 3D – color coding to be used, choice of data to be displayed, etc.). Visualisation of data is done in the form of 2D graphs or 3D models defined using java-script.

- Participants: Patricio Inzaghi, Peter Sturm, Huu Phuoc Nguyen, Fausto Lo Feudo and Thomas Capelle
- Contact: Peter Sturm
- URL: https://gitlab.inria.fr/tranus/QGIS_Tranus_Reports

6.5. REDEM

REDuction Of EMission

FUNCTIONAL DESCRIPTION

REDEM soft is a tool designed for the benchmarking of national GHG emission reduction trajectories. The actual version of the software is implemented in Visual Basic under Microsoft Excel in order to facilitate handling and diffusion to climate/energy economists.

- Participants: Emmanuel Prados, Patrick Criqui, Constantin Ilasca, Olivier Boucher and Hélène Benveniste
- Partners: EDDEN - IPSL
- Contact: Emmanuel Prados
- URL: http://redem.gforge.inria.fr/

6.6. REDEM web

REDEM Web is a reimplementation of the REDEM soft as a web application. The main library which contains the code corresponding to REDEM model is written in Python and the web part uses Javascript.
KEYWORDS: Benchmarking - Climate change - Global warming - Greenhouse gas emissions

- Participants: Emmanuel Prados, Patrick Criqui, Constantin Ilasca, Olivier Boucher, Hélène Benveniste and Nicolas Assouad
- Partners: EDDEN - UPMC
- Contact: Emmanuel Prados
- URL: http://redem.inria.fr/

6.7. Wassily

SCIENTIFIC DESCRIPTION

The software is structured in three different modules:

- the database module stores all the input-output data coming from Eurostat, OCDE, Insee or other sources.
- the computation module performs the input-output calculations
- the visualization module displays the results in a synthetic manner.

The database module is based on the SQlite format and makes use of SQL to manipulate the various tables involved in the process. The goal of this module is to provide a normalized data interface for the computation module, from various types of input-output data which are often stored as Excel sheet on web sites.
FUNCTIONAL DESCRIPTION

The purpose of this software ans website is to automatize most of the work of standard input-output analysis and to visualize the resultes in a user-friendly way in order to efficently adress related key environmental questions.

- Participants: Julien Alapetite and Jean-Yves Courtonne
- Contact: Jean-Yves Courtonne

7. New Results

7.1. Ecological accounting

Besides the publication of the article [2] on environmental pressures in supply chains in the leading journal in the field (*Journal of Industrial Ecology*), the most important result obtained on this front this year bears on the quantification of the errors associated with the national road freight transport database (SITRAM). This database is informed year by year through a dedicated sampling campaign, but the errors associated with the various types of material goods transported have never been quantified. This was achieved by our team through the use of appropriate error estimators. This result is eagerly awaited by a number of scientific teeams and public territorial agencies. Furthermore, the methodology that we have developed can easily be transposed to other countries. This result constitutes an important piece in the overall effort that the team has devoted to the question of the quantification of uncertainties in material flow analyses.

7.2. Modeling of human-mediated dispersal via road network in invasive spreads

In the case of ecosystem invasions, human-mediated dispersal often acts as a vector for many exotic species, both at the introduction and secondary spread stages. The introduction stage is mainly a consequence of human-mediated long distance dispersal and is known to happen at continental or global scales. Secondary spread, however occurs at smaller spatial and time scales (e.g. landscape), and can result from natural or human-mediated dispersal. Despite the importance of local goods and materials transportation (e.g. for landscaping, construction, or road-building) potentially promoting the spreading of invasive species, few studies have investigated short distance human-mediated dispersal. This lack of consideration seems to be the consequence of multiple factors:

- human-mediated dispersal is generally considered as a long distance dispersal process, more important for invasive species introduction than for secondary spread;
- it is difficult to qualify and quantify this mode of dispersal because of the multiplicity of potentially involved human activities;
- for organisms that can disperse naturally, it is complicated to distinguish between natural and human-mediated dispersal, as they may occur at similar scales.

Even though a range of methodologies are available for describing population spread by natural dispersal, only few models have been developed to describe and predict human-mediated dispersal consequences at small scales, and none of them take into account the topology of the transport infrastructure (roads, waterways). In this result, and in order to fill this gap and provide new insights into how invasion dynamics impact ecosystem services, we combined ecological (invasive species occurrence data) and geographical (transportationnetwork topology) data in a computer model to provide estimated frequencies and distances of materials transportations through the landscape. In this study (cf. [7]), we investigated the spreading pattern of Lasius neglectus, an invasive ant species originating from Turkey, which spread into Europe in the last decades. In this species, no mating or dispersal flights are performed, and its spread is therefore solely ensured by the transport of soil materials in which individuals are present. We built a numerical model enabling the estimation of multiple human-mediated dispersal parameters based on ground-truth sampling and a priori minimizing. After having built a model of the landscape-level spreading process that takes explicitly into account the topology of the road network, we localized the most probable sites of introduction, the number of jump events, as well as parameters of jump distances linked to the road network. Our model was also able to compute presence probability map, and can be used to calibrate sampling campaigns, explore invasion scenarios, and more generally perform invasion spread predictions. It could be applied to all the species that can be disseminated at local to regional scales by human activities through transportation networks.

7.3. A computer framework for measuring urban land-use mix

The number of people living in cities has been increasing considerably since 1950, from 746 million to 3.9 billion in 2014, and more than 66% of the world's population are projected to live in urban areas by 2050. As this continuing population growth and urbanization are projected to add 2.5 billion people to the world's urban population in 30 years, this situation brings new challenges on how to conceive cities that host such amounts of population in a sustainable way. This sustainability question should address several aspects, ranging from economical to social and environmental matters among others. In this work, we focus on the formalization of a measure of mixed use development or land use mix in a city, i.e. how the structure of the city can help to provide a car-free sustainable living. Such type of land use mix has been largely proven to contain beneficial outcomes in terms of sustainability and to positively contribute to societal outcome, health, and public transportation among others. We developped a framework to compute mixed uses development index. A main caracteristic of our approach is to use only crowd-sourcing data (from OpenStreetMap) to extract the geo-localized land uses. Due to the universality of this data source, we are able to process any geographical area in the world, as long as sufficient data are available in OSM. A Kernel Density Estimation is performed for each of the land uses, outputing the spatial distribution of the different land uses. Based on this representation, a measure of land use mix is then calculated using the Entropy Index. The resulting GIS output shows enriched information for urban planners, supporting and aiding the decision-making procedure.

The framework, still in the phase of validation, was applied on the cities of London and Grenoble [9]. Future work includes integrating the LUM output for measuring the urban sprawl phenomenon and performing numerical interpretations of desirable mixed use values. We will also study the potential integration to transportation models, where land use mix correlation with the activities and residential uses can help to improve demand estimation. In addition, further investigation can be done by means of analyzing in detail the different types of activities. Finally, the estimation of LUM can be refined by taking into account, besides their location, the accessibility between different land uses, which is partly conditioned by the transportation infrastructure.

7.4. Calibration and sensitivity analysis for LUTI models

This year, we have consolidated our previous works on calibration of LUTI models, in particular of the Tranus model [6]. The developed approaches are currently applied to instantiate a complete Tranus model for the Grenoble catchment area, in collaboration with AURG (Urban Planning Agency of the Grenoble area) and Brian Morton (U North Carolina).

We have also collaborated with the AIRSEA project-team towards applying novel sensitivity analysis tools to study the influence of the different parameter sets of a Tranus model [13]. The rationale is to then apply optimization methods to the most influential parameters. As a result, we were able to calibrate a real-life Tranus model such that results were of higher quality than with the baseline ad hoc approach, while reducing calibration time significantly.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

The PhD thesis of Jean-Yves Courtonne has been co-sponsored by ARTELIA and Inria, via a bilateral contract.

9. Partnerships and Cooperations

9.1. Regional Initiatives

The design of our LUTI model of Grenoble based on TRANUS platform takes place in the framework of a tight collaboration with the AURG, the Urban Planning Agency of the Grenoble area.

9.2. National Initiatives

9.2.1. ANR

CITiES (*Calibrage et valIdation de modèles Transport - usagE des Sols*)

Program: "*Modèles Numériques*" 2012, ANR
Duration: 2013 – 2016
Coordinator: Emmanuel Prados (STEEP)
Other partners: LET, IDDRI, IRTES-SET ("Systemes and Transports" lab of Univ. of Tech. of Belfort-Montbéliard), IFSTTAR-DEST Paris (formerly INRETS), LVMT ("*Laboratoire Ville Mobilité Transport*", Marne la Vallée), VINCI (Pirandello Ingenierie, Paris), IAU Île-De-France (Urban Agency of Paris), AURG (Urban Agency of Grenoble), MOISE (Inria project-team)
Abstract: Calibration and validation of transport and land use models.

9.2.2. FRB (Fondation pour la Recherche sur la Biodiversité)

ESNET (Futures of ecosystem services networks for the Grenoble region)
Program: “Modeling and Scenarios of Biodiversity" flagship program, Fondation pour la Recherche sur la Biodiversité (FRB). This project is funded by ONEMA (*Office National de l’Eau et des Milieux Aquatiques*).
Duration: 2013 – 2016
Coordinator: Sandra Lavorel (LECA)
Other partners: EDDEN (UPMF/CNRS), IRSTEA Grenoble (formerly CEMAGREF), PACTE (UJF/CNRS), ERIC (Lyon 2/CNRS)
Abstract: This project explores alternative futures of ecosystem services under combined scenarios of land-use and climate change for the Grenoble urban area in the French Alps. In this project, STEEP works in particular on the modeling of the land use and land cover changes, and to a smaller extent on the interaction of these changes with some specific services.

9.3. International Research Visitors

9.3.1. Visits of International Scientists

9.3.1.1. Internships

- Songyou Peng (summer internship, MSc student in the ViBOT Erasmus Mundus program).

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Selection

10.1.1.1. Member of the Conference Program Committees

- Association for the Advancement of Artificial Intelligence (AAAI) 2016 Computational Sustainability and AI (S. Fenet)
- International Conference on Principles and Practices of Constraint Programming (CP) 2016 Computational Sustainability track (S. Fenet)
- CompSust@CP-2016 (the 22nd International Conference on Principles and Practice of Constraint Programming), Toulouse, France, September 2016 (E. Prados)
- Journées Scientifiques Inria – Inria Science Days (P. Sturm)
- German Conference on Pattern Recognition (P. Sturm)

10.1.1.2. Reviewer

- EVOSTAR 2016 (S. Fenet)

10.1.2. Invited Talks

- E. Prados has been invited by the Wimmics team to give a seminar at Inria Sophia-Antipolis (Conference title : “Comment réduire l’impact d’un éventuel effondrement ? Comment construire le monde d’après ?”, Sophia-Antipolis, France, 10th of November, 2016).
- E. Prados gave a seminar at the Conseil Scientifique de l’AURG (Conference title : “Modèle TRANUS d’usage des sols et transport pour l’agglomération grenobloise”, Grenoble, France, 6th of July, 2016).
- P. Sturm gave an invited seminar at the Czech Technical University (Prague, Czech Republic), on former work in computer vision.

10.1.3. Scientific Expertise

- P. Sturm: Expert for the European Eureka/Eurostars program and for the regional ARC6 program.

10.1.4. Research Administration

- P. Sturm is Deputy Scientific Director of Inria, in charge of domain "Perception, Cognition and Interaction".
- E. Prados and P. Sturm organized the Inria – FING partnership. The FING (Fondation Internet Nouvelle Génération) is a think tank working on socio-economic changes inspired by technology and its uses. In 2016, they organized two workshops in the framework of the project "Transition^2" [http://www.transitions2.net/], see https://team.inria.fr/steep/fing/

10.2. Teaching - Supervision - Juries

10.2.1. Supervision

PhD: Jean-Yves Courtonne, Evaluation environnementale de territoires à travers l'analyse de filières - La comptabilité biophysique pour l'aide à la décision délibérative, Grenoble University, 28/06/2016, D. Dupré and P.Y. Longaretti

PhD: Laurent Gilquin, Echantillonnages Monte Carlo et quasi-Monte Carlo pour l'estimation des indices de Sobol'. Application à un modèle transport-urbanisme, Grenoble University, 17/10/2016, Elise Arnaud and C. Prieur

PhD in progress: Michela Bevione, Sustainability and territorial energy transition: coupling supply chains with LCA, 11/2016, N. Buclet and P.Y. Longaretti

PhD in progress: Thomas Capelle, Development of optimisation methods for land-use and transportation models, 10/2013, P. Sturm and A. Vidard

PhD in progress: Luciano Gervasoni, Modeling the dynamics of urban sprawl, 10/2015, S. Fenet and P. Sturm

PhD in progress: Julien Salotti, Spatio-temporal analysis of traffic data for smart mobility, 11/2014, S. Fenet, C. Solnon and N.-E. El Faouzi

PhD in progress: Lucas Foulon, Detection of anomalies in real-time ground–on board flows of the SNCF, 12/2016, S. Fenet, C. Rigotti and D. Jouvin

10.2.2. Juries

- P. Sturm was reviewer of the PhD thesis of Liming Yang, Ecole Centrale de Nantes.
- P. Sturm was reviewer of the PhD thesis of Jan Heller, Czech Technical University, Prague.

10.3. Popularization

STEEP team has organized a series of conferences entitled "Understanding and Acting" (six conferences in 2016). The conferences has been filmed, edited and posted on the video-sharing website, YouTube. A total of more than 500 people have attended to the conferences. The conferences received more than 2000 YouTube views (December 2016).
https://www.youtube.com/channel/UCJbcXCcOA63M8VMysAbmt_A
https://team.inria.fr/steep/les-conferences-debats-comprendre-et-agir/

Emmanuel Prados gave a "conférence-débat" at "Marie Reynoard" High school on "Sustainable development, territorial governance and democracy" (Villard-Bonnot, France, 16th of December, 2016).

Emmanuel Prados gave a conference at the "Café In" of Inria Sophia-Antipolis entitled "Comprendre les phénomènes d'effondrement de sociétés. Quel avenir pour la nôtre ?" (Sophia-Antipolis, France, 10th of November, 2016).

Emmanuel Prados has organized a workshop in collaboration with the EP SCOT Grenoble on the land-use and transport modelling and on its potential application to the follow up of the Grenoble' SCOT project (Grenoble, France, 14th of October, 2016). Representatives of all the main political and administrative authorities of Grenoble area attended to this workshop (Région Rhône-Alpes, Département of Isère, Grenoble-Alpes Métropole, AURG, municipalities communities of Grenoble employment catchment areas).

11. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journal

[1] M. Colloff, B. Martin-Lopez, S. C. Lavorel, B. D. Locatelli, R. Gorddard, P.-Y. Longaretti, G. Walters, L. C. Van Kerkhoff, W. Carina, A. C. Coreau, R. M. Wise, M. D. Dunlop, P. D. Degeorges, I. C. Overton, R. D. Williams, M. D. Doherty, T. T. Capon, S. Todd, H. T. Murphy.*An integrative research framework for enabling transformative adaptation*, in "Environmental Science & Policy", 2016 [*DOI :* 10.1016/j.envsci.2016.11.007], https://hal.archives-ouvertes.fr/hal-01415943.

[2] J.-Y. Courtonne, P.-Y. Longaretti, J. Alapetite, D. Dupré.*Environmental Pressures Embodied in the French Cereals Supply Chain*, in "Journal of Industrial Ecology", 2016, vol. 20, p. 423 - 434 [*DOI :* 10.1111/jiec.12431], https://hal.archives-ouvertes.fr/hal-01415792.

[3] S. Ramalingam, P. Sturm.*A Unifying Model for Camera Calibration*, in "IEEE Transactions on Pattern Analysis and Machine Intelligence", July 2016 [*DOI :* 10.1109/TPAMI.2016.2592904], https://hal.inria.fr/hal-01396809.

[4] M. Saujot, M. de Lapparent, E. Arnaud, E. Prados.*Making Land Use - Transport models operational tools for planning: from a top-down to an end-user approach*, in "Transport Policy", July 2016, vol. 49, p. 20 - 29 [*DOI :* 10.1016/j.tranpol.2016.03.005], https://hal.inria.fr/hal-01402863.

[5] C. Vannier, J. Lefebvre, P.-Y. Longaretti, S. Lavorel.*Patterns of landscape change in a rapidly urbanizing mountain region*, in "Cybergeo : Revue européenne de géographie / European journal of geography", 2016 [*DOI :* 10.4000/cybergeo.27800], https://hal.archives-ouvertes.fr/hal-01415887.

International Conferences with Proceedings

[6] T. Capelle, P. Sturm, A. Vidard, B. Morton.*Optimisation-Based Calibration and Model Selection for the Tranus Land Use Module*, in "14th World Conference on Transport Research", Shanghai, China, Transportation Research Procedia, Elsevier, July 2016, https://hal.inria.fr/hal-01396793.

[7] J. Gippet, S. Fenet, A. Dumet, B. Kaufmann, C. Rocabert.*MoRIS: Model of Routes of Invasive Spread. Human-mediated dispersal, road network and invasion parameters*, in "5th International Conference on Ecology and Transportation: Integrating Transport Infrastructures with Living Landscapes", Lyon, France, Proceedings of the IENE 2016 conference, August 2016, https://hal.inria.fr/hal-01412280.

Conferences without Proceedings

[8] D. DUPRÉ.*Un concept nouveau de monnaie par une approche philosophique praxéologique*, in "6ème congrès de l'Association Françoise d'Economie Politique (AFEP) « La frontière en économie»", Mulhouse , France, AFEP, July 2016, https://hal.archives-ouvertes.fr/hal-01326630.

[9] L. GERVASONI, M. BOSCH, S. FENET, P. STURM.*A framework for evaluating urban land use mix from crowd-sourcing data*, in "2nd International Workshop on Big Data for Sustainable Development", Washington DC, United States, December 2016, https://hal.inria.fr/hal-01396792.

[10] J. SALOTTI, R. BILLOT, N.-E. EL FAOUZI, S. FENET, C. SOLNON.*Vers l'utilisation de graphes de liens causaux pour l'amélioration de la prévision court-terme du trafic routier*, in "RFP-IA 2016 Journée Transports Intelligents", Clermont-Ferrand, France, June 2016, https://hal.archives-ouvertes.fr/hal-01318166.

Other Publications

[11] J. ARMAND.*Developing interfaces for the TRANUS system*, Université Grenoble Alpes, June 2016, https://hal.inria.fr/hal-01401264.

[12] M. BOSCH.*A Framework for Measuring Urban Sprawl from Crowd-Sourced Data*, Grenoble INP, Université de Grenoble, June 2016, https://hal.inria.fr/hal-01401376.

[13] L. GILQUIN, T. CAPELLE, E. ARNAUD, C. PRIEUR.*Sensitivity Analysis and Optimisation of a Land Use and Transport Integrated Model*, March 2016, working paper or preprint, https://hal.inria.fr/hal-01291774.

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Project-Team THOTH

Learning visual models from large-scale data

IN COLLABORATION WITH: Laboratoire Jean Kuntzmann (LJK)

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Vision, perception and multimedia interpretation

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Project-Team THOTH

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

Keywords:

Computer Science and Digital Science:

3.4. - Machine learning and statistics
5.4. - Computer vision

Other Research Topics and Application Domains:

5.6. - Robotic systems
5.8. - Learning and training
7.2. - Smart travel
8.4. - Security and personal assistance
8.5. - Smart society

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2. Overall Objectives

2.1. Overall Objectives

In 2018, it is expected that nearly 80% of the Internet traffic will be due to videos, and that it would take an individual over 5 million years to watch the amount of video that will cross global IP networks each month by then. Thus, there is a pressing and in fact increasing demand to annotate and index this visual content for home and professional users alike. The available text and speech-transcript metadata is typically not sufficient by itself for answering most queries, and visual data must come into play. On the other hand, it is not imaginable to learn the models of visual content required to answer these queries by manually and precisely annotating every relevant concept, object, scene, or action category in a representative sample of everyday conditions—if only because it may be difficult, or even impossible to decide a priori what are the relevant categories and the proper granularity level. This suggests reverting back to the original metadata as source of annotation, despite the fact that the information it provides is typically sparse (e.g., the location and overall topic of newscasts in a video archive) and noisy (e.g., a movie script may tell us that two persons kiss in some scene, but not when, and the kiss may occur off screen or not have survived the final cut). On the other hand, this weak form of “embedded annotation” is rich and diverse, and mining the corresponding visual data from the web, TV or film archives guarantees that it is representative of the many different scene settings depicted in situations typical of on-line content. Thus, leveraging this largely untapped source of information, rather than attempting to hand label all possibly relevant visual data, is a key to the future use of on-line imagery.

Today’s object recognition and scene understanding technology operates in a very different setting; it mostly relies on fully supervised classification engines, and visual models are essentially (piecewise) rigid templates learned from hand labeled images. The sheer scale of on-line data and the nature of the embedded annotation call for a departure from this fully supervised scenario. The main idea of the Thoth project-team is to develop a new framework for learning the structure and parameters of visual models by actively exploring large digital image and video sources (off-line archives as well as growing on-line content, with millions of images and thousands of hours of video), and exploiting the weak supervisory signal provided by the accompanying metadata. This huge volume of visual training data will allow us to learn complex non-linear models with a large number of parameters, such as deep convolutional networks and higher-order graphical models. This is an ambitious goal, given the sheer volume and intrinsic variability of the visual data available on-line, and the lack of a universally accepted formalism for modeling it. Yet, the potential payoff is a breakthrough in visual object recognition and scene understanding capabilities. Further, recent advances at a smaller scale suggest that this is realistic. For example, it is already possible to determine the identity of multiple people from news images and their captions, or to learn human action models from video scripts. There has also been recent progress in adapting supervised machine learning technology to large-scale settings, where the training data is very large and potentially infinite, and some of it may not be labeled. Methods that adapt the structure of visual models to the data are also emerging, and the growing computational power and storage capacity of modern computers are enabling factors that should of course not be neglected.

One of the main objective of Thoth is to transforming massive visual data into trustworthy knowledge libraries. For that, it addresses several challenges.

- designing and learning structured models capable of representing complex visual information.
- learning visual models from minimal supervision or unstructured meta-data.
- large-scale learning and optimization.

3. Research Program

3.1. Designing and learning structured models

The task of understanding image and video content has been interpreted in several ways over the past few decades, namely image classification, detecting objects in a scene, recognizing objects and their spatial extents in an image, estimating human poses, recovering scene geometry, recognizing activities performed by humans. However, addressing all these problems individually provides us with a partial understanding of the scene at best, leaving much of the visual data unexplained.

One of the main goals of this research axis is to go beyond the initial attempts that consider only a subset of tasks jointly, by developing novel models for a more complete understanding of scenes to address all the component tasks. We propose to incorporate the structure in image and video data explicitly into the models. In other words, our models aim to satisfy the complex sets of constraints that exist in natural images and videos. Examples of such constraints include: (i) relations between objects, like signs for shops indicate the presence of buildings, people on a road are usually walking or standing, (ii) higher-level semantic relations involving the type of scene, geographic location, and the plausible actions as a global constraint, e.g., an image taken at a swimming pool is unlikely to contain cars, (iii) relating objects occluded in some of the video frames to content in other frames, where they are more clearly visible as the camera or the object itself move, with the use of long-term trajectories and video object proposals.

This research axis will focus on three topics. The first is developing deep features for video. This involves designing rich features available in the form of long-range temporal interactions among pixels in a video sequence to learn a representation that is truly spatio-temporal in nature. The focus of the second topic is the challenging problem of modeling human activities in video, starting from human activity descriptors to building intermediate spatio-temporal representations of videos, and then learning the interactions among humans, objects and scenes temporally. The last topic is aimed at learning models that capture the relationships among several objects and regions in a single image scene, and additionally, among scenes in the case of an image collection or a video. The main scientific challenges in this topic stem from learning the structure of the probabilistic graphical model as well as the parameters of the cost functions quantifying the relationships among its entities. In the following we will present work related to all these three topics and then elaborate on our research directions.

- **Deep features for vision.** Deep learning models provide a rich representation of complex objects but in return have a large number of parameters. Thus, to work well on difficult tasks, a large amount of data is required. In this context, video presents several advantages: objects are observed from a large range of viewpoints, motion information allows the extraction of moving objects and parts, and objects can be differentiated by their motion patterns. We initially plan to develop deep features for videos that incorporate temporal information at multiple scales. We then plan to further exploit the rich content in video by incorporating additional cues, such as the detection of people and their body-joint locations in video, minimal prior knowledge of the object of interest, with the goal of learning a representation that is more appropriate for video understanding. In other words, a representation that is learned from video data and targeted at specific applications. For the application of recognizing human activities, this involves learning deep features for humans and their body-parts with all their spatiotemporal variations, either directly from raw video data or "pre-processed" videos containing human detections. For the application of object tracking, this task amounts to learning object-specific deep representations, further exploiting the limited annotation provided to identify the object.

- **Modeling human activities in videos.** Humans and their activities are not only one of the most frequent and interesting subjects in videos but also one of the hardest to analyze owing to the complexity of the human form, clothing and movements. As part of this task, the Thoth project-team plans to build on state-of-the-art approaches for spatio-temporal representation of videos. This will involve using the dominant motion in the scene as well as the local motion of individual parts undergoing a rigid motion. Such motion information also helps in reasoning occlusion relationships among people and objects, and the state of the object. This novel spatio-temporal representation ultimately provides the equivalent of object proposals for videos, and is an important component for learning algorithms using minimal supervision. To take this representation even further, we aim to integrate the proposals and the occlusion relationships with methods for estimating human pose in videos, thus leveraging the interplay among body-joint locations, objects in the scene, and the activity being performed. For example, the locations of shoulder, elbow and wrist of a person drinking coffee are constrained to move in a certain way, which is completely different from the movement observed when a person is typing. In essence, this step will model human activities by dynamics in terms of both low-level movements of body-joint locations and global high-level motion in the scene.
- **Structured models.** The interactions among various elements in a scene, such as, the objects and regions in it, the motion of object parts or entire objects themselves, form a key element for understanding image or video content. These rich cues define the structure of visual data and how it evolves spatio-temporally. We plan to develop a novel graphical model to exploit this structure. The main components in this graphical model are spatio-temporal regions (in the case of video or simply image regions), which can represent object parts or entire objects themselves, and the interactions among several entities. The dependencies among the scene entities are defined with a higher order or a global cost function. A higher order constraint is a generalization of the pairwise interaction term, and is a cost function involving more than two components in the scene, e.g., several regions, whereas a global constraint imposes a cost term over the entire image or video, e.g., a prior on the number of people expected in the scene. The constraints we plan to include generalize several existing methods, which are limited to pairwise interactions or a small restrictive set of higher-order costs. In addition to learning the parameters of these novel functions, we will focus on learning the structure of the graph itself—a challenging problem that is seldom addressed in current approaches. This provides an elegant way to go beyond state-of-the-art deep learning methods, which are limited to learning the high-level interaction among parts of an object, by learning the relationships among objects.

3.2. Learning of visual models from minimal supervision

Today's approaches to visual recognition learn models for a limited and fixed set of visual categories with fully supervised classification techniques. This paradigm has been adopted in the early 2000's, and within it enormous progress has been made over the last decade.

The scale and diversity in today's large and growing image and video collections (such as, e.g., broadcast archives, and personal image/video collections) call for a departure from the current paradigm. This is the case because to answer queries about such data, it is unfeasible to learn the models of visual content by manually and precisely annotating every relevant concept, object, scene, or action category in a representative sample of everyday conditions. For one, it will be difficult, or even impossible to decide a-priori what are the relevant categories and the proper granularity level. Moreover, the cost of such annotations would be prohibitive in most application scenarios. One of the main goals of the Thoth project-team is to develop a new framework for learning visual recognition models by actively exploring large digital image and video sources (off-line archives as well as growing on-line content), and exploiting the weak supervisory signal provided by the accompanying metadata (such as captions, keywords, tags, subtitles, or scripts) and audio signal (from which we can for example extract speech transcripts, or exploit speaker recognition models).

Textual metadata has traditionally been used to index and search for visual content. The information in metadata is, however, typically sparse (e.g., the location and overall topic of newscasts in a video archive [0]) and noisy (e.g., a movie script may tell us that two persons kiss in some scene, but not when, and the kiss may occur off screen or not have survived the final cut). For this reason, metadata search should be complemented by visual content based search, where visual recognition models are used to localize content of interest that is not mentioned in the metadata, to increase the usability and value of image/video archives. *The key insight that we build on in this research axis is that while the metadata for a single image or video is too sparse and noisy to rely on for search, the metadata associated with large video and image databases collectively provide an extremely versatile source of information to learn visual recognition models.* This form of "embedded annotation" is rich, diverse and abundantly available. Mining these correspondences from the web, TV and film archives, and online consumer generated content sites such as Flickr, Facebook, or YouTube, guarantees that the learned models are representative for many different situations, unlike models learned from manually collected fully supervised training data sets which are often biased.

The approach we propose to address the limitations of the fully supervised learning paradigm aligns with "Big Data" approaches developed in other areas: we rely on the orders-of-magnitude-larger training sets that have recently become available with metadata to compensate for less explicit forms of supervision. This will form a sustainable approach to learn visual recognition models for a much larger set of categories with little or no manual intervention. Reducing and ultimately removing the dependency on manual annotations will dramatically reduce the cost of learning visual recognition models. This in turn will allow such models to be used in many more applications, and enable new applications based on visual recognition beyond a fixed set of categories, such as natural language based querying for visual content. This is an ambitious goal, given the sheer volume and intrinsic variability of the every day visual content available on-line, and the lack of a universally accepted formalism for modeling it. Yet, the potential payoff is a breakthrough in visual object recognition and scene understanding capabilities.

This research axis is organized into the following three sub-tasks:

- **Weakly supervised learning.** For object localization we will go beyond current methods that learn one category model at a time and develop methods that learn models for different categories concurrently. This allows "explaining away" effects to be leveraged, i.e., if a certain region in an image has been identified as an instance of one category, it cannot be an instance of another category at the same time. For weakly supervised detection in video we will consider detection proposal methods. While these are effective for still images, recent approaches for the spatio-temporal domain need further improvements to be similarly effective. Furthermore, we will exploit appearance and motion information jointly over a set of videos. In the video domain we will also continue to work on learning recognition models from subtitle and script information. The basis of leveraging the script data which does not have a temporal alignment with the video, is to use matches in the narrative in the script and the subtitles (which do have a temporal alignment with the video). We will go beyond simple correspondences between names and verbs relating to self-motion, and match more complex sentences related to interaction with objects and other people. To deal with the limited amount of occurrences of such actions in a single movie, we will consider approaches that learn action models across a collection of movies.
- **Online learning of visual models.** As a larger number of visual category models is being learned, online learning methods become important, since new training data and categories will arrive over time. We will develop online learning methods that can incorporate new examples for existing category models, and learn new category models from few examples by leveraging similarity to related categories using multi-task learning methods. Here we will develop new distance-based classifiers and attribute and label embedding techniques, and explore the use of NLP techniques such as skipgram models to automatically determine between which classes transfer should occur. Moreover, NLP will be useful in the context of learning models for many categories to identify

[0] For example at the Dutch national broadcast archive Netherlands Institute of Sound and Vision, with whom we collaborated in the EU FP7 project AXES, typically one or two sentences are used in the metadata to describe a one hour long TV program.

synonyms, and to determine cases of polysemy (e.g. jaguar car brand v.s. jaguar animal), and merge or refine categories accordingly. Ultimately this will result in methods that are able to learn an“encyclopedia” of visual models.

- **Visual search from unstructured textual queries.** We will build on recent approaches that learn recognition models on-the-fly (as the query is issued) from generic image search engines such as Google Images. While it is feasible to learn models in this manner in a matter of seconds, it is challenging to use the model to retrieve relevant content in real-time from large video archives of more than a few thousand hours. To achieve this requires feature compression techniques to store visual representations in memory, and cascaded search techniques to avoid exhaustive search. This approach, however, leaves untouched the core problem of how to associate visual material with the textual query in the first place. The second approach we will explore is based on image annotation models. In particular we will go beyond image-text retrieval methods by using recurrent neural networks such as Elman networks or long short-term memory (LSTM) networks to generate natural language sentences to describe images.

3.3. Large-scale learning and optimization

We have entered an era of massive data acquisition, leading to the revival of an old scientific utopia: it should be possible to better understand the world by automatically converting data into knowledge. It is also leading to a new economic paradigm, where data is a valuable asset and a source of activity. Therefore, developing scalable technology to make sense of massive data has become a strategic issue. Computer vision has already started to adapt to these changes.

In particular, very high dimensional models such as deep networks are becoming highly popular and successful for visual recognition. This change is closely related to the advent of big data. On the one hand, these models involve a huge number of parameters and are rich enough to represent well complex objects such as natural images or text corpora. On the other hand, they are prone to overfitting (fitting too closely to training data without being able to generalize to new unseen data) despite regularization; to work well on difficult tasks, they require a large amount of labelled data that has been available only recently. Other cues may explain their success: the deep learning community has made significant engineering efforts, making it possible to learn in a day on a GPU large models that would have required weeks of computations on a traditional CPU, and it has accumulated enough empirical experience to find good hyper-parameters for its networks.

To learn the huge number of parameters of deep hierarchical models requires scalable optimization techniques and large amounts of data to prevent overfitting. This immediately raises two major challenges: how to learn without large amounts of labeled data, or with weakly supervised annotations? How to efficiently learn such huge-dimensional models? To answer the above challenges, we will concentrate on the design and theoretical justifications of deep architectures including our recently proposed deep kernel machines, with a focus on weakly supervised and unsupervised learning, and develop continuous and discrete optimization techniques that push the state of the art in terms of speed and scalability.

This research axis will be developed into three sub-tasks:

- **Deep kernel machines for structured data.** Deep kernel machines combine advantages of kernel methods and deep learning. Both approaches rely on high-dimensional models. Kernels implicitly operate in a space of possibly infinite dimension, whereas deep networks explicitly construct high-dimensional nonlinear data representations. Yet, these approaches are complementary: Kernels can be built with deep learning principles such as hierarchies and convolutions, and approximated by multilayer neural networks. Furthermore, kernels work with structured data and have well understood theoretical principles. Thus, a goal of the Thoth project-team is to design and optimize the training of such deep kernel machines.
- **Large-scale parallel optimization.** Deep kernel machines produce nonlinear representations of input data points. After encoding these data points, a learning task is often formulated as a *large-scale convex optimization problem*; for example, this is the case for linear support vector machines,

logistic regression classifiers, or more generally many empirical risk minimization formulations. We intend to pursue recent efforts for making convex optimization techniques that are dedicated to machine learning more scalable. Most existing approaches address scalability issues either in model size (meaning that the function to minimize is defined on a domain of very high dimension), or in the amount of training data (typically, the objective is a large sum of elementary functions). There is thus a large room for improvements for techniques that jointly take these two criteria into account.

- **Large-scale graphical models.** To represent structured data, we will also investigate graphical models and their optimization. The challenge here is two-fold: designing an adequate cost function and minimizing it. While several cost functions are possible, their utility will be largely determined by the efficiency and the effectiveness of the optimization algorithms for solving them. It is a combinatorial optimization problem involving billions of variables and is NP-hard in general, requiring us to go beyond the classical approximate inference techniques. The main challenges in minimizing cost functions stem from the large number of variables to be inferred, the inherent structure of the graph induced by the interaction terms (e.g., pairwise terms), and the high-arity terms which constrain multiple entities in a graph.

3.4. Datasets and evaluation

Standard benchmarks with associated evaluation measures are becoming increasingly important in computer vision, as they enable an objective comparison of state-of-the-art approaches. Such datasets need to be relevant for real-world application scenarios; challenging for state-of-the-art algorithms; and large enough to produce statistically significant results.

A decade ago, small datasets were used to evaluate relatively simple tasks, such as for example interest point matching and detection. Since then, the size of the datasets and the complexity of the tasks gradually evolved. An example is the Pascal Visual Object Challenge with 20 classes and approximately 10,000 images, which evaluates object classification and detection. Another example is the ImageNet challenge, including thousands of classes and millions of images. In the context of video classification, the TrecVid Multimedia Event Detection challenges, organized by NIST, evaluate activity classification on a dataset of over 200,000 video clips, representing more than 8,000 hours of video, which amounts to 11 months of continuous video.

Almost all of the existing image and video datasets are annotated by hand; it is the case for all of the above cited examples. In some cases, they present limited and unrealistic viewing conditions. For example, many images of the ImageNet dataset depict upright objects with virtually no background clutter, and they may not capture particularly relevant visual concepts: most people would not know the majority of subcategories of snakes cataloged in ImageNet. This holds true for video datasets as well, where in addition a taxonomy of action and event categories is missing.

Our effort on data collection and evaluation will focus on two directions. First, we will design and assemble video datasets, in particular for action and activity recognition. This includes defining relevant taxonomies of actions and activities. Second, we will provide data and define evaluation protocols for weakly supervised learning methods. This does not mean of course that we will forsake human supervision altogether: some amount of ground-truth labeling is necessary for experimental validation and comparison to the state of the art. Particular attention will be payed to the design of efficient annotation tools.

Not only do we plan to collect datasets, but also to provide them to the community, together with accompanying evaluation protocols and software, to enable a comparison of competing approaches for action recognition and large-scale weakly supervised learning. Furthermore, we plan to set up evaluation servers together with leader-boards, to establish an unbiased state of the art on held out test data for which the ground-truth annotations are not distributed. This is crucial to avoid tuning the parameters for a specific dataset and to guarantee a fair evaluation.

- **Action recognition.** We will develop datasets for recognizing human actions and human-object interactions (including multiple persons) with a significant number of actions. Almost all of today's action recognition datasets evaluate classification of short video clips into a number of predefined categories, in many cases a number of different sports, which are relatively easy to identify by their characteristic motion and context. However, in many real-world applications the goal is to identify and localize actions in entire videos, such as movies or surveillance videos of several hours. The actions targeted here are "real-world" and will be defined by compositions of atomic actions into higher-level activities. One essential component is the definition of relevant taxonomies of actions and activities. We think that such a definition needs to rely on a decomposition of actions into poses, objects and scenes, as determining all possible actions without such a decomposition is not feasible. We plan to provide annotations for spatio-temporal localization of humans as well as relevant objects and scene parts for a large number of actions and videos.

- **Weakly supervised learning.** We will collect weakly labeled images and videos for training. The collection process will be semi-automatic. We will use image or video search engines such as Google Image Search, Flickr or YouTube to find visual data corresponding to the labels. Initial datasets will be obtained by manually correcting whole-image/video labels, i.e., the approach will evaluate how well the object model can be learned if the entire image or video is labeled, but the object model has to be extracted automatically. Subsequent datasets will features noisy and incorrect labels. Testing will be performed on PASCAL VOC'07 and ImageNet, but also on more realistic datasets similar to those used for training, which we develop and manually annotate for evaluation. Our dataset will include both images and videos, the categories represented will include objects, scenes as well as human activities, and the data will be presented in realistic conditions.
- **Joint learning from visual information and text.** Initially, we will use a selection from the large number of movies and TV series for which scripts are available on-line, see for example http://www.dailyscript.com and http://www.weeklyscript.com. These scripts can easily be aligned with the videos by establishing correspondences between script words and (timestamped) spoken ones obtained from the subtitles or audio track. The goal is to jointly learn from visual content and text. To measure the quality of such a joint learning, we will manually annotate some of the videos. Annotations will include the space-time locations of the actions as well as correct parsing of the sentence. While DVDs will, initially, receive most attention, we will also investigate the use of data obtained from web pages, for example images with captions, or images and videos surrounded by text. This data is by nature more noisy than scripts.

4. Application Domains

4.1. Visual applications

Any solution to automatically understanding images and videos on a semantic level will have an immediate impact on a wide range of applications. For example:

- Semantic-level image and video access is highly relevant for visual search on the Web, in professional archives and personal collections.
- Visual data organization is applicable to organizing family photo and video albums as well as to large-scale information retrieval.
- Visual object recognition has potential applications ranging from surveillance, service robotics for assistance in day-to-day activities as well as the medical domain.
- Action recognition is highly relevant to visual surveillance, assisted driving and video access.
- Real-time scene understanding is relevant for human interaction through devices such as HoloLens, Oculus Rift.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

- Cordelia Schmid received the Humboldt Research Award, granted by the Alexander von Humboldt Foundation.
- Cordelia Schmid was awarded the Longuet-Higgins Prize at CVPR 2016 for the paper co-authored with Svetlana Lazebnik (University of Illinois at Urbana-Champaign) and Jean Ponce (ENS Paris/Inria) entitled "Beyond bags of features: spatial pyramid matching for recognizing natural scene categories".
- Cordelia Schmid was awarded the Inria - Académie des Sciences Grand Prize 2016.
- Thoth is one of the recipients of a hardware donation in the Facebook AI Research Partnership Program.
- Julien Mairal was awarded one of the ERC starting grants 2016.

6. New Software and Platforms

6.1. CoNFab: COnvolutional Neural FABric

Participants: Shreyas Saxena, Jakob Verbeek.

Despite the success of convolutional neural networks, selecting the optimal architecture for a given task remains an open problem. Instead of aiming to select a single optimal architecture, we propose Convolutional Neural Fabrics [20] that embed an exponentially large class of CNN architectures. The fabric consists of a 3D trellis that connects response maps at different layers, scales, and channels with a sparse homogeneous local connectivity pattern. The only hyper-parameters of the model (nr. of channels and layers) are not critical for performance. While individual CNN architectures can be recovered as paths in the trellis, the trellis can in addition ensemble all embedded architectures together, sharing their weights where their paths overlap. By the non-cyclic property of the trellis, its parameters can be efficiently learned using methods based on error back-propagation. The trellis parameters can be learned using standard methods based on back-propagation, at a cost that scales linearly in the fabric size. This software implements Convolutional Neural Fabrics by means of wrappers on top of the Caffe library to specify and learn such models.

6.2. Modl

Participants: Julien Mairal, Arthur Mensch [Parietal], Gael Varoquaux [Parietal], Bertrand Thirion [Parietal].

Modl is a new Python library written by Arthur Mensch for factorizing huge matrices. It implements the method presented in [25], [17], which targets matrices of several terabytes that do not fit into the main computer's memory.

6.3. M-CNN: Weakly-Supervised Semantic Segmentation using Motion Cues

Participants: Pavel Tokmakov, Cordelia Schmid, Karteek Alahari.

This is a public implementation of the method described in [23]. It includes a framework for integrating motion cues into training a deep network for weakly-supervised semantic segmentation, code for data preprocessing and trained models that correspond to the results reported in the paper. Our code is built on top of DeepLab https://bitbucket.org/aquariusjay/deeplab-public-ver2 extension of the Caffe deep learning framework http://caffe.berkeleyvision.org.

6.4. DALY: Daily Action Localization in Youtube

Participants: Philippe Weinzapfael, Xavier Martin, Cordelia Schmid.

DALY is a video dataset with spatial and temporal annotation of 10 everyday human actions in 31 hours of Youtube videos, which allows to train and benchmark methods for action recognition and localization in videos. It is available at http://thoth.inrialpes.fr/daly/. We developed the dataset jointly with a new action localization technique. Both are described in [33].

6.5. GUN-71

Participant: Gregory Rogez.

This dataset consist of 12,000 RGB-D images of object manipulation scenes (captured from a chest-mounted camera) that were labeled with one of 71 fine-grained grasps. We considered 28 objects per grasp, resulting in a total of 1988 different hand-object configurations with 5-6 views for each. The data were captured with 8 different subjects (4 males and 4 females) in 5 different houses, see http://www.gregrogez.net/research/egovision4health/gun-71/.

6.6. Synthetic human 3D pose dataset

Participants: Gregory Rogez, Cordelia Schmid.

Participants: Gregory Rogez, Cordelia Schmid This large-scale dataset consists of 2,000,000 artificial RGB images of humans and associated 2D and 3D pose annotations. This dataset was generated using the image-based rendering algorithm presented in [19] and has been used to train state-of-the-art Convolutional Neural Networks (CNN) for in-the-wild 3D human pose estimation, see http://www.gregrogez.net/research/human-pose-data-synthesis-for-cnn/.

7. New Results

7.1. Visual recognition in images

7.1.1. Convolutional Neural Fabrics

Participants: Shreyas Saxena, Jakob Verbeek.

Despite the success of CNNs, selecting the optimal architecture for a given task remains an open problem. Instead of aiming to select a single optimal architecture, in this work [20], we propose a “fabric” that embeds an exponentially large number of architectures. See 1 for a schematic illustration of how fabrics embed different architectures. The fabric consists of a 3D trellis that connects response maps at different layers, scales, and channels with a sparse homogeneous local connectivity pattern. The only hyper-parameters of a fabric are the number of channels and layers. While individual architectures can be recovered as paths, the fabric can in addition ensemble all embedded architectures together, sharing their weights where their paths overlap. Parameters can be learned using standard methods based on back-propagation, at a cost that scales linearly in the fabric size. We present benchmark results competitive with the state of the art for image classification on MNIST and CIFAR10, and for semantic segmentation on the Part Labels dataset.

7.1.2. Heterogeneous Face Recognition with CNNs

Participants: Shreyas Saxena, Jakob Verbeek.

Heterogeneous face recognition aims to recognize faces across different sensor modalities, see 2 for a schematic illustration. Typically, gallery images are normal visible spectrum images, and probe images are infrared images or sketches. Recently significant improvements in visible spectrum face recognition have been obtained by CNNs learned from very large training datasets. In this paper [21], we are interested in the question to what extent the features from a CNN pre-trained on visible spectrum face images can be used to perform heterogeneous face recognition. We explore different metric learning strategies to reduce the discrepancies between the different modalities. Experimental results show that we can use CNNs trained on visible spectrum images to obtain results that are on par or improve over the state-of-the-art for heterogeneous recognition with near-infrared images and sketches.

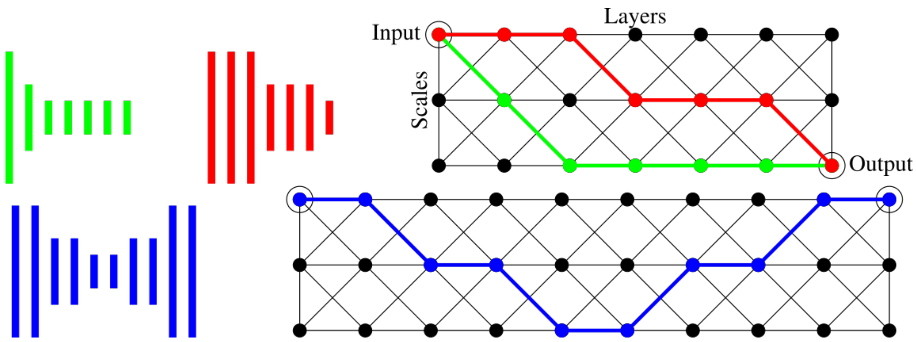

Figure 1. Fabrics embedding two seven-layer CNNs (red, green) and a ten-layer deconvolutional network (blue). Feature map size of the CNN layers are given by height. Fabric nodes receiving input and producing output are encircled. All edges are oriented to the right, down in the first layer, and towards the output in the last layer. The channel dimension of the 3D fabric is omitted for clarity.

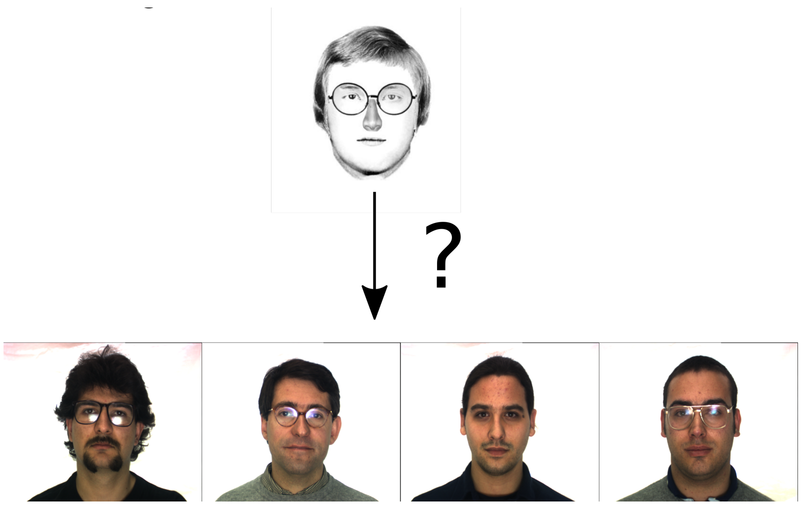

Figure 2. Schematic illustration for the task of heterogenous face recognition. The goal is to find the identity of the probe image (shown as a sketch) among one of the identities from the gallery set (shown in the bottom row). In contrast to standard face recognition, the probe and the gallery set do not share the same modality. In the illustartion, the probe image is a sketch and the galley images are normal visible spectrum images.

7.1.3. Mocap-guided Data Augmentation for 3D Pose Estimation in the Wild

Participants: Grégory Rogez, Cordelia Schmid.

In this paper [19], we address the problem of 3D human pose estimation in the wild. A significant challenge is the lack of training data, i.e., 2D images of humans annotated with 3D poses. Such data is necessary to train state-of-the-art CNN architectures. Here, we propose a solution to generate a large set of photorealistic synthetic images of humans with 3D pose annotations. We introduce an image-based synthesis engine that artificially augments a dataset of real images with 2D human pose annotations using 3D Motion Capture (MoCap) data. Given a candidate 3D pose our algorithm selects for each joint an image whose 2D pose locally matches the projected 3D pose. The selected images are then combined to generate a new synthetic image by stitching local image patches in a kinematically constrained manner. See examples in Figure 3. The resulting images are used to train an end-to-end CNN for full-body 3D pose estimation. We cluster the training data into a large number of pose classes and tackle pose estimation as a K-way classification problem. Such an approach is viable only with large training sets such as ours. Our method outperforms the state of the art in terms of 3D pose estimation in controlled environments (Human3.6M) and shows promising results for in-the-wild images (LSP). This demonstrates that CNNs trained on artificial images generalize well to real images.

Figure 3. Given a candidate 3D pose, our algorithm selects for each joint an image whose annotated 2D pose locally matches the projected 3D pose. The selected images are then combined to generate a new synthetic image by stitching local image patches in a kinematically constrained manner. We show 6 examples corresponding to the same 3D pose observed from 6 different camera viewpoints.

7.1.4. End-to-End Kernel Learning with Supervised Convolutional Kernel Networks

Participant: Julien Mairal.

In [16], we introduce a new image representation based on a multilayer kernel machine. Unlike traditional kernel methods where data representation is decoupled from the prediction task, we learn how to shape the kernel with supervision. We proceed by first proposing improvements of the recently-introduced convolutional kernel networks (CKNs) in the context of unsupervised learning; then, we derive backpropagation rules to take advantage of labeled training data. The resulting model is a new type of convolutional neural network, where optimizing the filters at each layer is equivalent to learning a linear subspace in a reproducing kernel Hilbert space (RKHS). We show that our method achieves reasonably competitive performance for image classification on some standard " deep learning " datasets such as CIFAR-10 and SVHN, and also for image super-resolution, demonstrating the applicability of our approach to a large variety of image-related tasks. The model is illustrated in Figure 4.

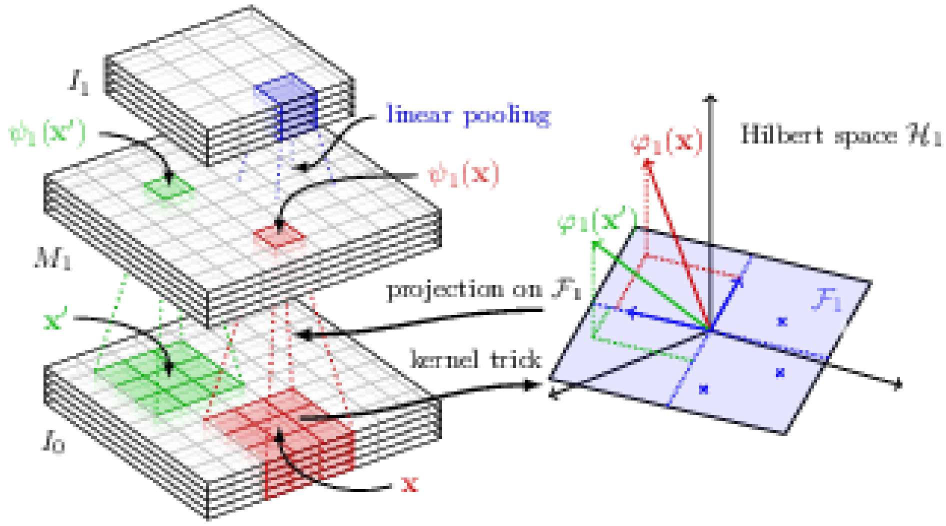

Figure 4. Our variant of convolutional kernel networks, illustrated between layers 0 and 1.

7.1.5. Semantic segmentation using Adversarial Networks

Participants: Pauline Luc, Camille Couprie [Facebook], Soumith Chintala [Facebook], Jakob Verbeek.

Adversarial training has been shown to produce state of the art results for generative image modeling. In [24], we propose an adversarial training approach to train semantic segmentation models. We train a convolutional semantic segmentation network along with an adversarial network that discriminates segmentation maps coming either from the ground truth or from the segmentation network, as shown in Figure 5. The motivation for our approach is that it can detect and correct higher-order inconsistencies between ground truth segmentation maps and the ones produced by the segmentation net. Our experiments show that our adversarial training approach leads to improved accuracy on the Stanford Background and PASCAL VOC 2012 datasets.

7.1.6. Enhancing Energy Minimization Framework for Scene Text Recognition with Top-Down Cues

Participants: Anand Mishra [IIIT Hyderabad], Karteek Alahari, C. v. Jawahar [IIIT Hyderabad].

Recognizing scene text, i.e., text in images such as the one in Figure 6, is a challenging problem, even more so than the recognition of scanned documents. This problem has gained significant attention from the computer vision community in recent years, and several methods based on energy minimization frameworks and deep learning approaches have been proposed. In our work presented in [8], we focus on the energy minimization framework and propose a model that exploits both bottom-up and top-down cues for recognizing cropped words extracted from street images. The bottom-up cues are derived from individual character detections from an image. We build a conditional random field model on these detections to jointly model the strength of the

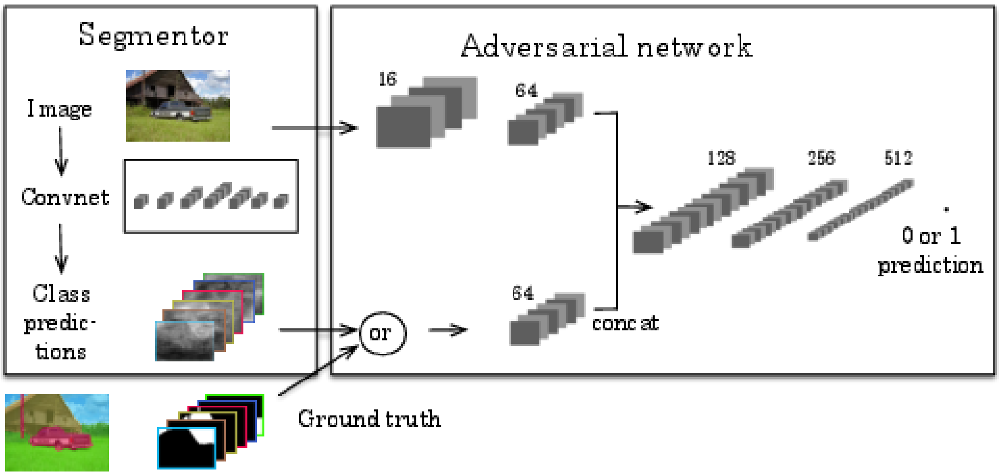

Figure 5. We use adversarial training to simultaneously learn a segmentation model (left) and a high order loss term to train it, given by the adversarial network (right). This encourages the segmentation model to output plausible segmentations, by enforcing forms of high order consistencies that are learned rather than manually designed.

detections and the interactions between them. These interactions are top-down cues obtained from a lexicon-based prior, i.e., language statistics. The optimal word represented by the text image is obtained by minimizing the energy function corresponding to the random field model. We evaluate our proposed algorithm extensively on a number of cropped scene text benchmark datasets, namely Street View Text, ICDAR 2003, 2011 and 2013 datasets, and IIIT 5K-word, and show better performance than comparable methods. We perform a rigorous analysis of all the steps in our approach and analyze the results. We also show that state-of-the-art convolutional neural network features can be integrated in our framework to further improve the recognition performance.

7.1.7. Local Convolutional Features with Unsupervised Training for Image Retrieval

Participants: Mattis Paulin, Matthijs Douze [Facebook], Zaid Harchaoui [University of Washington], Julien Mairal, Florent Perronnin [Xerox], Cordelia Schmid.

Patch-level descriptors underlie several important computer vision tasks, such as stereo-matching or content-based image retrieval. We introduce a deep convolutional architecture that yields patch-level descriptors, as an alternative to the popular SIFT descriptor for image retrieval. The proposed family of descriptors, called Patch-CKN[9], adapt the recently introduced Convolutional Kernel Network (CKN), an unsupervised framework to learn convolutional architectures. We present a comparison framework to benchmark current deep convolutional approaches along with Patch-CKN for both patch and image retrieval (see Fig. 7 for our pipeline), including our novel “RomePatches” dataset. Patch-CKN descriptors yield competitive results compared to supervised CNNs alternatives on patch and image retrieval.

7.2. Visual recognition in videos

7.2.1. Towards Weakly-Supervised Action Localization

Participants: Philippe Weinzaepfel, Xavier Martin, Cordelia Schmid.

Figure 6. A typical street scene image taken from Google Street View. It contains very prominent sign boards with text on the building and its windows. It also contains objects such as car, person, tree, and regions such as road, sky. Many scene understanding methods recognize these objects and regions in the image successfully, but overlook the text on the sign board, which contains rich, useful information. The goal of our work [8] is to address this gap in understanding scenes.

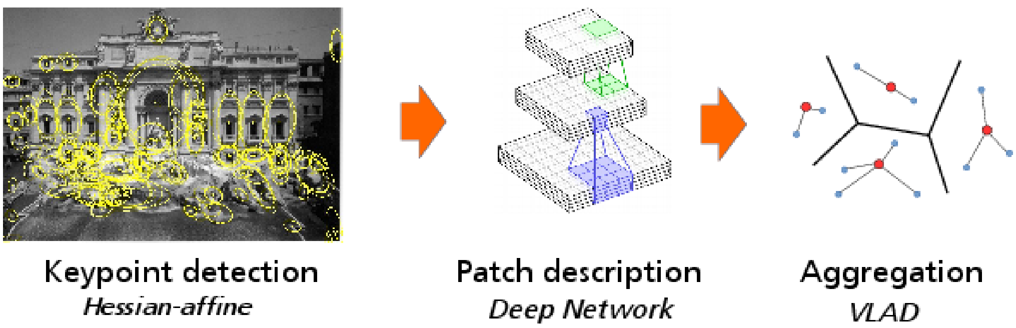

Figure 7. Image retrieval pipeline. Interest points are extracted with the Hessian-affine detector (left), encoded in descriptor space using convolutional features (middle), and aggregated into a compact representation using VLAD-pooling (right).

In this paper [33], we present a novel approach for weakly-supervised action localization, i.e., that does not require per-frame spatial annotations for training. We first introduce an effective method for extracting human tubes by combining a state-of-the-art human detector with a tracking-by-detection approach. Our tube extraction leverages the large amount of annotated humans available today and outperforms the state of the art by an order of magnitude: with less than 5 tubes per video, we obtain a recall of 95% on the UCF-Sports and J-HMDB datasets. Given these human tubes, we perform weakly-supervised selection based on multi-fold Multiple Instance Learning (MIL) with improved dense trajectories and achieve excellent results. Figure 8 summarizes the approach. We obtain a mAP of 84% on UCF-Sports, 54% on J-HMDB and 45% on UCF-101, which outperforms the state of the art for weakly-supervised action localization and is close to the performance of the best fully-supervised approaches. The second contribution of this paper is a new realistic dataset for action localization, named DALY (Daily Action Localization in YouTube). It contains high quality temporal and spatial annotations for 10 actions in 31 hours of videos (3.3M frames), which is an order of magnitude larger than standard action localization datasets. On the DALY dataset, our tubes have a spatial recall of 82%, but the detection task is extremely challenging, we obtain 10.8% mAP.

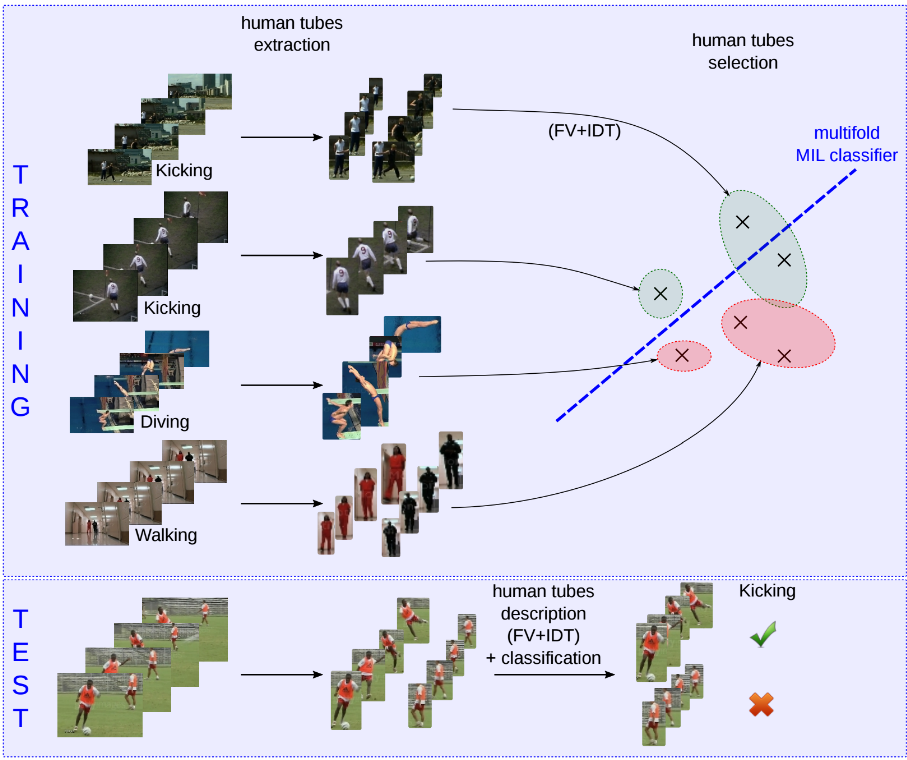

Figure 8. Overview of our approach for action localization without spatial supervision.

7.2.2. The DALY dataset

Participants: Philippe Weinzaepfel, Xavier Martin, Cordelia Schmid.

We introduce a new action localization dataset named DALY (Daily Action Localization in YouTube). DALY consists of more than 31 hours of videos (3.3M frames) from YouTube with 10 realistic daily actions, see Figure 9, and 3.6k spatio-temporal instances. Annotations consist in the start and end time of each action instance, with high-quality spatial annotation for a sparse subset of frames. The task is to localize relatively short actions (8 seconds in average) in long untrimmed videos (3min 45 in average). Furthermore, it includes videos with multiple humans performing actions simultaneously. It overcomes the limitations of existing benchmarks that are limited to trimmed or almosttrimmed videos with specific action types, e.g. sports only, showing in most cases one human per video.

Figure 9. Overview of our approach for action localization without spatial supervision.

7.2.3. Weakly-Supervised Semantic Segmentation using Motion Cues

Participants: Pavel Tokmakov, Karteek Alahari, Cordelia Schmid.

Fully convolutional neural networks (FCNNs) trained on a large number of images with strong pixel-level annotations have become the new state of the art for the semantic segmentation task. While there have been recent attempts to learn FCNNs from image-level weak annotations, they need additional constraints, such as the size of an object, to obtain reasonable performance. To address this issue, in [23] we present motion-CNN (M-CNN), a novel FCNN framework which incorporates motion cues and is learned from video-level weak annotations. Our learning scheme to train the network uses motion segments as soft constraints, thereby handling noisy motion information, as shown in Figure 10. When trained on weakly-annotated videos, our method outperforms the state-of-the-art EM-Adapt approach on the PASCAL VOC 2012 image segmentation benchmark. We also demonstrate that the performance of M-CNN learned with 150 weak video annotations is on par with state-of-the-art weakly-supervised methods trained with thousands of images. Finally, M-CNN substantially outperforms recent approaches in a related task of video co-localization on the YouTube-Objects dataset.

7.2.4. Multi-region two-stream R-CNN for action detection

Participants: Xiaojiang Peng, Cordelia Schmid.

This work [18] introduces a multi-region two-stream R-CNN model for action detection, see Figure 11. It starts from frame-level action detection based on faster R-CNN and makes three contributions. The first one is the introduction of a motion region proposal network (RPN) complementary to a standard appearance RPN. The second is the stacking of optical flow over several frames, which significantly improves frame-level action detection. The third is the addition of a multi-region scheme to the faster R-CNN model, which adds complementary information on body parts. Frame-level detections are linked with the Viterbi algorithm, and action are temporally localized with the maximum subarray method. Experimental results on the UCF-Sports, J-HMDB and UCF101 action detection datasets show that the approach outperforms the state of the art with a significant margin in both frame-mAP and video-mAP.

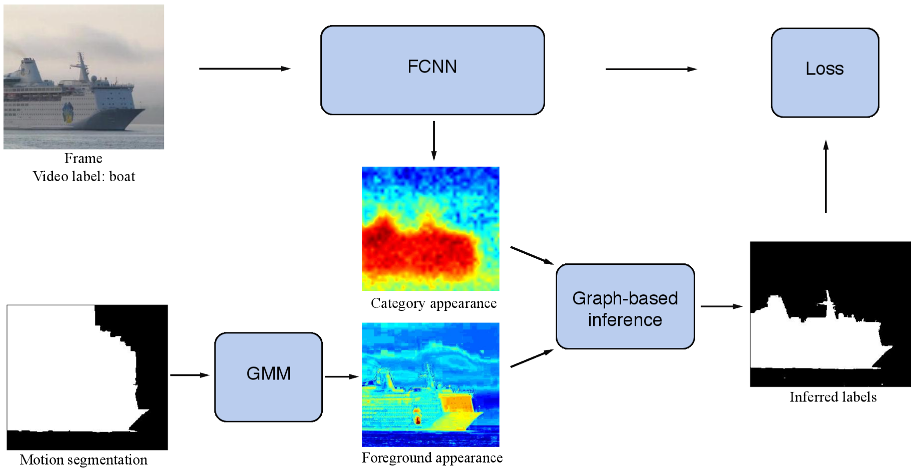

Figure 10. Overview of our M-CNN framework, where we show only one frame from a video example for clarity. The soft potentials (foreground appearance) computed from motion segmentation and the FCNN predictions (category appearance) jointly determine the latent segmentation (inferred labels) to compute the loss, and thus the network update.

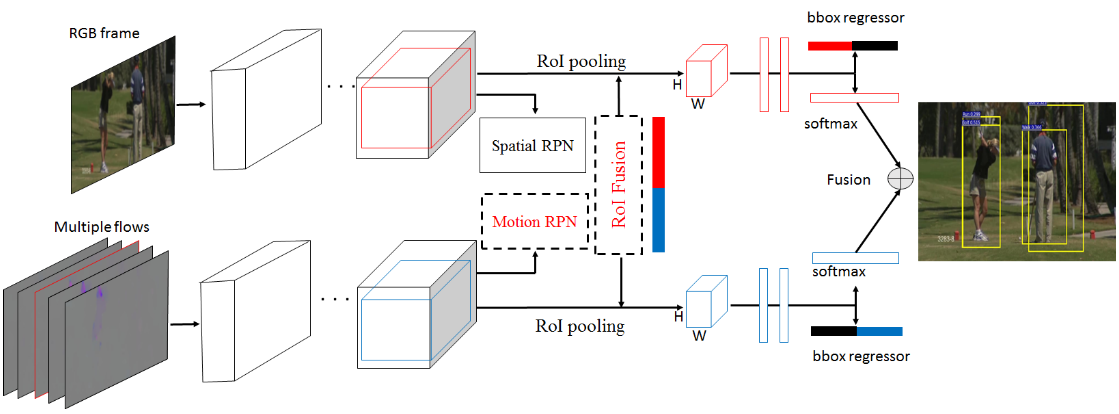

Figure 11. Two-stream faster R-CNN for spatio-temporal action detection.

7.2.5. Analysing domain shift factors between videos and images for object detection

Participants: Vicky Kalogeiton, Vittorio Ferrari [Univ. Edinburgh], Cordelia Schmid.

Object detection is one of the most important challenges in computer vision. Object detectors are usually trained on bounding-boxes from still images. Recently, video has been used as an alternative source of data. Yet, for a given test domain (image or video), the performance of the detector depends on the domain it was trained on. In this paper [7], we examine the reasons behind this performance gap. We define and evaluate different domain shift factors (see Figure 12): spatial location accuracy, appearance diversity, image quality and aspect distribution. We examine the impact of these factors by comparing performance before and after factoring them out. The results show that all four factors affect the performance of the detectors and their combined effect explains nearly the whole performance gap.

Figure 12. Example of apperance diversity domain shift factor. (top row): Frames in the same shot that contain near identical samples of an object. (bottom row): Example of near identical samples in the same image.

7.3. Large-scale statistical learning

7.3.1. Dictionary Learning for Massive Matrix Factorization

Participants: Julien Mairal, Arthur Mensch [Parietal], Gael Varoquaux [Parietal], Bertrand Thirion [Parietal].

Sparse matrix factorization is a popular tool to obtain interpretable data decompositions, which are also effective to perform data completion or denoising. Its applicability to large datasets has been addressed with online and randomized methods, that reduce the complexity in one of the matrix dimension, but not in both of them. In [25], [17], we tackle very large matrices in both dimensions. We propose a new factorization method that scales gracefully to terabyte-scale datasets. Those could not be processed by previous algorithms in a reasonable amount of time. We demonstrate the efficiency of our approach on massive functional Magnetic Resonance Imaging (fMRI) data, and on matrix completion problems for recommender systems, where we obtain significant speed-ups compared to state-of-the art coordinate descent methods. The main principle of the method is illustrated in Figure 13.

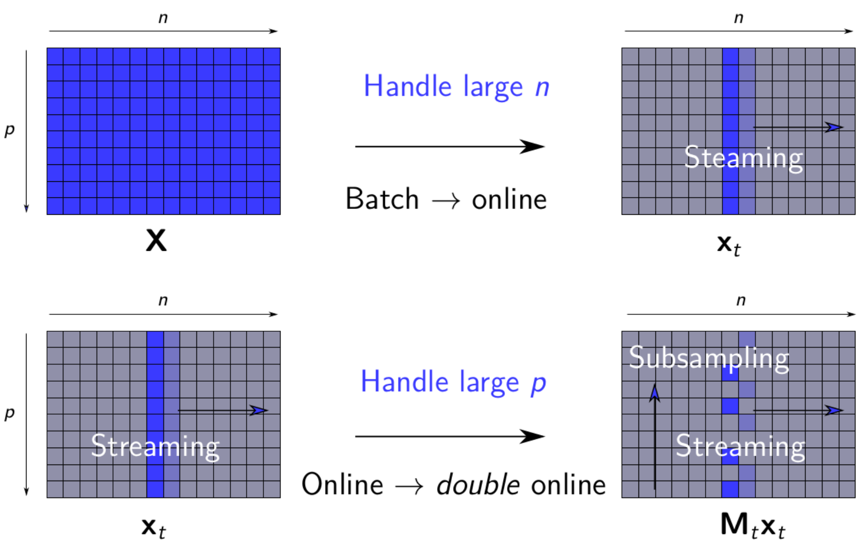

Figure 13. Illustration of the matrix factorization algorithm, which streams columns in one dimension while subsampling them.

7.3.2. Stochastic Optimization with Variance Reduction for Infinite Datasets with Finite-Sum Structure

Participants: Alberto Bietti, Julien Mairal.

Stochastic optimization algorithms with variance reduction have proven successful for minimizing large finite sums of functions. However, in the context of empirical risk minimization, it is often helpful to augment the training set by considering random perturbations of input examples. In this case, the objective is no longer a finite sum, and the main candidate for optimization is the stochastic gradient descent method (SGD). In this paper [26], we introduce a variance reduction approach for this setting when the objective is strongly convex. After an initial linearly convergent phase, the algorithm achieves a $O(1/t)$ convergence rate in expectation like SGD, but with a constant factor that is typically much smaller, depending on the variance of gradient estimates due to perturbations on a single example.

7.3.3. QuickeNing: A Generic Quasi-Newton Algorithm for Faster Gradient-Based Optimization

Participants: Hongzhou Lin, Julien Mairal, Zaid Harchaoui [University of Washington].

In this paper [28], we propose an approach to accelerate gradient-based optimization algorithms by giving them the ability to exploit curvature information using quasi-Newton update rules. The proposed scheme, called QuickeNing, is generic and can be applied to a large class of first-order methods such as incremental and block-coordinate algorithms; it is also compatible with composite objectives, meaning that it has the ability to provide exactly sparse solutions when the objective involves a sparsity-inducing regularization. QuickeNing relies on limited-memory BFGS rules, making it appropriate for solving high-dimensional optimization problems; with no line-search, it is also simple to use and to implement. Besides, it enjoys a worst-case linear convergence rate for strongly convex problems. We present experimental results, see Figure 14, where QuickeNing gives significant improvements over competing methods for solving large-scale high-dimensional machine learning problems.

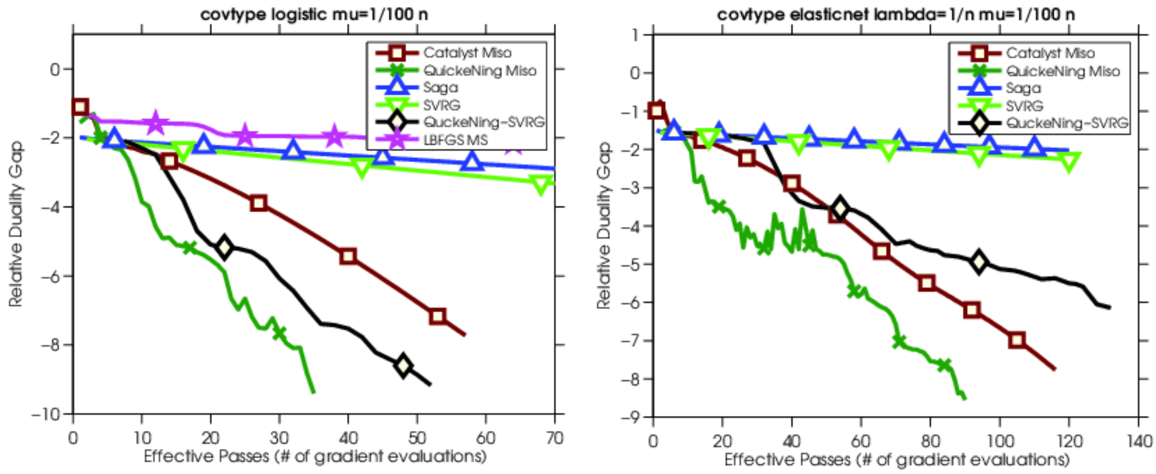

Figure 14. Relative duality gap for different number of passes performed over dataset covtype.

7.3.4. Dictionary Learning from Phaseless Measurements

Participants: Julien Mairal, Yonina Eldar [Technion], Andreas Tillmann [TU Darmstadt].

In [22], [12], we propose a new algorithm to learn a dictionary for reconstructing and sparsely encoding signals from measurements without phase. Specifically, we consider the task of estimating a two-dimensional image from squared-magnitude measurements of a complex-valued linear transformation of the original image. Several recent phase retrieval algorithms exploit underlying sparsity of the unknown signal in order to improve recovery performance. In this work, we consider such a sparse signal prior in the context of phase retrieval, when the sparsifying dictionary is not known in advance. Our algorithm jointly reconstructs the unknown signal—possibly corrupted by noise—and learns a dictionary such that each patch of the estimated image can be sparsely represented. Numerical experiments demonstrate that our approach can obtain significantly better reconstructions for phase retrieval problems with noise than methods that cannot exploit such “hidden” sparsity. Moreover, on the theoretical side, we provide a convergence result for our method.

8. Bilateral Contracts and Grants with Industry

8.1. MSR-Inria joint lab: scientific image and video mining

Participants: Cordelia Schmid, Karteek Alahari, Yang Hua.

This collaborative project, which started in September 2008, brings together the WILLOW and Thoth project-teams with researchers at Microsoft Research Cambridge and elsewhere. It builds on several ideas articulated in the “2020 Science” report, including the importance of data mining and machine learning in computational science. Rather than focusing only on natural sciences, however, we propose here to expand the breadth of e-science to include humanities and social sciences. The project focuses on fundamental computer science research in computer vision and machine learning, and its application to archeology, cultural heritage preservation, environmental science, and sociology.

8.2. MSR-Inria joint lab: structured large-scale machine learning

Participants: Julien Mairal, Alberto Bietti, Hongzhou Lin.

Machine learning is now ubiquitous in industry, science, engineering, and personal life. While early successes were obtained by applying off-the-shelf techniques, there are two main challeges faced by machine learning in the “ big data ” era : structure and scale. The project proposes to explore three axes, from theoretical, algorithmic and practical perspectives: (1) large-scale convex optimization, (2) large-scale combinatorial optimization and (3) sequential decision making for structured data. The project involves two Inria sites and four MSR sites and started at the end of 2013.

8.3. Amazon

Participants: Grégory Rogez, Cordelia Schmid.

We received an Amazon Faculty Research Award end of 2016. The objective is 3D human action recognition from monocular RGB videos. The idea is to extend our recent work on human 3D pose estimation [19] to videos and to develop an approach for action recognition based on temporal pose based on appropriate 3D features.

8.4. Google

Participants: Karteek Alahari, Cordelia Schmid.

We received a Google Faculty Research Award in 2015. The objective is to interpret video semantically in the presence of weak supervision. We will focus on answering questions such as *who* is in the scene, *what* they are doing, and *when* exactly did they perform their action(s). We propose to develop models for detection and recognition of objects and actions learned from minimally annotated training data.

8.5. Facebook

Participants: Cordelia Schmid, Jakob Verbeek, Karteek Alahari, Julien Mairal.

The collaboration started in 2016. The topics include image retrieval with CNN based descriptors, weakly supervised semantic segmentation, and learning structure models for action recognition in videos. In 2016, Pauline Luc started her PhD funded by a CIFRE grant, jointly supervised by Jakob Verbeek (Inria) and Camille Couprie (Facebook). THOTH has been selected in 2016 as a recipient for the Facebook GPU Partnership program. In this context Facebook will donate a state-of-the-art server with 8 GPUs.

8.6. MBDA

Participants: Jakob Verbeek, Julien Bardonnet.

Since 2004 we have collaborated with MBDA on a variety of subjects, namely object detection, tracking and matching. Several PhD students have been funded by MBDA, and code has been transferred which is integrated in products. Our collaboration resulted in 2010 in the award of the MBDA prize for innovation. Since May 2015 we have one engineer funded by MBDA working on incremental learning of object detection models. The goal is to take pre-existing vehicle models, and to quickly adapt them to new images of these vehicles when they are acquired in the field.

8.7. Xerox Research Center Europe

Participants: Mattis Paulin, Karteek Alahari, Vladyslav Sydorov, Cordelia Schmid, Julien Mairal, Jakob Verbeek.

The collaboration with Xerox has been on-going since October 2009 with two co-supervised CIFRE scholarships (2009–2012; 2011-2014). Starting June 2014 we signed a third collaborative agreement for a duration of three years. The goal is to develop approaches for deep learning based image description and pose estimation in videos. Jakob Verbeek (Inria) and Diane Larlus (XRCE) jointly supervise a PhD-level intern for a period of 6 months in 2016-2017.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. DeCore (Deep Convolutional and Recurrent networks for image, speech, and text)

Participants: Jakob Verbeek, Maha Elbayad.

DeCore is a project-team funded by the Persyval Lab for 3.5 years (september 2016 - February 2020), coordinated by Jakob Verbeek. It unites experts from Grenoble's applied-math and computer science labs LJK, GIPSA-LAB and LIG in the areas of computer vision, machine learning, speech, natural language processing, and information retrieval. The purpose of DeCore is to stimulate collaborative interdisciplinary research on deep learning in the Grenoble area, which is likely to underpin future advances in machine perception (vision, speech, text) over the next decade. It provides funding for two full PhD students. Maha Elbayad is one of them, supervised by Jakob Verbeek and Laurant Besacier (UGA).

9.2. National Initiatives

9.2.1. ANR Project Physionomie

Participants: Jakob Verbeek, Shreyas Saxena, Guosheng Hu.

Face recognition is nowadays an important technology in many applications ranging from tagging people in photo albums, to surveillance, and law enforcement. In this 3-year project (2013–2016) the goal is to broaden the scope of usefulness of face recognition to situations where high quality images are available in a dataset of known individuals, which have to be identified in relatively poor quality surveillance footage. To this end we will develop methods that can compare faces despite an asymmetry in the imaging conditions, as well as methods that can help searching for people based on facial attributes (old/young, male/female, etc.). The tools will be evaluated by law-enforcement professionals. The participants of this project are: Morpho, SensorIT, Université de Caen, Université de Strasbourg, Fondation pour la Recherche Stratégique, Préfecture de Police, Service des Technologies et des Systèmes d'Information de la Sécurité Intérieure, and Thoth. The project ended in June 2016.

9.2.2. ANR Project Macaron

Participants: Julien Mairal, Zaid Harchaoui [University of Washington], Laurent Jacob [CNRS, LBBE Laboratory], Michael Blum [CNRS, TIMC Laboratory], Joseph Salmon [Telecom ParisTech].

The project MACARON is an endeavor to develop new mathematical and algorithmic tools for making machine learning more scalable. Our ultimate goal is to use data for solving scientific problems and automatically converting data into scientific knowledge by using machine learning techniques. Therefore, our project has two different axes, a methodological one, and an applied one driven by explicit problems. The methodological axis addresses the limitations of current machine learning for simultaneously dealing with large-scale data and huge models. The second axis addresses open scientific problems in bioinformatics, computer vision, image processing, and neuroscience, where a massive amount of data is currently produced, and where huge-dimensional models yield similar computational problems.

This is a 3 years and half project, funded by ANR under the program "Jeunes chercheurs, jeunes chercheuses", which started in October 2014. The principal investigator is Julien Mairal.

9.2.3. ANR Project DeepInFrance

Participant: Jakob Verbeek.

DeepInFrance (Machine learning with deep neural networks) project also aims at bringing together complementary machine learning, computer vision and machine listening research groups working on deep learning with GPUs in order to provide the community with the knowledge, the visibility and the tools that brings France among the key players in deep learning. The long-term vision of Deep in France is to open new frontiers and foster research towards algorithms capable of discovering sense in data in an automatic manner, a stepping stone before the more ambitious far-end goal of machine reasoning. The project partners are: INSA Rouen, Univ. Caen, Inria, UPMC, Aix-Marseille Univ., Univ. Nice Sophia Antipolis.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. ERC Advanced grant Allegro

Participants: Cordelia Schmid, Pavel Tokmakov, Nicolas Chesneau, Vicky Kalogeiton, Konstantin Shmelkov, Daan Wynen, Xiaojiang Peng.

The ERC advanced grant ALLEGRO started in April 2013 for a duration of five years. The aim of ALLEGRO is to automatically learn from large quantities of data with weak labels. A massive and ever growing amount of digital image and video content is available today. It often comes with additional information, such as text, audio or other meta-data, that forms a rather sparse and noisy, yet rich and diverse source of annotation, ideally suited to emerging weakly supervised and active machine learning technology. The ALLEGRO project will take visual recognition to the next level by using this largely untapped source of data to automatically learn visual models. We will develop approaches capable of autonomously exploring evolving data collections, selecting the relevant information, and determining the visual models most appropriate for different object, scene, and activity categories. An emphasis will be put on learning visual models from video, a particularly rich source of information, and on the representation of human activities, one of today's most challenging problems in computer vision.

9.3.1.2. EU Marie Curie project: Egovision4health

Participants: Grégory Rogez, Cordelia Schmid.

After the 2-year outgoing phase hosted by the University of California, Irvine, G. Rogez spent the return (and final) phase of the project in the team. In 2015, he analyzed functional object manipulations focusing on fine-grained hand-object interactions and created a large dataset of 12000 RGB-D images covering 71 everyday grasps in natural interactions. This Grasp UNderstanding dataset (GUN-71) has been made publicly available in 2016 (http://www.gregrogez.net/research/egovision4health/gun-71/). In the last period of the fellowship, G. Rogez and C. Schmid addressed the more general problem of full-body 3D pose estimation in third-person images. They developed a new data synthesis technique to generate large-scale (2 millions images) training data that were later used to train Deep Convolutional Neural Networks. The collaboration resulted in a publication [19]. Dataset, code and models will be released soon.

9.4. International Initiatives

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

9.4.1.1. GAYA: Semantic and Geometric Models for Video Interpretation

We have formed an associate team GAYA, with the primary goal of interpreting videos in terms of recognizing actions, understanding the human-human and human-object interactions. Despite several years of research, it is yet unclear what is an efficient and robust video representation to attack this challenge. In order to address this, GAYA will focus on building semantic models, wherein we learn the video feature representation with limited supervision, and also geometric models, where we study the geometric properties of object shapes to better recognize them. The team consists of researchers from two Inria project-teams (Thoth and WILLOW) and a US university (Carnegie Mellon University [CMU]). It will allow the three teams to effectively combine their respective strengths in areas such as inference and machine learning approaches for vision tasks, feature representation, large-scale learning, geometric reasoning. The main expected outcomes of this collaboration are: effective learnt representations of video content, new machine learning algorithms for handling minimally annotated data, large-scale public datasets for benchmarking, theoretical analysis of objects shapes and contours. Cordelia Schmid and Karteek Alahari are involved in this associate team.

9.4.2. Inria International Partners

9.4.2.1. Informal International Partners

- **University of Edinburgh:** C. Schmid collaborates with V. Ferrari, associate professor at university of Edinburgh. Vicky Kalogeiton started a co-supervised PhD in September 2013; she is bi-localized between Uni. Edinburgh and Inria. Her subject is the automatic learning of object representations in videos. The collaboration resulted in a joint publication in IEEE PAMI [7]
- **MPI Tübingen:** C. Schmid collaborates with M. Black, a research director at MPI, starting in 2013. She spent one month at MPI in May 2016. End of 2015 she was award a Humbolt research award funding a long-term research project with colleagues at MPI. In 2016 the project resulted in the development of a large-scale synthetic human action dataset.
- **Technion:** J. Mairal started a collaboration with Yonina Eldar (Technion) and Andreas Tillmann (Darmstadt university) to develop dictionary learning techniques for phase retrieval. Their collaboration resulted in a paper accepted to the ICASSP'16 conference [22] and a paper accepted to IEEE Transaction on signal processing [12].
- **UC Berkeley:** This collaboration between Bin Yu, Jack Gallant, Yuval Benjamini, Adam Bloniarz, Yuansi Chen (UC Berkeley), and Julien Mairal (Inria Thoth) aims to discover the functionalities of areas of the visual cortex. We have introduced an image representation for area V4, adapting tools from computer vision to neuroscience data. The collaboration started when Julien Mairal was a post-doctoral researcher at UC Berkeley and is still ongoing.

9.4.3. Participation in Other International Programs

- **Indo-French project EVEREST** with IIIT Hyderabad, India, funded by CEFIPRA (Centre Franco-Indien pour la Promotion de la Recherche Avancee). The aim of this project between Cordelia Schmid, Karteek Alahari and C. V. Jawahar (IIIT Hyderabad) is to enable the use of rich, complex models that are required to address the challenges of high-level computer vision. The work plan for the project will follow three directions. First, we will develop a learning framework that can handle weak annotations. Second, we will build formulations to solve the non-convex optimization problem resulting from the learning framework. Third, we will develop efficient and accurate energy minimization algorithms, in order to make the optimization computationally feasible.
- **France-Berkeley fund:** Julien Mairal was awarded in 2014 a grant from the France-Berkeley fund for a project with Pr. Bin Yu (statistics department, UC Berkeley) on “Invariant image representations and high dimensional sparse estimation for neurosciences”. The award amounts to 10,000 USD, from November 2014 to April 2016. The funds are meant to support scientific and scholarly exchanges and collaboration between the two teams.

9.5. International Research Visitors

9.5.1. Visits to International Teams

9.5.1.1. Research Stays Abroad

- H. Lin visited Microsoft Research at New York from September to December 2016, as part of the MSR-Inria joint centre collaboration.
- G. Chéron visited Microsoft Research at Cambridge from April to July 2016, as part of the MSR-Inria joint centre collaboration.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Organizing Committees

- G. Rogez. Co-organizer of the CVPR workshop on Observing and Understanding Hands in Action (HANDS 2016).
- J. Verbeek. Organized Symposium on Computer Vision and Deep Learning on June 9th in Grenoble with around 80 attendants.

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

- C. Schmid: area chair for ECCV'16, ICCV'17.
- J. Mairal: area chair for CVPR 2016, ECCV 2016, ICLR 2016 and NIPS 2016.
- J. Verbeek: tutorial chair for ECCV'16.

10.1.2.2. Reviewer

The permanent members of the team reviewed numerous papers for numerous international conferences in computer vision and machine learning: CVPR, ECCV, NIPS, ICML, AISTATS.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- C. Schmid: Editor in Chief of the International Journal of Computer Vision, since 2013.
- C. Schmid: Associate editor for Foundations and Trends in Computer Graphics and Vision, since 2005.
- J. Verbeek: Associate editor for Image and Vision Computing Journal, since 2011.
- J. Verbeek: Associate editor for the International Journal on Computer Vision, since 2014.
- J. Mairal: Associate editor of the International Journal of Computer Vision (IJCV), since 2015.
- J. Mairal: Senior associate editor for IEEE Signal Processing Letters, since Feb 2015 (editor since Aug. 2014).
- J. Mairal: Associate editor of Journal of Mathematical Imaging and Vision (JMIV), since 2015.

10.1.3.2. Reviewer - Reviewing Activities

The permanent members of the team reviewed numerous papers for numerous international journals in computer vision (IJCV, PAMI,CVIU), machine learning (JMLR, Machine Learning). Some of them are also reviewing for journals in optimization (SIAM Journal on Optimization, Mathematical Programming), image processing (SIAM Imaging Science).

10.1.4. Invited Talks

- C. Schmid. Invited speaker at Large-scale Computer Vision Workshop in conjunction with NIPS'16, December 2016.
- C. Schmid. Keynote speaker at IEEE International Conference on Image Processing, Phoenix, September 2016.
- C. Schmid. Invited speaker at Robust Features Workshop in conjunction with CVPR'16, June 2016.
- C. Schmid. Invited speaker at collège de France seminar (chair of Yann LeCun), Mars 2016.
- C. Schmid. Invited speaker at the LIG (laboratoire d'informatique de Grenoble) keynote talks, February 2016.
- C. Schmid. Seminar at Google, Montain View, July 2016.
- C. Schmid. Seminar at "journées scientifiques Inria", June 2016.
- C. Schmid. Seminar at Karlsruhe Technology Institute, June 2016.
- C. Schmid. Seminar at MPI, Tübingen, April 2016.
- C. Schmid. Seminar at INSA Lyon, April 2016.
- C. Schmid. Seminar at New York University, January 2016.

- J. Verbeek. Invited speaker at NVIDIA GPU Technology Conference, Amsterdam, The Netherlands. September 2016.
- J. Verbeek. Seminar GREYC, University of Caen, France, December 2016.
- J. Verbeek. Seminar PSI team, department of Electrical Engineering (ESAT), University of Leuven, Belgium, October 2016.
- J. Mairal. Invited talk at the Dagstuhl seminar “New Directions for Learning with Kernels and Gaussian Processes”, December 2016.
- J. Mairal. Invited talk at workshop Phi-Tab, Telecom ParisTech, November 2016.
- J. Mairal. Invited talk at Journées GDR-Isis, Telecom ParisTech, September 2016.
- J. Mairal. Invited talk at Journées MAS, Grenoble, France, August 2016.
- J. Mairal. Invited talk at ICCOPT, Tokyo, Japan, August 2016.
- J. Mairal. Seminar at UC Berkeley, EECS department, USA, March 2016.
- J. Mairal. Seminar at UBC Vancouver, Canada, February 2016.
- J. Mairal. Invited talk at the MIA’16 workshop, Paris, France, January 2016.
- K. Alahari. Seminar at Carnegie Mellon University, USA, July 2016.
- K. Alahari. invited talk at Mysore Park workshop on vision, language and AI, India, December 2016.
- G. Rogez. Invited talk at Journées CNRS-GDR Isis, Telecom Paris, May 2016.
- G. Rogez. Invited speaker at CVPR Tutorial on First-person Visual Sensing: Theory, Models, and Application, Las Vegas, June 2016.
- G. Rogez. Seminar at LIRMM, Université de Montpellier, December 2016.
- H. Lin. Seminar at New York University, USA, April 2016.
- H. Lin. Seminar at Princeton University, USA, April 2016.
- H. Lin. Invited talk at ICCOPT, Tokyo, Japan, August 2016.

10.1.5. Scientific Expertise

- C. Schmid is member of the PAMI-TC awards committee, and the PAMI-TC executive commitee.
- K. Alahari: reviewer for National Sciences and Engineering Research Council of Canada (NSERC), Canada, Agence Nationale de la Recherche (ANR), and Icelandic Research Fund (IRF), Iceland.
- J. Mairal: reviewer for ANR.

10.1.6. Research Administration

- C. Schmid is member of the “comité d’orientations scientifiques”. Inria Grenoble, 2016.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Doctorat: C. Schmid, Tutorial on action recognition at the Winter School in Computer Vision, Jerusalem, January 2017.

Doctorat: J. Mairal, Lecturer at the summer school MAESTRA, Ohrid, Macedonia.

Master : C. Schmid, “Object recognition and computer vision”, 9H eqTD, M2, ENS Cachan, France.

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Master: J. Mairal, “Kernel methods for statistical learning”, 27H eqTD, M2, Ecole Normale Supérieure, Cachan.

Master: J. Mairal, “Introduction to sparse estimation”, 6H eq-TD, M2, PSL-ITI, France.

Master: K. Alahari, “Introduction to Discrete Optimization”, Ecole Centrale Paris, 27H eq-TD, M1, Paris, France.

Master: K. Alahari, “Understanding Big Visual Data”, Grenoble INP, 13.5H eq-TD, M2, Grenoble, France.

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10.2.2. Supervision

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PhD: Y. Hua, Towards robust visual object tracking : proposal selection and occlusion reasoning, supervision 50% C. Schmid and 50% K. Alahari, June 2016.

PhD: A. Mishra, Understanding Text in Scene Images, supervision 50% K. Alahari and 50% Prof. C. V. Jawahar, November 2016.

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C. Schmid: Pedro Oliveira Pinheiro, January 2017, rapporteur, these, EPFL.

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K. Alahari: Guillaume Seguin, 2016, examinateur, these, Ecole Normale Superieure, Paris, France.

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Project-Team TYREX

Types and Reasoning for the Web

IN COLLABORATION WITH: Laboratoire d'Informatique de Grenoble (LIG)

IN PARTNERSHIP WITH:
CNRS
Institut polytechnique de Grenoble
Université Grenoble Alpes

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Data and Knowledge Representation and Processing

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Project-Team TYREX

Creation of the Team: 2012 November 01, updated into Project-Team: 2014 July 01

Keywords:

Computer Science and Digital Science:

2.1.1. - Semantics of programming languages
2.1.3. - Functional programming
2.1.7. - Distributed programming
2.1.10. - Domain-specific languages
2.2.1. - Static analysis
2.2.4. - Parallel architectures
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3.1.1. - Modeling, representation
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Other Research Topics and Application Domains:

6.1. - Software industry
6.3.1. - Web
6.5. - Information systems
8.2. - Connected city
9.4.1. - Computer science
9.4.5. - Data science
9.7.2. - Open data
9.9. - Risk management
9.9.2. - Financial risks

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2. Overall Objectives

2.1. Objectives

The TyReX team aims at developing a vision of a web where content is enhanced and protected, applications made easier to build, maintain and secure. It seeks to open new horizons for the development of the web, enhancing its potential, effectiveness, and dependability. In particular, we aim at making contributions by obtaining fundamental results, by building advanced experimental applications showcasing these results and by contributing to web standards. One fundamental problem of our time is a lack of formalisms, concepts and tools for reasoning simultaneously about content or data, programs, and communication aspects. Our main scientific goal is to establish a unifying development framework for designing advanced (robust, flexible, rich, efficient and novel) web applications.

To tackle our overall goal, we decomposed the problem along three dimensions, each corresponding to a more specific objective and research theme:

1. models, to deal with the issues of heterogeneous data and application complexity by abstracting away from document formats and programming language syntax;
2. analysis, verification and optimization; and
3. design of advanced distributed web application, to address programming in mobile and large-scale distributed systems.

3. Research Program

3.1. Modeling

Modeling consists in capturing various aspects of document and data processing and communication in a unifying model. Our modeling research direction mainly focuses on three aspects.

The first aspect aims at reducing the impedance mismatch. The impedance mismatch refers to the complexity, difficulty and lack of performance induced by various web application layers which require the same piece of information to be represented and processed differently. The mismatch occurs because programming languages use different native data models than those used for documents in browsers and for storage in databases. This results in complex and multi-tier software architectures whose different layers are incompatible in nature. This, in turn, results in expensive, inefficient, and error-prone web development. For reducing the impedance mismatch, we will focus on the design of a unifying software stack and programming framework, backed by generic and solid logical foundations similar in spirit to the NoSQL approach.

The second aspect aims at harnessing heterogeneity. Web applications increasingly use diverse data models: ordered and unordered tree-like structures (such as XML), nested records and arrays (such as JSON), graphs (like RDF), and tables. Furthermore, these data models involve a variety of languages for expressing constraints over data (e.g. XML schema, RelaxNG, and RDFS to name just a few). We believe that this heterogeneity is here to stay and is likely to increase. These differences in representations imply loads of error-prone and costly conversions and transformations. Furthermore, some native formats (e.g. JSON) are repurposed from an internal representation to a format for data exchange. This often results in a loss of information and in errors that need to be tracked and corrected. In this context, it is important to seek methods for reducing risks of information loss during data transformation and exchange. For harnessing heterogeneity, we will focus on the integration of data models through unified formal semantics and in particular logical interpretation. This allows using the same programming language constructs on different data models. At the programming language level, this is similar to languages such as JSonIq for JSON and XML.

Finally, the third aspect aims at making applications and data more compositional. Most web programming technologies are currently limited from a compositional point of view. For example, tree grammars (like schema languages for XML) are monolithic in the sense that they require the full description of the considered structures, instead of allowing the assembly of smaller and reusable building blocks. As a consequence, this translates into monolithic web applications, which makes their automated verification harder by making modular analyses more difficult. The need for compositionality is illustrated in the industry by the increasing development of fragmented W3C specifications organised in ad-hoc modules. For making applications and data more compositional, we will focus on the design of modular schema and programming languages. For this purpose, we will notably rely on succinct yet expressive formalisms (like two-way logics, polymorphic types, session types) that ease the process of expressing modular specifications.

3.2. Analysis, verification and optimization

This research direction aims at guaranteeing two different kinds of properties: safety and efficiency.

The first kind of properties concerns the safety of web applications. Software development was traditionally split between critical and non-critical software. Advanced (and costly) formal verification techniques were reserved to the former whereas non-critical software relied almost exclusively on testing, which only offers a ‘best-effort’ guarantee (removes most bugs but some of them may not be detected). The central idea was that in a non-critical system, the damage a failure may create is not worth the cost of formal verification. However, as web applications grow more pervasive in everyday life and gain momentum in corporates and various social organizations, and touch larger numbers of users, the potential cost of failure is rapidly and significantly increasing. In that sense, we can consider that web applications are becoming more and more critical. The growing dependency on the web as a tool, combined with the fact that some applications involve very large user bases, is becoming problematic as it seems to increase rapidly but silently. Some errors like crashes and confidential information leaks, if not discovered, can have massive effects and cause significant financial or reputation damage.

The second kind of properties concerns the efficiency of web applications. One particular characteristic of web programming languages is that they are essentially data-manipulation oriented. These manipulations rely on query and transformation languages whose performance is critical. This performance is very sensitive to data size and organization (constraints) and to the execution model (e.g. streaming evaluators). Static analysis can be used to optimize runtime performance by compile-time automated modification of the code (e.g.

substitution of queries by more efficient ones). One major scientific difficulty here consists in dealing with problems close to the frontier of decidability, and therefore in finding useful trade-offs between programming ease, expressivity, complexity, succinctness, algorithmic techniques and effective implementations.

3.3. Design of advanced (robust, flexible, rich, novel) web applications

The generalized use of mobile terminals deeply affects the way users perceive and interact with their environment. The ubiquitous use of search engines capable of producing results in fractions of a second raised user expectations to a very high level: users now expect relevant information to be made available to them instantly and directly by context sensitivity to the environment itself. However, the information that needs to be processed is becoming more and more complex compared to the traditional web. In order to unlock the potential introduced by this new generation of the web, a radical rethinking of how web information is produced, organized and processed is necessary.

Until now, content rendering on the web was mainly based on supporting media formats separately. It is still notably the case in HTML5 for example where, for instance, vector graphics, mathematical content, audio and video are supported only as isolated media types. With the increasing use of web content in mobile terminals, we also need to take into account highly dynamic information flowing from sensors (positioning and orientation moves) and cameras. To reach that goal, web development platforms need to ease the manipulation of such content with carefully designed programming interfaces and by developing supporting integrative methods.

More precisely, we will focus on the following aspects: (1) **Build Rich content models**. This requires combining in a single model several content facets such as 3D elements, animations, user interactions, etc. We will focus on feature-compositional methods, which have become a prerequisite for the production of compelling web applications. (2) **Physical environment modeling and integration**. This consists of modeling and representing urban data such as buildings, pathways, points of interest. It requires developing appropriate languages and techniques to represent, process and query such environment models. In particular, we will focus on tracking positional user information and design techniques capable of combining semantic annotations, content, and representation of the physical world. (3) **Native streams support**. This consists of capturing new data flows extracted from various sensors in mobile terminals and various equipments. (4) **Cross-platform abstractions**. We will contribute to the design of appropriate abstractions to make applications run in a uniform way across various devices and environments. Our goal is to provide a viable alternative to current (platform-specific) mobile application development practices.

4. Application Domains

4.1. Web Programming Technologies

Despite the major social and economic impacts of the web revolution, current web programming methods and content representation are lagging behind and remain severely limited and in many respects archaic. Dangerously, designing web applications even becomes increasingly complex as it relies more and more on a jungle of programming languages, tools and data formats, each targeted toward a different application layer (presentation, application and storage). This often yields complex and opaque applications organized in silos, which are costly, inefficient, hard to maintain and evolve, and vulnerable to errors and security holes. In addition, the communication aspects are often handled independently via remote service invocations and represent another source of complexity and vulnerability. We believe that we reached a level where there is an urgent need and a growing demand for alternative programming frameworks that capture the essence of web applications: advanced content, data and communication. Therefore, successful candidate frameworks must capture rich document formats, data models and communication patterns. A crucial aspect is to offer correction guarantees and flexibility in the application architecture. For instance, applications need to be checked, optimized and managed as a whole while leveraging on the consistency of their individual components and data fragments. For all these reasons, we believe that a new generation of tools must be created and developed in order to overcome the aforementioned limitations of current web technologies.

4.2. Multimedia and Augmented Environments

The term Augmented Environments refers collectively to ubiquitous computing, context-aware computing, and intelligent environments. The goal of our research on these environments is to introduce personal Augmented Reality (AR) devices, taking advantage of their embedded sensors. We believe that personal AR devices such as mobile phones or tablets will play a central role in augmented environments. These environments offer the possibility of using ubiquitous computation, communication, and sensing to enable the presentation of context-sensitive information and services to the user. AR applications often rely on 3D content and employ specialized hardware and computer vision techniques for both tracking and scene reconstruction and exploration. Our approach tries to seek a balance between these traditional AR contexts and what has come to be known as mobile AR browsing. It first acknowledges that mobile augmented environment browsing does not require that 3D content be the primary means of authoring. It provides instead a method for HTML5 and audio content to be authored, positioned in the surrounding environments and manipulated as freely as in modern web browsers. The applications we develop to guide and validate our concepts are pedestrian navigation techniques and applications for cultural heritage visits. Features found in augmented environments are demanding for the other activities in the team. They require all kinds of multimedia information, that they have to combine. This information has to be processed efficiently and safely, often in real time, and it also, for a significant part, has to be created by human users.

5. New Software and Platforms

5.1. Benchmarks Attitude Smartphones

KEYWORDS: Experimentation - Motion analysis - Sensors - Performance analysis - Smartphone

SCIENTIFIC DESCRIPTION

We investigate the precision of attitude estimation algorithms in the particular context of pedestrian navigation with commodity smartphones and their inertial/magnetic sensors. We report on an extensive comparison and experimental analysis of existing algorithms. We focus on typical motions of smartphones when carried by pedestrians. We use a precise ground truth obtained from a motion capture system. We test state-of-the-art attitude estimation techniques with several smartphones, in the presence of magnetic perturbations typically found in buildings. We discuss the obtained results, analyze advantages and limits of current technologies for attitude estimation in this context. Furthermore, we propose a new technique for limiting the impact of magnetic perturbations with any attitude estimation algorithm used in this context. We show how our technique compares and improves over previous works.

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5.2. CSS Analyzer

FUNCTIONAL DESCRIPTION

This software now consists in two distinct prototypes: two static analyzers (with a different purpose) that share a common compiler for CSS. The first prototype is used for bug detection and verification of a cascading style sheet (CSS) file. It involves a compiler for CSS rules (and in particular selectors) into logical formulas, adapted for the semantics of CSS (see the initial WWW'12 paper). The second prototype performs automated refactoring for size reduction of CSS style sheets. It reuses the first compiler and the logical solver for detecting which rules can be refactored and how. It implements various optimisation techniques (like early pruning), for the purpose of dealing with large-size real CSS files. This prototype reduces the size of CSS files found in the most popular websites (such as CNN, facebook, Google Sites, Apple, etc.) by up to 30

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5.3. RDFHive

KEYWORDS: Hadoop - RDF - SPARQL

SCIENTIFIC DESCRIPTION

SPARQL is the W3C standard query language for querying data expressed in RDF (Resource Description Framework). The increasing amounts of RDF data available raise a major need and research interest in building efficient and scalable distributed SPARQL query evaluators.

In this context, we propose and share RDFHive: a simple implementation of a distributed RDF datastore benefiting from Apache Hive. RDFHive is designed to leverage existing Hadoop infrastructures for evaluating SPARQL queries. RDFHive relies on a translation of SPARQL queries into SQL queries that Hive is able to evaluate.

Technically, RDFHive directly evaluates SPARQL queries i.e. there is no preprocessing step, indeed an RDF triple file is seen by Hive as a three-column table. Thus, the bash translator simply translates SPARQL queries according to this scheme. This method has two advantages: first, creating a database is very fast, second, since the upfront investment is light, RDFHive is an interesting tool to evaluate a few SPARQL queries at once.

- Participants: Damien Graux, Nabil Layaida and Pierre Geneves
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- URL: https://github.com/tyrex-team/rdfhive

5.4. Tree Reasoning Solver

SCIENTIFIC DESCRIPTION

The tree reasoning solver is a software tool which implements research advances in tree logics, and in the analysis of query and programming languages for the web. The core algorithm is a satisfiability solver of an expressive tree logic. The underlying logic is very expressive: it is a μ-calculus variant for finite trees, which is MSO-complete, and equipped with additional features (converse modalities, nominals, logical combinators...)

The decision procedure has an optimal worst-case complexity, and its implementation performs quite well in practice. This allows efficient reasoning with tree structures. In particular, it opens the way for solving a wide variety of problems that require reasoning with very large sets of trees.

Initially developed for the analysis of XML/XPath queries, this tool has been extended by the team to support more general query analysis, reasoning with schema constraints, with functions, and with domain specific languages such as cascading style sheets.

- Participants: Pierre Geneves, Nabil Layaida and Nils Gesbert
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5.5. XQuery Type-Checker

SCIENTIFIC DESCRIPTION

This prototype implements a sound static type-system for an XQuery core. The type language supported is a large subset of RelaxNG+Schematron, which is novel in static type checking. It also supports the static typing of backward axes, which is not supported by any other system nor the XQuery recommendation. Our type checker successfully verifies complex programs for which existing type-checkers (either known from the literature or those developed in commercial software) fail by reporting false alarms. One major benefit is to allow the cost of validation to be deferred from runtime to compile-time (once only). This prototype is implemented in Scala and interacts with the solver by issuing externals calls for deciding complex subtyping relations.

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5.6. SPARQLGX

KEYWORDS: RDF - SPARQL - Distributed computing

SCIENTIFIC DESCRIPTION

SPARQL is the W3C standard query language for querying data expressed in RDF (Resource Description Framework). The increasing amounts of RDF data available raise a major need and research interest in building efficient and scalable distributed SPARQL query evaluators.

In this context, we propose and share SPARQLGX: our implementation of a distributed RDF datastore based on Apache Spark. SPARQLGX is designed to leverage existing Hadoop infrastructures for evaluating SPARQL queries. SPARQLGX relies on a translation of SPARQL queries into executable Spark code that adopts evaluation strategies according to (1) the storage method used and (2) statistics on data. Using a simple design, SPARQLGX already represents an interesting alternative in several scenarios.

- Participants: Damien Graux, Louis Jachiet, Nabil Layaida and Pierre Geneves
- Contact: Pierre Genevès, Damien Graux
- URL: https://github.com/tyrex-team/sparqlgx

6. New Results

6.1. Experimental evaluation of attitude estimation algorithms for smartphones

- **Context:** Pervasive applications on smartphones increasingly rely on techniques for estimating attitude. Attitude is the orientation of the smartphone with respect to Earth's local frame.

  Modern smartphones embed sensors such as accelerometer, gyroscope, and magnetometer which make it possible to leverage existing attitude estimation algorithms.
- **Contribution:** We investigated the precision of attitude estimation algorithms in the context of commodity smartphones carried by pedestrians. We considered eight typical motions (such as texting, phoning, running, etc.) with various impacts on external accelerations, as well as the presence/absence of magnetic perturbations typically found in indoor environments. We systematically analyzed, compared and evaluated eight state-of-the-art algorithms (and their variants). We precisely quantified the attitude estimation error obtained with each technique, owing to the use of a precise ground truth obtained with a motion capture system (the Inria Kinovis platform). We made our benchmark available (see Sec. 5.1 above) and payed attention to the reproducibility of results. We analyzed and discussed the obtained results and reported on lessons learned [7] [17]. We also presented a new technique which helps in improving precision by limiting the effect of magnetic perturbations with all considered algorithms.

6.2. Efficient Distributed Evaluation of SPARQL Queries

- **Context:** SPARQL is the standard query language for retrieving and manipulating data represented in the Resource Description Framework (RDF). SPARQL constitutes one key technology of the semantic web and has become very popular since it became an official W3C recommendation.

  The construction of efficient SPARQL query evaluators faces several challenges. First, RDF datasets are increasingly large, with some already containing more than a billion triples. To handle efficiently this growing amount of data, we need systems to be distributed and to scale. Furthermore, semantic data often have the characteristic of being dynamic (frequently updated). Thus being able to answer quickly after a change in the input data constitutes a very desirable property for a SPARQL evaluator.

- **Contributions:** First of all, to constitute a common basis of comparative analysis, we evaluated on the same cluster of machines various SPARQL evaluation systems from the literature [15]. These experiments led us to point several observations: (i) the solutions have very different behaviors; (ii) most of the benchmarks only use temporal metrics and forget other ones e.g. network traffic. That is why we proposed a larger set of metrics; and thanks to a new reading grid based on 5 features, we proposed new perspectives which should be considered when developing distributed SPARQL evaluators.

  Second, we developed and shared several distributed SPARQL evaluators which take into account these new considerations we introduced:

  - A SPARQL evaluator named SPARQLGX (see Sec. 5.6): an implementation of a distributed RDF datastore based on Apache Spark. SPARQLGX is designed to leverage existing Hadoop infrastructures for evaluating SPARQL queries. It relies on a translation of SPARQL queries into executable Spark code that adopts evaluation strategies according to the storage method used and statistics on data.

    In [12], [11], [8], [13], we showed that SPARQLGX makes it possible to evaluate SPARQL queries on billions of triples distributed across multiple nodes, while providing attractive performance figures. We reported on experiments which show how SPARQLGX compares to related state-of-the-art implementations and we showed that our approach scales better than these systems in terms of supported dataset size. With its simple design, SPARQLGX represents an interesting alternative in several scenarios.

  - Two SPARQL direct evaluators i.e. without a preprocessing phase: SDE (stands for Sparqlgx Direct Evaluator) lays on the same strategy than SPARQLGX but the translation process is modified in order to take the orign data files as argument. RDFHive (see Sec. 5.3) evaluates translated SPARQL queries on top of Apache Hive which is a distributed relational data warehouse based on Apache Hadoop.

6.3. An Efficient Translation from a modal μ-Calculus with Converse to Tree Automata

In [16], we presented a direct translation from a sub-logic of μ-calculus to non-deterministic binary automata of finite trees. The logic is an alternation-free modal μ-calculus, restricted to finite trees and where formulae are cycle-free. This logic is expressive enough to encode significant fragments of query languages (such as Regular XPath). The size of the generated automaton (the number of transitions) is bounded by 2^n where n is the size of a Fischer-Ladner closure of the formula. This is an improvement over previous translations in 2^{n^2}. We have implemented our translation. In practice, our prototype effectively decides static analysis problems that were beyond reach, such as the XPath containment problem with DTDs of significant size.

6.4. SPARQL Query Containment with ShEx Constraints

ShEx (Shape Expressions) is a language for expressing constraints on RDF graphs. In [14], we considered the problem of SPARQL query containment in the presence of ShEx constraints. We first investigated the complexity of the problem according to the fragments considered for SPARQL queries and for ShEx constraints. In particular, we showed that the complexity of SPARQL query containment remains the same with or without ShEx constraints. We developed two radically different approaches for solving the problem and we evaluated them. The first approach relies on the joint use of a ShEx validator and a tool for checking query containment without constraints. In a second approach, we showed how the problem can be solved by a reduction to a fragment of first-order logic with two variables. This alternative approach allows to take advantage of any of the many existing FOL theorem provers in this context. We evaluated how the two approaches compare experimentally, and reported on lessons learned. To the best of our knowledge, this is the first work addressing SPARQL query containment in the presence of ShEx constraints.

6.5. XQuery Static Type-Checking

In the context of our ongoing work on XQuery static type-checking [3], we extended our type system and improved the associated software accordingly (see Sec. 5.5 and 5.4). The type language it is based on is now a subset of RelaxNG+Schematron (instead of DTDs), which is novel in the context of static typing: Schematron is normally used to validate a document after it has been generated, whereas our system is able to ensure statically that a program will always generate a valid document.

Schematron constraints present the advantage of describing some properties in a very concise way compared to schema languages based on regular tree types, e.g. it allows writing in one line that nested anchors are forbidden in HTML, a constraint which appears in the specification but not in the formal DTD schema because of the verbosity it would involve.

7. Partnerships and Cooperations

7.1. Regional Initiatives

AGIR

Title: Data-CILE

Call: Appel à projet Grenoble Innovation Recherche (AGIR-Pole)

Duration: 2016-2018

Coordinator: Nabil Layaïda

Abstract: The goal of this project is to contribute to foundational and algorithmic challenges introduced by increasingly popular data-centric paradigms for programming on distributed architectures such as spark and the massive production of big linked open data. The focus of the project is on building robust and more efficient workflows of transformations of rich web data. We will investigate effective programming models and compilation techniques for producing specialised language runtimes. We will focus on high-level specifications of pipelines of data transformations and extraction for producing valuable knowledge from rich web data. We will study how to synthesise code which is correct and optimised for execution on distributed platforms. The overall expected outcome is to make the development of rich-data-intensive applications less error-prone and more efficient.

7.2. National Initiatives

7.2.1. Investissements d'avenir

Datalyse

Title: Entrepôt Intelligent pour Big Data hétérogènes. Investissements d'Avenir Développement de l'Economie Numérique.

Call: Cloud Computing, num 3 – Big Data.

Duration: May 2013 - November 2016

Coordinator: Business & Decision Eolas

Others partners: Groupement des Mousquetaires, Inria Saclay (OAK EPC), LIG (Hadas and Erods teams), LIRMM (Montpellier), LIFL (Lille).

See also: http://www.datalyse.fr/

Abstract: Project Datalyse aims at designing and deploying an infrastructure for big data storage, collection, certification, integration, categorisation, enrichment and sharing over very large heterogeneous data sets. It relies on an industrial platform, to be made available on the cloud, and focuses on three flagship applications, showcasing three uses of big data over different data sets:

- Data-Center Monitoring: The goal of this application is to provide features such as traceability, reporting, optimisation and analysis of abnormal behaviour regarding energy efficiency and security issues. The application will be built with an existing application called ScopeBR (Eolas) and will be deployed in two different green data centers, those of Eolas and GDF SUEZ.
- 'Territoire de données ouvertes et liées': This application aims at extracting and provisioning public open data collected from the city of Grenoble and its suburbs. The goal is to make public data available to third-party application developers and to federate local actors around a single platform.
- Real-time Business Intelligence for the management and processing of points of sale: this application will focus on real-time data analytics and will be deployed within 'Groupement des Mousquetaires' in support of their business intelligence platforms.

7.2.2. ANR

CLEAR

Title: Compilation of intermediate Languages into Efficient big dAta Runtimes

Call: Appel à projets générique 2016 défi 'Société de l'information et de la communication' – JCJC

Duration: October 2016 – September 2020

Coordinator: Pierre Genevès

See also: http://tyrex.inria.fr/clear

Abstract: This project addresses one fundamental challenge of our time: the construction of effective programming models and compilation techniques for the correct and efficient exploitation of big and linked data. We study high-level specifications of pipelines of data transformations and extraction for producing valuable knowledge from rich and heterogeneous data. We investigate how to synthesize code which is correct and optimized for execution on distributed infrastructures.

7.2.3. PERSYVAL-lab LabEx

Title: Mobile Augmented Reality Applications for Smart Cities

Call: Persyval Labex ('Laboratoire d'excellence').

Duration: 2014 – 2017

Coordinators: Pierre Genevès and Nabil Layaïda

Others partners: NeCS team at GIPSA-Lab laboratory.

Abstract: The goal of this project is to increase the relevance and reliability of augmented reality (AR) applications, through three main objectives:

1. Finding and developing appropriate representations for describing the physical world (3D maps, indoor buildings, ways...), integrated advanced media types (3D, 3D audio, precisely geo-tagged pictures with lat., long. and orientation, video...)
2. Integrating the different abstraction levels of these data streams (ranging from sensors data to high level rich content such as 3D maps) and bridging the gap with Open Linked Data (the semantic World). This includes opening the way to query the environment (filtering), and adapt AR browsers to users' capabilities (e.g. blind people). The objective here is to provide an open and scalable platform for mobile-based AR systems (just like the web represents).
3. Increasing the reliability and accuracy of localization technologies. Robust and high-accuracy localization technologies play a key role in AR applications. Combined with geographical data, they can also be used to identify user-activity patterns, such as walking, running or being in an elevator. The interpretation of sensor values, coupled with different walking models, allows one to ensure the continuity of the localization, both indoor and

outdoor. However, dead reckoning based on Inertial Navigation Systems (INS) or Step-and-Heading Systems (SHS) is subject to cumulative errors due to many factors (sensor drift (accelerometers, gyroscopes, etc.), missed steps, bad estimation of the length of each stride, etc.). One objective is to reduce such errors by merging and mixing these approaches with various external signals such as GPS and Wi-Fi or relying on the analyses of user trajectories with the help of a structured map of the environment. Some filtering methods (Kalman Filter, observer, etc.) will be useful to achieve this task.

7.3. European Initiatives

7.3.1. Collaborations in European Programs, Except FP7 & H2020

Program: COST

Project acronym: BETTY

Project title: Behavioural Types for Reliable Large-Scale Software Systems

Duration: October 2012 – October 2016

Coordinator: Professor Simon Gay, University of Glasgow, UK

Other partners: Bosnia and Herzegovina, Croatia, Cyprus, Denmark, Estonia, fYR Macedonia, Germany, Greece, Ireland, Italy, Lithuania, Malta, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Spain, Sweden, United Kingdom

Abstract: Modern society is increasingly dependent on large-scale software systems that are distributed, collaborative and communication-centred. Correctness and reliability of such systems depend on compatibility between components and services that are newly developed or may already exist. The consequences of failure are severe, including security breaches and unavailability of essential services. Current software development technology is not well suited to producing these large-scale systems, because of the lack of high-level structuring abstractions for complex communication behaviour.

This Action will use behavioural type theory as the basis for new foundations, programming languages, and software development methods for communication-intensive distributed systems. Behavioural type theory encompasses concepts such as interfaces, communication protocols, contracts, and choreography. As a unifying structural principle it will transform the theory and practice of distributed software development.

The significance of behavioural types has been recognised world-wide during the last five years. European researchers are internationally leading. There is an urgent need for European co-ordination to avoid duplication of effort, facilitate interactions among research groups, and ensure that the field proceeds efficiently from academic research to industrial practice. This Action will provide the co-ordination layer and leverage the efforts of European researchers, to increase the competitiveness of the European software industry.

See also: http://behavioural-types.eu

7.4. International Research Visitors

7.4.1. Internships

Jakob Zietsch from Technische Universität München visited the team from March to July to work on geolocalization with smartphones based on fingerprinting.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. Member of the Organizing Committees

- C. Roisin is a member of the steering committee of the ACM Symposium on Document Engineering. (until Sept. 2016)

8.1.2. Scientific Events Selection

8.1.2.1. Member of the Conference Program Committees

- P. Genevès has been external review committee member for the 21st ACM SIGPLAN International Conference on Functional Programming (ICFP'16).
- P. Genevès has been program committee member for the 16th ACM Symposium on Document Engineering (DocEng'16).
- C. Roisin has been program committee member for the 16th ACM Symposium on Document Engineering (DocEng'16).

8.1.2.2. Reviewer

- P. Genevès has been a referee for the '32ème Conférence sur la Gestion de Données - Principes, Technologies et Applications' (BDA 2016)

8.1.3. Journal

8.1.3.1. Reviewer - Reviewing Activities

- N. Gesbert has been a referee for Logical Methods in Computer Science (LMCS).
- C. Roisin has been a referee for Journal of Visual Languages & Computing, Elsevier (JVLC).

8.1.4. Leadership within the Scientific Community

- C. Roisin is member of the section 27 of the CNU (Conseil National des Universités).

8.1.5. Scientific Expertise

Oppidoc

Title: Choice of Methods and Algorithms for XQuery Static Analyses in the Oppidum Framework

Duration: November - December 2016

Coordinator: Pierre Genevès

Abstract: The Oppidoc startup develops 'Oppidum': an XQuery web application framework which simplifies the development of XML-REST-XQuery applications (XRX) with the full XML technology stack (XQuery, XSLT, native XML database). It relies on a RESTful approach and on a well defined application model using concepts (routes, conventions, pipelines) popularized in other frameworks such as Ruby On Rails, Orbeon Forms and more recently Express on nodejs. Our collaboration concerns a study about the introduction of advanced static analyses techniques in the Oppidum development process.

8.1.6. Research Administration

- P. Genevès is co-responsible of the doctoral school of Grenoble University for Computer Science (around 400 PhD students).
- P. Genevès is a permanent member of the committee in charge of hiring research engineers at Inria Grenoble - Rhône-Alpes research center.
- N. Layaïda is 'référent budget' member of the budget commission of the Inria Grenoble – Rhône-Alpes research center. The role of this commission is to allocate yearly budget ('dotation') to Inria project teams and services. On a yearly basis, we meet with team and service leaders individually, collect their financial needs and set their budget.
- N. Layaïda is member of the Scientific Board of Advanced Data-mining of the Persyval Labex.
- N. Layaïda is member of the experts pool (selection committee) of the minalogic competitive cluster.
- N. Layaïda is a permanent member of the jury in charge of evaluation harmonisation of the Master of Science in Informatics at Grenoble.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

Master : P. Genevès, 'Semantic web: from XML to OWL', 36 h, M2, Univ. Grenoble-Alpes

Licence : N. Gesbert, 'Logique pour l'informatique', 45 h eq TD, L3, Grenoble INP

Licence : N. Gesbert, 'Bases de la programmation impérative', 33 h eq TD, L3, Grenoble INP

Licence : N. Gesbert, academic tutorship of an apprentice, 5 h eq TD, L3, Grenoble INP

Master : N. Gesbert, 'Fondements logiques pour l'informatique', 12 h eq TD, M1, Grenoble INP

Master : N. Gesbert, 'Construction d'applications Web', 22 h 30 eq TD, M1, Grenoble INP

Master : N. Gesbert, 'Analyse, conception et validation de logiciels', 41 h 15 eq TD, M1, Grenoble INP

Licence : C. Roisin, 'Programmation C', 12h eq TD, L2, IUT2, Univ. Grenoble-Alpes

Licence : C. Roisin, 'Architecture des réseaux', 112h eq TD, L1, IUT2, Univ. Grenoble-Alpes

Licence : C. Roisin, 'Services réseaux', 22h eq TD, L2, IUT2, Univ. Grenoble-Alpes

Licence : C. Roisin, 'Introduction système Linux', 21h eq TD, L1, IUT2, Univ. Grenoble-Alpes

Licence : C. Roisin, 'Système et réseaux', 14h eq TD, L3, IUT2, Univ. Grenoble-Alpes

Licence : C. Roisin, academic tutorship of four apprentices, 20h eq TD, L3, IUT2, Univ. Grenoble-Alpes

Licence : C. Roisin, academic tutorship of 18 students, 13h eq TD, L1, IUT2, Univ. Grenoble-Alpes

N. Gesbert is responsible of the L3-level course 'logique pour l'informatique' (25 apprentices) and of the M1-level course 'construction d'applications Web' (72 students).

P. Genevès is co-responsible of the Master-level course 'Semantic Web: from XML to OWL' in the Mosig, Univ. Grenoble Alpes.

C. Roisin is responsible of the Licence Professionnelle en Alternance 'Administration et Sécurité des Systèmes et des Réseaux' , L3, IUT2, Univ. Grenoble-Alpes (15 apprentices).

C. Roisin is responsible of the L1-level course 'Architecture des réseaux' (150 students).

8.2.2. Supervision

PhD : D. Graux, On the Efficient Distributed Evaluation of SPARQL Queries, Université Grenoble-Alpes, 15 December 2016, N. Layaïda and P. Genevès

PhD in progress : A. Abbas, Web query rewriting for heterogeneous data sources, since October 2014, N. Layaïda and P. Genevès

PhD in progress : T. Michel, Mobile Augmented Reality Applications for Smart Cities, since October 2014, P. Genevès, N. Layaïda and H. Fourati

PhD in progress : L. Jachiet, Reasoning with NoSQL Data Flows in Massively Parallel Systems, since October 2014, N. Layaïda and P. Genevès

8.2.3. Juries

- C. Roisin has been referee and jury member of the Mira Sarkis PhD thesis, Telecom ParisTech (oct 2016).

9. Bibliography

Major publications by the team in recent years

[1] M. BOSCH, P. GENEVÈS, N. LAYAÏDA.*Reasoning with Style*, in "International Joint Conference On Artificial Intelligence (IJCAI 2015)", Buenos Aires, Argentina, July 2015, https://hal.inria.fr/hal-01149248.

[2] S. J. GAY, N. GESBERT, A. RAVARA, V. T. VASCONCELOS.*Modular session types for objects*, in "Logical Methods in Computer Science", December 2015, vol. 4, n^{o} 12, 76 [*DOI :* 10.2168/LMCS-11(4:12)2015], https://hal.archives-ouvertes.fr/hal-00700635.

[3] P. GENEVÈS, N. GESBERT.*XQuery and Static Typing: Tackling the Problem of Backward Axes*, in "ICFP (International Conference on Functional Programming)", Vancouver, Canada, ACM SIGPLAN, August 2015 [*DOI :* 10.1145/2784731.2784746], https://hal.inria.fr/hal-01082635.

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[7] T. MICHEL, H. FOURATI, P. GENEVÈS, N. LAYAÏDA.*A Comparative Analysis of Attitude Estimation for Pedestrian Navigation with Smartphones*, in "Indoor Positioning and Indoor Navigation", Banff, Canada, October 2015, vol. 2015 International Conference on Indoor Positioning and Indoor Navigation, 10, https://hal.inria.fr/hal-01194811.

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Doctoral Dissertations and Habilitation Theses

[8] D. GRAUX.*On the Efficient Distributed Evaluation of SPARQL Queries*, Université Grenoble Alpes, December 2016, https://hal.inria.fr/tel-01405319.

Articles in International Peer-Reviewed Journal

[9] D. ANCONA, V. BONO, M. BRAVETTI, J. CAMPOS, G. CASTAGNA, P.-M. DENIÉLOU, S. J. GAY, N. GESBERT, E. GIACHINO, R. HU, E. B. JOHNSEN, F. MARTINS, V. MASCARDI, F. MONTESI, R. NEYKOVA, N. NG, L. PADOVANI, V. T. VASCONCELOS, N. YOSHIDA.*Behavioral Types in Programming Languages*, in "Foundations and Trends in Programming Languages", July 2016, vol. 3, n° 2-3, p. 95-230 [*DOI :* 10.1561/2500000031], https://hal.inria.fr/hal-01348054.

International Conferences with Proceedings

[10] D. GRAUX, P. GENEVÈS, N. LAYAÏDA.*Smart Trip Alternatives for the Curious*, in "15th International Semantic Web Conference (ISWC 2016 demo paper)", Kobe, Japan, October 2016, https://hal.inria.fr/hal-01342030.

[11] D. GRAUX, L. JACHIET, P. GENEVÈS, N. LAYAÏDA.*SPARQLGX in Action: Efficient Distributed Evaluation of SPARQL with Apache Spark*, in "15th International Semantic Web Conference (ISWC 2016 demo paper)", Kobe, Japan, October 2016, https://hal.inria.fr/hal-01358125.

[12] D. GRAUX, L. JACHIET, P. GENEVÈS, N. LAYAÏDA.*SPARQLGX: Efficient Distributed Evaluation of SPARQL with Apache Spark*, in "The 15th International Semantic Web Conference", Kobe, Japan, October 2016 [*DOI :* 10.1007/978-3-319-46547-0_9], https://hal.inria.fr/hal-01344915.

National Conferences with Proceeding

[13] D. GRAUX, L. JACHIET, P. GENEVÈS, N. LAYAÏDA.*SPARQLGX : Une Solution Distribuée pour RDF Traduisant SPARQL vers Spark*, in "BDA 2016 - 32ème Conférence sur la Gestion de Données - Principes, Technologies et Applications", Poitiers, France, November 2016, https://hal.inria.fr/hal-01412035.

Other Publications

[14] A. ABBAS, P. GENEVE`S, C. ROISIN, N. LAYAÏDA.*SPARQL Query Containment with ShEx Constraints*, October 2016, Submitted, https://hal.inria.fr/hal-01414509.

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Team URBANET

Réseaux capillaires urbains

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Networks and Telecommunications

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Team URBANET

Creation of the Team: 2012 February 01, end of the Team: 2016 December 31

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Computer Science and Digital Science:

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1.2.1. - Dynamic reconfiguration
1.2.2. - Supervision
1.2.3. - Routing
1.2.4. - QoS, performance evaluation
1.2.5. - Internet of things
1.2.6. - Sensor networks
1.4. - Ubiquitous Systems
5.11. - Smart spaces
5.11.1. - Human activity analysis and recognition
6.2.6. - Optimization
7.3. - Optimization
7.11. - Performance evaluation

Other Research Topics and Application Domains:

6.3.2. - Network protocols
6.4. - Internet of things
8. - Smart Cities and Territories
8.2. - Connected city
8.5.2. - Crowd sourcing

1. Members

Research Scientist

Hervé Rivano [Team leader, Inria, Researcher, HDR]

Faculty Members

Isabelle Auge Blum [INSA Lyon, Associate Professor]
Walid Bechkit [INSA Lyon, Associate Professor]
Razvan Stanica [INSA Lyon, Associate Professor]
Fabrice Valois [INSA Lyon, Professor, HDR]

Technical Staff

Stephane d'Alu [INSA Lyon (30%)]
Romain Pujol [INSA Lyon, from Oct. 2016]

PhD Students

Yosra Bahri Zguira [University of Sousse, Tunisia government grant]
Abderrahman Ben Khalifa [INSA Lyon, from Nov. 2016]
Ahmed Boubrima [Inria]
Soukaina Cherkaoui [Inria, ADR Green grant]
Jin Cui [INSA Lyon, Chinese Scholarship Council grant, until Jun. 2016]
Rodrigue Domga Komguem [University of Yaoundé I, AUF grant]

Alexis Duque [Rtone, CIFRE grant]
Guillaume Gaillard [Orange Labs, CIFRE grant]
Leo Le Taro [University of Lyon, IMU UrPolSens grant]
Jad Oueis [INSA Lyon]

Post-Doctoral Fellows
Angelo Furno [Inria, until Sep. 2016]
Junaid Khan [INSA Lyon, from Oct. 2016]
Anh Dung Nguyen [Inria, until Apr. 2016]

Visiting Scientist
Khaled Boussetta [Univ. Paris XIII, Associate Professor]

Administrative Assistants
Aude Montillet [Inria, until Aug. 2016 (50%)]
Caroline Tremeaud [Inria, Sep. 2016 - Nov. 2016 (50%)]
Sophie Karsai [Inria, since Dec. 2016 (50%)]

2. Overall Objectives

2.1. Introduction

This is the last activity report of the Inria UrbaNet team, which officially ended in December 2016. Team UrbaNet's overall objectives were to study and characterize the architectures of urban capillary wireless networks and to propose mechanisms and protocols that are designed for the specific settings of the urban environment. This required taking into account constraints on the node deployment, heterogeneous and dynamic wireless connectivity, and requirements yielded by the usage of the city and the societal trends. Our methodology consisted in combining formal verification and combinatorial optimization methods with simulation based and analytical performance assessments to guide the development of relevant mechanisms. We entered this experience in 2012, with a group of researchers with a background on generic multi-hop wireless networks and we end it now, after four great years, in which we initiated collaborations with experts in transportation, air pollution, urbanism, economics or robotics. These collaborations brought us closer to the real problem of networking in an urban environment and challenged our view of wireless multi-hop networks. We are now studying hybrid (short and long range communications) architectures, new communication technologies (RFID, VLC), and new networking paradigms (energy harvesting). We are focusing on the dense deployment of nodes and functionalities, and the challenges this brings. And, finally, we try to extract as much information as possible from real massive data, obtained from our collaborators or collected by us. If you are curious about how will this go, follow us as team Agora from January 2017.

3. Research Program

3.1. Capillary networks

The definition of Smart Cities is still constantly redefined and expanded so as to comprehensively describe the future of major urban areas. The Smart City concept mainly refers to granting efficiency and sustainability in densely populated metropolitan areas while enhancing citizens' life and protecting the environment. The Smart City vision can be primarily achieved by a clever integration of ICT in the urban tissue. Indeed, ICTs are enabling an evolution from the current duality between the "real world" and its digitalized counterpart to a continuum in which digital contents and applications are seamlessly interacting with classical infrastructures and services. The general philosophy of smart cities can also be seen as a paradigm shift combining the Internet of Things (IoT) and Machine-to-Machine (M2M) communication with a citizen-centric model, all together leveraging massive data collected by pervasive sensors, connected mobile or fixed devices, and social applications.

The fast expansion of urban digitalization yields new challenges that span from social issues to technical problems. Therefore, there is a significant joint effort by public authorities, academic research communities and industrial companies to understand and address these challenges. Within that context, the application layer, i.e., the novel services that ICT can bring to digital urban environments, have monopolized the attention. Lower-layer network architectures have gone instead quite overlooked. We believe that this might be a fatal error, since the communication network plays a critical role in supporting advanced services and ultimately in making the Smart City vision a reality. The UrbaNet project deals precisely with that aspect, and the study of network solutions for upcoming Smart Cities represents the core of our work.

Most network-related challenges along the road to real-world Smart Cities deal with efficient mobile data communication, both at the backbone and at the radio access levels. It is on the latter that the UrbaNet project is focused. More precisely, the scope of the project maps to that of capillary networks, an original concept we define next.

The capillary networking concept represents a unifying paradigm for wireless last-mile communication in smart cities. The term we use is reminiscent of the pervasive penetration of different technologies for wireless communication in future digital cities. Indeed, capillary networks represent the very last portion of the data distribution and collection network, bringing Internet connectivity to every endpoint of the urban tissue in the same exact way capillary blood vessels bring oxygen and collect carbon dioxide at tissues in the human body. Capillary networks inherit concepts from the self-configuring, autonomous, ad hoc networks so extensively studied in the past decade, but they do so in a holistic way. Specifically, this implies considering multiple technologies and applications at a time, and doing so by accounting for all the specificities of the urban environment.

3.2. Specific issues and new challenges of capillary networks

Capillary networks are not just a collection of independent wireless technologies that can be abstracted from the urban environment and/or studied separately. That approach has been in fact continued over the last decade, as technologies such as sensor, mesh, vehicular, opportunistic, and – generally speaking – M2M networks have been designed and evaluated in isolation and in presence of unrealistic mobility and physical layer, simplistic deployments, random traffic demands, impractical application use cases and non-existent business models. In addition, the physical context of the network has a significant impact on its performances and cannot be reduced to a simple random variable. Moreover, one of the main element of a network never appears in many studies: the user. To summarize, networks issues should be addressed from a user- and context-centric perspective.

Such abstractions and approximations were necessary for understanding the fundamentals of wireless network protocols. However, real world deployments have shown their limits. The finest protocols are often unreliable and hardly applicable to real contexts. That also partially explains the marginal impact of multi-hop wireless technologies on today's production market. Industrial solutions are mostly single-hop, complex to operate, and expensive to maintain.

In the UrbaNet project we consider the capillary network as an ensemble of strongly intertwined wireless networks that are expected to coexist and possibly co-operate in the context of arising digital cities. This has three major implications:

- Each technology contributing to the overall capillary network should not be studied apart. As a matter of fact, mobile devices integrate today a growing number of sensors (e.g., environment sensing, resource consumption metering, movement, health or pollution monitoring) and multiple radio interfaces (e.g., LTE, WiFi, ZigBee,. . .), and this is becoming a trend also in the case of privately owned cars, public transport vehicles, commercial fleets, and even city bikes. Similarly, access network sites tend to implement heterogeneous communication technologies so as to limit capital expenses. Enabling smart-cities needs a dense sensing of its activities, which cannot be achieved without multi-service sensor networks. Moreover, all these devices are expected to inter-operate so as to make the communication more sustainable and reliable. Thus, the technologies that build up the capillary network shall be studied as a whole in the future.

- The capillary network paradigm necessarily accounts for actual urban mobility flows, city land-use layouts, metropolitan deployment constraints, and expected activity of the citizens. Often, these specificities do not arise from purely networking features, but relate to the study of city topologies and road layouts, social acceptability, transportation systems, energy management, or urban economics. Therefore, addressing capillary network scenarios cannot but rely on strong multidisciplinary interactions.
- Digital and smart cities are often characterized by arising M2M applications. However, a city is, before all, the gathering of citizens, who use digital services and mobile Internet for increasing their quality of life, empowerment, and entertainment opportunities. Some data flows should be gathered to, or distributed from, an information system. Some other should be disseminated to a geographically or time constrained perimeter. Future usage may induce peer-to-peer like traffics. Moreover these services are also an enabler of new usages of the urban environment. Solutions built within the capillary network paradigm have to manage this heterogeneity of traffic requirements and user behaviors.

By following these guidelines, the UrbaNet ambition is to go one step beyond traditional approaches discussed above. The capillary network paradigm for Smart Cities is tightly linked to the specificities of the metropolitan context and the citizens' activity. Our proposal is thus to re-think the way capillary network technologies are developed, considering a broader and more practical perspective.

3.3. Characterizing urban networks

Our first objective is to understand and model those properties of real-world urban environments that have an impact on the design, deployment and operation of capillary networks. It means to collect and analyze data from actual deployments and services, as well as testbeds experiments. These data have then to be correlated with urban characteristics, e.g. topography, density of population and activities. The objective is to deduce analytical models, simulations and traces of realistic scenarios that can be leveraged afterward. We structure the axis into three tasks that correspond to the three broad categories of networking aspects affected by the urban context.

- **Topological characteristics**. Nowadays, the way urban wireless network infrastructures are typically represented in the literature is dissatisfying. As an example, wireless links are mostly represented as symmetric, lossless channels whose signal quality depends continuously on the distance between the transmitter and the receiver. No need to say, real-world behaviors are very far from these simplified representations. Another example, topologies are generally modeled according to deterministic (e.g., regular grids and lattices, or perfect hexagonal cell coverages) or stochastic (e.g., random uniform distributions over unbound surfaces) approaches. These make network problems mathematically tractable and simulations easier to set up, but are hardly representative of the layouts encountered in the real world. Employing simplistic models helps understanding some fundamental principles but risks to lead to unreliable results, both from the viewpoint of the network architecture design and from that of its performance evaluation. It is thus our speculation that the actual operations and the real-world topologies of infrastructured capillary networks are key to the successful deployment of these technologies, and, in this task, we aim at characterizing them. To that end, we leverage existing collaborations with device manufacturers (Alcatel-Lucent, HiKob) and operators (Orange), as well as collaboration such as the Sense City project and testbed experiments, in order to provide models that faithfully mimic the behavior of real world network devices. The goal is to understand the important features of the topologies, including, e.g., their overall connectivity level, spatial density, degree distribution, regularity, etc. Building on these results, we try to define network graph models that reproduce such major features and can be employed for the development and evaluation of capillary network solutions.
- **Mobilities**. We aim at understanding and modeling the mobile portion of capillary networks as well as the impact of the human mobility on the network usage. Our definition of "mobile portion" includes traditional mobile users as well as all communication-enabled devices that autonomously

interact with Internet-based servers and among themselves. There have been efforts to collect real-world movement traces, to generate synthetic mobility dataset and to derive mobility models. However, real-world traces remain limited to small scenarios or circumstantial subsets of the users (e.g., cabs instead of the whole road traffic). Synthetic traces are instead limited by their scale and by their level of realism, still insufficient. Finally, even the most advanced models cannot but provide a rough representation of user mobility in urban areas, as they do not consider the street layout or the human activity patterns. In the end, although often deprecated, random or stochastic mobility models (e.g., random walks, exponential inter-arrivals and cell residence times) are still the common practice. We are well aware of the paramount importance of a faithful representation of device and user mobility within capillary networks and, in order to achieve it, we leverage a number of realistic sources, including Call Detail Records (CDR) collected by mobile operators, Open Data initiatives, real-world social network data, and experiments. We collect data and analyze it, so as to infer the critical properties of the underlying mobility patterns.

- **Data traffic patterns**. The characterization of capillary network usages means understanding and modeling when, where and how the wireless access provided by the diverse capillary network technologies is exploited by users and devices. In other words, we are interested in learning which applications are used at different geographical locations and day times, which urban phenomena generate network usage, and which kind of data traffic load they induce on the capillary network. Properly characterizing network usages is as critical as correctly modeling network topology and mobility. Indeed, the capillary networks being the link directly collecting the data from end devices, we cannot count on statistical smoothing which yields regular distributions. Unfortunately, the common practice is to consider, e.g., that each user or device generates a constant data traffic or follows on/off models, that the offered load is uniform over space and does not vary over time, that there is small difference between uplink and downlink behaviors, or that source/destination node pairs are randomly distributed in the network. We plan to go further on the specific scenarios we address, such as smart-parking, floating car data, tele-metering, road traffic management of pollution detection. To that end, we collect real-world data, explore it and derive properties useful to the accurate modeling of content consumption.

3.4. Autonomic networking protocols

While the capillary networks concept covers a large panel of technologies, network architectures, applications and services, common challenges remain, regardless the particular choice of a technology or architecture. Our record of research on spontaneous and multi-hop networks let us think that autonomic networking appears as the main issue: the connectivity to Internet, to cyber-physical systems, to Information Systems should be transparent for the user, context-aware and location-aware. To address these challenges, a capillary network model is required. Unfortunately, very few specific models fit this task today. However, a number of important, specific capillary networks properties can already be inferred from recent experiments: distributed and localized topologies, very high node degree, dynamic network diameter, unstable / asymmetric / non-transitive radio links, concurrent topologies, heterogeneous capabilities, etc. These properties can already be acknowledged in the design of networking solutions, and they are particularly challenging for the functioning of the MAC layer and QoS support. Clearly, capillary networks provide new research opportunities with regard to networking protocols design.

- **Self-* protocols**. In this regard, self-configuration, self-organization and self-healing are some of the major concerns within the context of capillary networks. Solving such issues would allow spontaneous topologies to appear dynamically in order to provide a service depending of the location and the context, while also adapting to the interactions imposed by the urban environment. Moreover, these mechanisms have the capacity to alleviate the management of the network and the deployment engineering rules, and can provide efficient support to the network dynamics due to user mobility, environment modifications, etc. The designed protocols have to be able to react to traffic requests and local node densities. We address such self-adaptive protocols as a transversal solution to several scenarios, e.g. pollution monitoring, smart-services depending on human activities, vehicle to infrastructure communications, etc. In architectures where self-* mechanisms govern the protocol design, both robustness and energy are more than ever essential challenges at the network layer. Solutions such as energy-harvesting can significantly increase the network lifetime in this case, therefore we investigate their impact on the mechanisms at both MAC and network layers.

- **Quality of service issues**. The capillary networks paradigm implies a simultaneous deployment of multiple wireless technologies, and by different entities (industry, local community, citizens). This means that some applications and services can be provided concurrently by different parts of the capillary network, while others might require the cooperation of multiple parties. The notion of Service Level Agreement (SLA) for traffic differentiation, quality of service support (delay, reliability, etc.) is a requirement in these cases for scalability purposes and resource sharing. We contribute to a proper definition of this notion and the related network mechanisms in the settings of low power wireless devices. Because of the urban context, but also because of the wireless media itself, network connectivity is always temporary, while applications require a delivery ratio close to 100%. We investigate different techniques that can achieve this objective in an urban environment.
- **Data impact**. Capillary networks suffer from low capacity facing the increasing user request. In order to cope with network saturation, a promising strategy is to consider the nature of the transmitted data in the development of the protocols. Data aggregation and data gathering are two concepts with a major role to play in this context of limited capacity. In particular, combining local aggregation and measurement redundancy for improving on data reliability is a promising idea, which can also be important for energy saving purposes. Even if the data flow is well known and regular, e.g. temperature or humidity metering, developing aggregation schemes tailored to the constraints of the urban environment is a challenge we address within the UrbaNet team. Many urban applications generate data which has limited spatial and temporal perimeters of relevance, e.g. smart-parking applications, community information broadcasting, etc. When solely a spatial range of relevance is considered, the underlying mechanisms are denoted “geocasting”. We also address these spatio-temporal constraints, which combine geocasting approaches with real-time techniques.

3.5. Optimizing cellular network usage

The capacity of cellular networks, even those that are now being planned, does not seem able to cope with the increasing demands of data users. Moreover, new applications with high bandwidth requirements are also foreseen, for example in the intelligent transportation area, and an exponential growth in signaling traffic is expected in order to enable this data growth. Cumulated with the lack of available new spectrum, this leads to an important challenge for mobile operators, who are looking at both licensed and unlicensed technologies for solutions. The usual strategy consists in a dramatic densification of micro-cells coverage, allowing both to minimize the transmission power of cellular networks as well as to increase the network capacity. However, this solution has obvious physical limits, which we work on determining, and we propose exploiting the capillarity of network interfaces as a complementary solution.

- **Green cellular network**. Increasing the density of micro-cells means multiplying the energy consumption issues. Indeed, the energy consumption of actual LTE eNodeBs and relays, whatever their state, idle, transmitting or receiving, is a major and growing part of the access network energy consumption. For a sustainable deployment of such micro-cell infrastructures and for a significative decrease of the overall energy consumption, an operator needs to be able to switch off cells when they are not absolutely needed. The densification of the cells induces the need for an autonomic control of the on/off state of cells. One solution in this sense can be to adapt the WSN mechanisms to the energy models of micro-cells and to the requirements of a cellular network. The main difficulty here is to be able to adapt and assess the proposed solutions in a realistic environment (in terms of radio propagation, deployment of the cells, user mobility and traffic dynamics).
- **Offloading**. Offloading the cellular infrastructure implies taking advantage of the wealth of connectivity provided by capillary networks instead of relying solely on 4G connectivity. Cellular operators usually possess an important ADSL or cable infrastructure for wired services, the development of

femtocell solutions thus becomes very popular. However, while femtocells can be an excellent solution in zones with poor coverage, their extensive use in areas with a high density of mobile users leads to serious interference problems that are yet to be solved. Taking advantage of capillarity for offloading cellular data relies on using IEEE 802.11 Wi-Fi (or other similar technologies) access points or direct device-to-device communications. The ubiquity of Wi-Fi access in urban areas makes this solution particularly interesting, and many studies have focused on its potential. However, these studies fail to take into account the usually low quality of Wi-Fi connections in public areas, and they consider that a certain data rate can be sustained by the Wi-Fi network regardless of the number of contending nodes. In reality, most public Wi-Fi networks are optimized for connectivity, but not for capacity, and more research in this area is needed to correctly assess the potential of this technology. Direct opportunistic communication between mobile users can also be used to offload an important amount of data. This solution raises a number of major problems related to the role of social information and multi-hop communication in the achievable offload capacity. Moreover, in this case the business model is not yet clear, as operators would indeed offload traffic, but also lose revenue as direct ad-hoc communication would be difficult to charge and privacy issues may arise. However, combining hotspot connectivity and multi-hop communications is an appealing answer to broadcasting geo-localized informations efficiently.

4. Application Domains

4.1. Smart urban infrastructure

Unlike the communication infrastructure that went through a continuous development in the last decades, the distribution networks in our cities including water, gas and electricity are still based on 19th century infrastructure. With the introduction of new methods for producing renewable but unpredictable energy and with the increased attention towards environmental problems, modernizing distribution networks became one of the major concerns in the urban world. An essential component of these enhanced systems is their integration with information and communications technology, the result being a smart distribution infrastructure, with improved efficiency and reliability. This evolution is mainly based on the increased deployment of automatic equipment and the use of machine-to-machine and sensor-to-actuator communications that would allow taking into account the behavior and necessities of both consumers and suppliers

Another fundamental urban infrastructure is the transportation system. The progress made in the transportation industry over the last century has been an essential factor in the development of today's urban society, while also triggering the birth and growth of other economic branches. However, the current transportation system has serious difficulties coping with the continuous growth in the number of vehicles, especially in an urban environment. As a major increase in the capacity of a city road infrastructure, already in place for tens or even hundreds of years, would imply dissuasive costs, the more realistic approach is to optimize the use of the existing transportation system. As in the case of distribution networks, the intelligence of the system can be achieved through the integration of information and communication capabilities. However, for smart transportation the challenges are somehow different, because the intelligence is no longer limited to the infrastructure, but propagates to vehicles themselves. Moreover, the degree of automation is reduced in transportation systems, as most actions resulting in reduced road congestion, higher reliability or improved safety must come from the human driver (at least in the foreseeable future)

Finally, smart spaces are becoming an essential component of our cities. The classical architecture tools used to design and shape the urban environment are more and more challenged by the idea of automatically modifying private and public spaces in order to adapt to the requirements and preferences of their users. Among the objectives of this new urban planning current, we can find the transformation of the home in a proactive health care center, fast reconfigurable and customizable workplaces, or the addition of digital content in the public spaces in order to reshape the urban scene. Bringing these changing places in our daily lives is conditioned by a major shift in the construction industry, but it also involves important advancements in digital infrastructure, sensing, and communications

4.2. Urban participatory sensing

Urban sensing can be seen as the same evolution of the environment digitalization as social networking has been for information flows. Indeed, besides dedicated and deployed sensors and actuators, still required for specific sensing operations such as the real-time monitoring of pollution levels, there is a wide range of relevant urban data that can be collected without the need for new communication infrastructures, leveraging instead on the pervasiveness of smart mobile terminals. With more than 80% of the population owning a mobile phone, the mobile market has a deeper penetration than electricity or safe drinking water. Originally designed for voice transmitted over cellular networks, mobile phones are today complete computing, communication and sensing devices, offering in a handheld device multiple sensors and communication technologies.

Mobile devices such as smartphones or tablets are indeed able to gather a wealth of informations through embedded cameras, GPS receivers, accelerometers, and cellular, WiFi and bluetooth radio interfaces. When collected by a single device, such data may have small value per-se, however its fusion over large scales could prove critical for urban sensing to become an economically viable mainstream paradigm.

This is even more true when less traditional mobile terminals are taken into account: privately-owned cars, public transport means, commercial fleets, and even city bikes are starting to feature communication capabilities and the Floating Car Data (FCD) they generate can bring a dramatic contribution to the cause of urban sensing. Indeed, other than enlarging the sensing scope even further, e.g., through Electronic Control Units (ECUs), these mobile terminals are not burdened by strong energy constraints and can thus significantly increase the granularity of data collection. This data can be used by authorities to improve public services, or by citizens who can integrate it in their choices. However, in order to kindle this hidden information, important problems related to data gathering, aggregation, communication, data mining, or even energy efficiency need to be solved.

4.3. Human-centric networks

Combining location awareness and data recovered from multiple sources like social networks or sensing devices can surface previously unknown characteristics of the urban environment, and enable important new services. As a few examples, one could think of informing citizens about often disobeyed (and thus risky) traffic signs, polluted neighborhoods, or queue waiting times at current exhibitions in the urban area.

Beyond letting their own devices or vehicles autonomously harvest data from the environment through embedded or onboard sensors, mobile users can actively take part in the participatory sensing process because they can, in return, benefit from citizen-centric services which aim at improving their experience of the urban life. Crowdsourcing applications have the potential to turn citizens into both sources of information and interactive actors of the city. It is not a surprise that emerging services built on live mobile user feedback are rapidly meeting a large success. In particular, improving everyone's mobility is probably one of the main services that a smart city shall offer to its inhabitants and visitors. This implies providing, through network broadcast data or urban smart-furniture, an accurate and user-tailored information on where people should head in order to find what they are looking for (from a specific kind of shop to a free parking slot), on their current travel time estimates, on the availability of better alternate means of transport to destination. Depending on the context, such information may need to be provided under hard real-time constraints, e.g., in presence of road accidents, unauthorized public manifestations, or delayed public transport schedules.

In some cases, information can also be provided to mobile users so as to bias or even enforce their mobility: drivers can be alerted of the arrival of an emergency vehicle so that they leave the leftmost lane available, or participants leaving vast public events can be directed out of the event venue through diverse routes displayed on their smartphones so as to dynamically balance the pedestrian flows and reduce their waiting times.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

The paper by A. Boubrima *et al.* - "Cost-Precision Tradeoffs in 3D Air Pollution Mapping using WSN" received the Best Paper Award at the 2nd International Symposium on Ubiquitous Networking (UNET 2016).

Ahmed Boubrima was awarded the third place in the Best MS Thesis competition by IEEE ComSoc Chapter Francefor his work on optimal deployment of wireless sensor networks to monitor urban pollution (supervised by Walid Bechkit and Hervé Rivano).

BEST PAPERS AWARDS :

[13] **UNET 2016 - 2nd International Symposium on Ubiquitous Networking**. A. BOUBRIMA, W. BECHKIT, H. RIVANO, L. SOULHAC.

6. New Software and Platforms

6.1. PrivaMovApp

FUNCTIONAL DESCRIPTION

UrbaNet is leading the development of an Android application for user data collection purposes. The application is based on the Funf framework, and is currently available on Google Play.

- Participants: Razvan Stanica and Hervé Rivano.
- Contact: Razvan Stanica
- URL: http://liris.cnrs.fr/privamov/project/

6.2. TAPASCologne

Travel and Activity PAtterns Simulation Cologne

FUNCTIONAL DESCRIPTION

TAPASCologne is an initiative by the Institute of Transportation Systems at the German Aerospace Center (ITS-DLR), aimed at reproducing, with the highest level of realism possible, car traffic in the greater urban area of the city of Cologne, in Germany.

To that end, different state-of-art data sources and simulation tools are brought together, so to cover all of the specific aspects required for a proper characterization of vehicular traffic:

The street layout of the Cologne urban area is obtained from the OpenStreetMap (OSM) database, The microscopic mobility of vehicles is simulated with the Simulation of Urban Mobility (SUMO) software, The traffic demand information on the macroscopic traffic flows across the Cologne urban area (i.e., the O/D matrix) is derived through the Travel and Activity PAtterns Simulation (TAPAS) methodology, The traffic assignment of the vehicular flows described by the TAPASCologne O/D matrix over the road topology is performed by means of Gawron's dynamic user assignment algorithm.

- Participants: Marco Fiore and Razvan Stanica.
- Contact: Razvan Stanica
- URL: http://kolntrace.project.citi-lab.fr/

6.3. Platforms

6.3.1. Sense in the City

Sense in the city is a lightweight experimentation platform for wireless sensor networks in development. The main objective of this platform is to be easily transferable and deployable on the field. It allows a simplified deployment of the code running on the sensors and the collection of logs generated by the instrumentation of the code on a centralized database. In the early stage of the platform, the sensors are powered by small PCs, e.g. Raspberry Pis, but we are investigating the integration of energy harvesting capabilities such as solar panels.

- Participants: Khaled Boussetta, Hervé Rivano.
- Contact: Khaled Boussetta

6.3.2. Extention of the FIT IoT Lab Equipex in Tech La Doua Campus

This testbed is located in an experimentation room which belongs to the CITI laboratory and the Telecommunications Department of INSA Lyon, Villeurbanne. The target usages of this room are quite diverse: practical works with students, robots/drones testing, wireless sensor networks experimentation, Wi-Fi security evaluation, services deployment, etc. During an experimentation, this room could be shared with others practical works. Basically, we claim that this room is useful to observe the behavior of nodes with this dense interactivity. 18 M3 open nodes, 11 A8 nodes and 12 mobile on robots are available for experimentation.

- Participants: Romain Pujol, Hervé Rivano, Fabrice Valois.
- Contact: Fabrice Valois
- URL: https://www.iot-lab.info/deployment/lyon/

7. New Results

7.1. Network deployment and characterization

Participants: Ahmed Boubrima, Angelo Furno, Walid Bechkit, Khaled Boussetta, Hervé Rivano, Razvan Stanica.

7.1.1. Deployment of Wireless Sensor Networks for Pollution Monitoring

Monitoring air quality has become a major challenge of modern cities, where the majority of population lives, because of industrial emissions and increasing urbanization, along with traffic jams and heating/cooling of buildings. Monitoring urban air quality is therefore required by municipalities and by the civil society. Current monitoring systems rely on reference sensing stations that are precise but massive, costly and therefore seldom. Wireless sensor networks seem to be a good solution to this problem, thanks to sensors' low cost and autonomy, as well as their fine-grained deployment. A careful deployment of sensors is therefore necessary to get better performances, while ensuring a minimal financial cost.

We have tackled the issue of WSN deployment for air pollution monitoring in a series of papers this year. In [10], we tackled the optimization problem of sensor deployment and we proposed an integer programming model, which allows to find the optimal network topology while ensuring air quality monitoring with a high precision and the minimum financial cost. Most of existing deployment models of wireless sensor networks are generic and assume that sensors have a given detection range. This assumption does not fit pollutant concentrations sensing. Our model takes into account interpolation methods to place sensors in such a way that pollution concentration is estimated with a bounded error at locations where no sensor is deployed. This solution was further tested and evaluated on a data set of the Lyon city [9], giving insights on how to establish a good compromise between the deployment budget and the precision of air quality monitoring.

In practice, multiple pollution sources can be present in an area. For this reason, in [11] we propose to apply a spatial clustering algorithm to the air pollution data in order to determine pollution zones that are due to the same pollutant sources and group them together to find candidate sites for the deployment of sensors. This approach was tested on real world data, namely the Paris pollution data, which was recorded in March 2014.

A very important deployment parameter is the height at which the sensor is placed. In [12], we demonstrate the impact of this parameter, usually neglected in the literature. This pushed us to study a 3D deployment model, based on an air pollution dispersion model issued from real experiments, performed in wind tunnels emulating the pollution emitted by a steady state traffic flow in a typical street canyon.

7.1.2. Access Point Deployment

The problem of designing wireless local networks (WLANs) involves deciding where to install the access points (APs), and assigning frequency channels to them with the aim to cover the service area and to guarantee enough capacity to users. In [5], we propose different solutions to the problems related to the WLAN design. In the first part, we focus on the problem of designing a WLAN by treating separately the AP positioning and the channel assignment problems. For the AP positioning issue, we formulate it as a set covering problem. Since the computation complexity limits the exact solution, we propose two heuristics to offer efficient solutions. On the other hand, for the channel assignment, we define this issue as a minimum interference frequency assignment problem and propose three heuristics: two of them aim to minimize the interference at AP locations, and the third one minimizes the interference at the TPs level. In the second part, we treat jointly the two aforementioned issues based on the concept of virtual forces. In this case, we start from an initial solution provided by the separated approach and try to enhance it by adjusting the APs positions and reassigning their operating frequencies.

7.1.3. Mobile Traffic Analysis

The analysis of operator-side mobile traffic data is a recently emerged research field, and, apart a few outliers, relevant works cover the period from 2005 to date, with a sensible densification over the last four years. In [8], we provided a thorough review of the multidisciplinary activities that rely on mobile traffic datasets, identifying major categories and sub-categories in the literature, so as to outline a hierarchical classification of research lines and proposing a complete introductory guide to the research based on mobile traffic analysis.

The usage of these datasets in the design of new networking solutions, in order to achieve the so-called cognitive networking paradigm, is one of the most important applications of these analytics methods. In fact, cognitive networking techniques root in the capability of mining large amounts of mobile traffic data collected in the network, so as to understand the current resource utilization in an automated manner and realize a more dynamic management of network resources, that adapts to the significant spatiotemporal fluctuations of the mobile demand. In [6], we take a first step towards cellular cognitive networks by proposing a framework that analyzes mobile operator data, builds profiles of the typical demand, and identifies unusual situations in network-wide usages. We evaluate our framework on two real-world mobile traffic datasets, and show how it extracts from these a limited number of meaningful mobile demand profiles. In addition, the proposed framework singles out a large number of outlying behaviors in both case studies, which are mapped to social events or technical issues in the network.

7.2. Data Collection in Multi-hop Networks

Participants: Jin Cui, Jad Oueis, Hervé Rivano, Razvan Stanica, Fabrice Valois.

7.2.1. Data Aggregation in Wireless Sensor Networks

Wireless Sensor Networks (WSNs) have been regarded as an emerging and promising field in both academia and industry. Currently, such networks are deployed due to their unique properties, such as self-organization and ease of deployment. However, there are still some technical challenges needed to be addressed, such as energy and network capacity constraints. Data aggregation, as a fundamental solution, processes information at sensor level as a useful digest, and only transmits the digest to the sink. The energy and capacity consumptions are reduced due to less data packets transmission.

As a key category of data aggregation, aggregation function, solving how to aggregate information at sensor level, was investigated in the Ph.D. thesis of Jin Cui [1]. In this work, we make four main contributions: firstly, we propose two new networking-oriented metrics to evaluate the performance of aggregation function: aggregation ratio and packet size coefficient. Aggregation ratio is used to measure the energy saving by data aggregation, and packet size coefficient allows to evaluate the network capacity change due to data aggregation. Using these metrics, we confirm that data aggregation saves energy and capacity whatever the routing or MAC protocol is used. Secondly, to reduce the impact of sensitive raw data, we propose a data-independent aggregation method which benefits from similar data evolution and achieves better recovered fidelity. This solution, named Simba, is detailed in [15] as well. Thirdly, a property-independent aggregation function is proposed to adapt the dynamic data variations. Comparing to other functions, our proposal can fit the latest raw data better and achieve real adaptability without assumption about the application and the network topology. Finally, considering a given application, a target accuracy, we classify the forecasting aggregation functions by their performance. The networking-oriented metrics are used to measure the function performance, and a Markov Decision Process is used to compute them. Dataset characterization and classification framework are also presented to guide researcher and engineer to select an appropriate functions under specific requirements.

7.2.2. Energy Harvesting in Wireless Sensor Networks

Energy harvesting capabilities are challenging our understanding of wireless sensor networks by adding recharging capacity to sensor nodes. This has a significant impact on the communication paradigm, as networking mechanisms can benefit from these potentially infinite renewable energy sources. In [23], we study photovoltaic energy harvesting in wireless sensor networks, by building a harvesting analytical model, linking three components: the environment, the battery, and the application. Given information on two of the components, limits on the third one can be determined. To test this model, we adopt several use cases with various indoor and outdoor locations, battery types, and application requirements. Results show that, for predefined application parameters, we are able to determine the acceptable node duty cycle given a specific battery, and vice versa. Moreover, the suitability of the deployment environment (outdoor, well lighted indoor, poorly lighted indoor) for different application characteristics and battery types is discussed .

In a second contribution [22], we study the consequences of implementing photovoltaic energy harvesting on the duty cycle of a wireless sensor node, in both outdoor and indoor scenarios. We show that, for the static duty cycle approach in outdoor scenarios, very high duty cycles, in the order of tens of percents, are achieved. This further eliminates the need for additional energy conservation schemes. In the indoor case, our analysis shows that the dynamic duty cycle approach based solely on the battery residual energy does not necessarily achieve better results than the static approach. We identify the main reasons behind this behavior, and test new design considerations by adding information on the battery level variation to the duty cycle computation. We demonstrate that this approach always outperforms static solutions when perfect knowledge of the harvestable energy is assumed, as well as in realistic deployments, where this information is not available.

7.2.3. Data Collection with Moving Nodes

Patrolling with mobile nodes (robots, drones, cars) is mainly used in situations where the need of repeatedly visiting certain places is critical. In [24], we consider a deployment of a wireless sensor network (WSN) that cannot be fully meshed because of the distance or obstacles. Several robots are then in charge of getting close enough to the nodes in order to connect to them, and perform a patrol to collect all the data in time. We discuss the problem of multi-robot patrolling within the constrained wireless networking settings. We show that this is fundamentally a problem of vertex coverage with bounded simple cycles (CBSC). We offer a formalization of the CBSC problem and prove it is NP-hard and at least as hard as the Traveling Salesman Problem (TSP). Then, we provide and analyze heuristics relying on clusterings and geometric techniques. The performances of our solutions are assessed in regards to robot limitations (storage and energy), networking parameters, but also to random and particular graph models.

Also related to data collection, in [3], we advocate the use of conventional vehicles equipped with storage devices as data carriers whilst being driven for daily routine journeys. The road network can be turned into a large-capacity transmission system to offload bulk transfers of delay-tolerant data from the Internet. The challenges we address include how to assign data to flows of vehicles and while coping with the complexity of the road network. We propose an embedding algorithm that computes an offloading overlay where each logical link spans over multiple stretches of road from the underlying road infrastructure. We then formulate the data transfer assignment problem as a novel linear programming model we solve to determine the optimal logical paths matching the performance requirements of a data transfer. We evaluate our road traffic allocation scheme using actual road traffic counts in France. The numerical results show that 20% of vehicles in circulation in France equipped with only one Terabyte of storage can offload Petabyte transfers in a week.

7.2.4. Network Resilience

The notion of Shared Risk Link Groups (SRLG) captures survivability issues when a set of links of a network may fail simultaneously. The theory of survivable network design relies on basic combinatorial objects that are rather easy to compute in the classical graph models: shortest paths, minimum cuts, or pairs of disjoint paths. In the SRLG context, the optimization criterion for these objects is no longer the number of edges they use, but the number of SRLGs involved. Unfortunately, computing these combinatorial objects is NP-hard and hard to approximate with this objective in general. Nevertheless some objects can be computed in polynomial time when the SRLGs satisfy certain structural properties of locality which correspond to practical ones, namely the star property (all links affected by a given SRLG are incident to a unique node) and the span 1 property (the links affected by a given SRLG form a connected component of the network). The star property is defined in a multi-colored model where a link can be affected by several SRLGs while the span property is defined only in a mono-colored model where a link can be affected by at most one SRLG. In [4], we extend these notions to characterize new cases in which these optimization problems can be solved in polynomial time. We also investigate the computational impact of the transformation from the multi-colored model to the mono-colored one. Experimental results are presented to validate the proposed algorithms and principles.

7.3. Networks in the Internet of Things

Participants: Soukaina Cherkaoui, Alexis Duque, Guillaume Gaillard, Hervé Rivano, Razvan Stanica, Fabrice Valois.

7.3.1. Service Level Agreements in the Internet of Things

With the growing use of distributed wireless technologies for modern services, the deployments of dedicated radio infrastructures do not enable to ensure large-scale, low-cost and reliable communications. The Ph.D. thesis of Guillaume Gaillard [2] aims at enabling an operator to deploy a radio network infrastructure for several client applications, hence forming the Internet of Things (IoT). We evaluate the benefits earned by sharing an architecture among different traffic flows, in order to reduce the costs of deployment, obtaining a wide coverage through efficient use of the capacity on the network nodes. We thus need to ensure a differentiated Quality of Service (QoS) for the flows of each application.

We propose to specify QoS contracts, namely Service Level Agreements (SLAs), in the context of the IoT. SLAs include specific Key Performance Indicators (KPIs), such as the transit time and the delivery ratio, concerning connected devices that are geographically distributed in the environment. The operator agrees with each client on the sources and amount of traffic for which the performance is guaranteed. Secondly, we describe the features needed to implement SLAs on the operated network, and we organize them into an SLA management architecture. We consider the admission of new flows, the analysis of current performance and the configuration of the operator's relays. Based on a robust, multi-hop technology, IEEE Std 802.15.4-2015 TSCH mode, we provide two essential elements to implement the SLAs : a mechanism for the monitoring of the KPIs [19], and KAUSA, a resource allocation algorithm with multi-flow QoS constraints [18]. The former uses existing data frames as a transport medium to reduce the overhead in terms of communication resources. We compare different piggybacking strategies to find a tradeoff between the performance and the efficiency of the monitoring. With the latter, KAUSA, we dedicate adjusted time-frequency resources for each message, hop by hop. KAUSA takes into account the interference, the reliability of radio links and the expected load to improve the distribution of allocated resources and prolong the network lifetime [17]. We show the gains and the validity of our contributions with a simulation based on realistic traffic scenarios and requirements.

7.3.2. Channel Access in Machine-to-Machine Communications

The densification of the urban population and the rise of smart cities applications foster the need for capillary networks collecting data from sensors monitoring the cities. Among the multiple networking technologies considered for this task, cellular networks, such as LTE-A, bring an ubiquitous coverage of most cities. It is therefore necessary to understand how to adapt LTE-A, and what should be the future 5G architecture, in order to provide efficient connectivity to Machine-to-Machine (M2M) devices alongside the main target of mobile networks, Human-to-Human devices. Indeed, cellular random access procedures are known to suffer from congestion in presence of a large number of devices, while smart cities scenarios expect huge density of M2M devices. Several solutions have been investigated for the enhancement of the current LTE-A access management strategy. In [14], we contribute to the modeling and computation of the capacity of the LTE-A Random Access Channel (RACH) in terms of simultaneous successful access. In particular, we investigate the hypothesis of piggybacking the payload of Machine Type Communications from M2M devices within the RACH, and show that M2M densities considered realistic for smart cities applications are difficult to sustain by the current LTE-A architecture.

7.3.3. Visible Light Communications in the Internet of Things

The Internet of Things connects devices, such as everyday consumer objects, enabling information gathering and improved user experience. Also, this growing and dynamic market makes that consumers nowadays expect electronic products, even the cheapest, to include wireless connectivity. However, despite the fact that radio based solutions exist, such as Bluetooth Low Energy, the manufacturing costs introduced by these radio technologies are non-negligible compared to the initial product price. As most of the home electronics already integrate small light emitting diodes, Visible Light Communication appears as a competitive alternative. However, its broad adoption is suffering from a lack of integration with smartphones, which represent the communication hubs for most of the users. To overcome this issue, in [16], we propose a line of sight LED-to-camera communication system based on a small color LED and a smartphone. We design a cheap prototype as proof of concept of a near communication framework for the Internet of Things. We evaluate the system performance, its reliability and the environment influence on the LED-to-camera communication, highlighting that a throughput of a few kilobits per second is reachable. Finally, we design a real time, efficient LED detection and image processing algorithm to leverage the specific issues encountered in the system.

7.3.4. Radio Frequency Identification in Dense Environments

Radio Frequency Identification (RFID) is another cheap technology shaping the Internet of Things. The rapid development of RFID has allowed its large adoption and led to increasing deployments of RFID solutions in diverse environments under varying scenarios and constraints. The nature of these constraints ranges from the amount to the mobility of the readers deployed, which in turn highly affects the quality of the RFID system, causing reading collisions. However, the technology suffers from a recurring issue: the reader-to-reader collisions. Numerous protocols have been proposed to attempt to reduce them, but remaining reading errors still heavily impact the performance and fairness of dense RFID deployments.

In order to ensure collision-free reading, a scheduling scheme is needed to read tags in the shortest possible time. In [25], we study this scheduling problem in a stationary setting and the reader minimization problem in a mobile setting. We show that the optimal schedule construction problem is NP-complete and provide an approximation algorithm that we evaluate our techniques through simulation. Moving closer to practical solutions, [20] introduces a new Distributed Efficient & Fair Anticollision for RFID (DEFAR) protocol. DEFAR reduces both monochannel and multichannel collisions, as well as interference, by a factor of almost 90% in comparison with the best state of the art protocols. The fairness of the medium access among the readers is improved to a 99% level. Such improvements are achieved by applying a TDMA-based "server-less" approach and assigning different priorities to readers depending on their behavior over precedent rounds. A distributed reservation phase is organized between readers with at least one winning reader afterwards. Then, multiple reading phases occur within a single frame in order to obtain fast coverage and high throughput. The use of different reader priorities based on reading behaviors of previous frames also contributes to improve both fairness and efficiency.

Another type of collisions appears when the RFID tags are not only dense, but also mobile. mDEFAR [21] is an adaptation of DEFAR, while CORA [7] is more of a locally mutual solution where each reader relies on its neighborhood to enable itself or not. Using a beaconing mechanism, each reader is able to identify potential (non-)colliding neighbors in a running frame and as such chooses to read or not. Performance evaluation shows high performance in terms of coverage delay for both proposals quickly achieving 100% coverage depending on the considered use case while always maintaining consistent efficiency levels above 70%. Compared to the state of the art, our solutions proved to be better suited for highly dense and mobile environments, offering both higher throughput and efficiency. The results reveal that depending on the application considered, choosing either mDEFAR or CORA helps improve efficiency and coverage delay.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

- We have contracted bilateral cooperation with Rtone, an SME focusing on the connected objects area. This collaboration is associated with the CIFRE PhD grant for Alexis Duque, on the subject of Visible Light Communication.
- We have contracted bilateral cooperation with industrial and academic partners in the context of the PSPC Fed4PMR project (2015-2018). In this context, we are working on the design of new professional mobile radio solutions, compatible with 4G and 5G standards. This collaboration funds the PhD thesis of Jad Oueis and a part of the PhD thesis of Abderrahman Ben Khalifa.

8.2. Bilateral Grants with Industry

- Common Laboratory Inria/Nokia Bell Labs - ADR Green.
  UrbaNet is part of the ADR Green of the common laboratory Inria/Nokia Bell Labs. This ADR provides the PhD grant of Soukaina Cherkaoui on the channel access capacity evaluation in 5G networks.
- Spie - INSA Lyon IoT Chaire.
  Urbanet is involved in the SPIE INSA Lyon IoT Chaire, launched in November 2016. The PhD thesis work of Alexis Duque and Abderrahman Ben Khalifa are our main contributions in this structure.
- Volvo - INSA Lyon Chaire.
  Urbanet is involved in the Volvo Chaire at INSA Lyon, on the area of autonomous electrical distribution vehicle in urban environments. Razvan Stanica is a member in the steering committee of this structure.

9. Partnerships and Cooperations

9.1. Regional Initiatives

- BQR INSA CROME 12/2013-12/2016
  Participants: Fabrice Valois
  The partners in this project are the CITI DynaMid team and LIRIS. The project studies the coordination of a fleet of mobile robots for the multi-view analysis of complex scenes.
- Labex IMU Priva'Mov 10/2013-10/2016
  Participants: Stéphane D'Alu, Hervé Rivano, Razvan Stanica
  The partners in this project are DRIM LIRIS, Inria Privatics, INSA EVS, and LET ENTPE. The aim of this project is to develop and deploy a crowdsensing platform to collect mobility traces from a sample of real users equipped with android devices, while carrying research on privacy preservation issues. Our contribution consists on developing the platform and using the collected data to analyze cellular network offloading strategies.

- Labex IMU UrPolSens 10/2015-10/2018
  Participants: Ahmed Boubrima, Leo Le Taro, Walid Bechkit, Hervé Rivano
  The partners in this project are Ifsttar, LMFA, EVS, TUBA, and Air Rhone-Alpes, with Inria Urbanet leading the project. UrPolSens deals with the monitoring of air pollution using low-cost sensors interconnected by a wireless networks. Although they are less accurate than the high-end sensors used today, low-cost autonomous air quality sensors allow to achieve a denser spatial granularity and, hopefully, a better monitoring of air pollution. The main objectives of this project are to improve the modeling of air pollution dispersion; propose efficient models to optimize the deployment the sensors while considering the pollution dispersion and the impact of urban environment on communications; deploy a small-scale network for pollution monitoring as a proof of concept; compare the measured and estimated levels of exposure; study the spatial disparities in exposure between urban areas.
- Capt-PolAir 01/2016-12/2016
  PEPS project CNRS and Université de Lyon
  Participants: Ahmed Boubrima, Leo Le Taro, Walid Bechkit, Hervé Rivano
  The partners in this project are Ifsttar, LMFA, EVS, and TUBA, with Inria Urbanet leading the project. This project deals with the practical issues of the low cost wireless sensor deployment for air pollution monitoring. This projet complete the experimental part of UrPolSens.
- ARC6 “Robot fleet mobility under communication constraints” 10/2016-09/2019
  Participants: Fabrice Valois
  This work is a joint project with the Inria Chroma research group. Considering a fleet of drones moving in a 3D area, looking for a given target, we focus on how to maintain the wireless connectivity of the network of drones while the drones patroll autonomously.The other partners in this project are University of Grenoble and Viameca.

9.2. National Initiatives

9.2.1. ANR

- ANR ABCD 10/2013-04/2017.
  Participants: Angelo Furno, Anh-Dung Nguyen, Razvan Stanica
  The partners in the ANR ABCD project are: Orange Labs, Ucopia, Inria UrbaNet, UPMC LIP6 PHARE, Telecom ParisTech. The objective of ABCD is to characterize large-scale user mobility and content consumption in urban areas via mobile data mining, so as to achieve efficient deployment and management of cloud resources via virtual machines. Our contribution in the project consists on the characterization of human mobility and service consumption at a city scale, and the design of appropriate resource allocation techniques at the cellular network level.
- ANR IDEFIX 10/2013-04/2017.
  Participants: Soukaina Cherkaoui, Hervé Rivano, Fabrice Valois
  The partners in the ANR IDEFIX project are: Orange Labs, Alcatel Lucent - Bell Labs, Telecom Paris Tech, Inria UrbaNet, Socrate and Dyogene.

9.2.2. DGA

- DGA CLOTHO 10/2016-03/2018.
  Particpants: Junaid Khan, Romain Pujol, Razvan Stanica, Fabrice Valois
  The partners in the DGA CLOTHO project are Traqueur and Sigfox. The objective of the project is to reduce the energy consumption of the device tracking functionality, by taking profit of short-range communications between the tracked objects.

9.2.3. PIA

- PIA ADAGE 07/2016-06/2018.
  Particpants: Razvan Stanica
  The partners in the PIA ADAGE project are Orange, LAAS-CNRS and Inria Privatics. The objective of the ADAGE project is to design and evaluate anonymization algorithms for the specific case of mobile traffic data. Our role in the project is focused on evaluating whether the anonymized data is still usable for adaptive networking mechanisms.

9.2.4. Pôle ResCom

- Ongoing participation (since 2006)
  Communication networks, working groups of GDR ASR/RSD, CNRS (http://rescom.inrialpes.fr). Hervé Rivano is member of the scientific committee of ResCom.

9.2.5. EquipEx

- SenseCity
  We have coordinated the participation of several Inria teams to the SenseCity EquipEx. Within the SenseCity project, several small reproduction of 1/3rd scale city surroundings will be built under a climatically controlled environment. Micro and nano sensors will be deployed to experiment on smart cities scenarios, with a particular focus on pollution detection and intelligent transport services. Urbanet will have the opportunity to tests some of its capillary networking solutions in a very realistic but controlled urban environment. A proof of concept test site has been built in 2015. We have deployed an experiment on low cost sensor network for vehicle detection and one on atmospheric pollution sensor calibration. The operational site is under construction and should be finalized in 2017.

9.2.6. Inria Project lab

- CityLab
  Urbanet is involved in the CityLab Inria Project Lab lead by Valérie Issarny. Within this project, Hervé Rivano co-advises, with Nathalie Mitton (FUN team, Inria Lille-Nord-Europe), the PhD thesis of Abdoul Aziz Mbacke on "Data gathering in sensor and passive RFID with energy harvesting for urban infrastructure monitoring".

9.3. International Initiatives

9.3.1. Inria International Partners

9.3.1.1. Informal International Partners

- **University of Waterloo, ON, Canada**. Joint publications and visits to/from the group of Prof. Catherine Rosenberg.
- **CNR-IEIIT, Turin, Italy**. Joint publications and projects with Dr. Marco Fiore.
- **IMDEA Networks, Madrid, Spain**. Collaboration around the OpenVLC platform with the group of Dr. Domenico Giustiniano.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

- Catherine Rosenberg, Professor, University of Waterloo, Canada: invited professor at INSA Lyon (Spring semester, 2016).
- Michele Noguiera, Professor, University of Parana, Brazil : visiting professor (one week, February 2016).
- Wei Wennie Shu, Professor, University of New Mexico, USA : visiting professor (one month, December 2016).

- Min-You Wy, Professor, University of Shanghai Jiao Tong, China : visiting professor (one month, December 2016).

9.4.2. Visits to International Teams

9.4.2.1. Research Stays Abroad

- Alexis Duque visited the group of Dr. Domenico Giustinano, at IMDEA Networks, Madrid, Spain (one week, Nov. 2016).
- Alexis Duque visited the group of Prof. Josep Paradells Aspas, at Universitat Politecnica de Catalunya, Barcelona, Spain (one week, Nov. 2016).

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

- Razvan Stanica was general co-chair of CoRes 2016, the first French national conference on protocol design, performance evaluation and experimentation, held in Bayonne in May 2016.

10.1.2. Scientific Events Selection

10.1.2.1. Chair of Conference Program Committees

- Razvan Stanica was the co-chair of the track "Vehicular and Delay Tolerant Networks" at the Wireless Days 2016 conference, held in Toulouse in March 2016.

10.1.2.2. Member of the Conference Program Committees

- Walid Bechkit was in the TPC of IEEE ICC and IEEE GlobeCom.
- Razvan Stanica was in the TPC of the following conferences: IEEE ICC, IEEE GlobeCom, IEEE VTC Spring/Fall, AdHoc-Now, GIIS, IEEE ISC2, IEEE UIC, WF-IoT.
- Fabrice Valois was in the TPC of the following conferences: IEEE Globecom, IEEE ICC, IEEE ICT, IEEE WCNC, IEEE WCMC, WiSARN.

10.1.2.3. Reviewer

- Razvan Stanica was a reviewer for IEEE Infocom and IEEE WoWMoM.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- Razvan Stanica was Guest Editor for the Elsevier Computer Communication special issue on Mobile Traffic Analytics.
- Fabrice Valois is Associated Editor for Annals of Telecommunications.

10.1.3.2. Reviewer - Reviewing Activities

- Walid Bechkit was a reviewer for ACM Transactions on Sensor Networks, Journal of Network and Computer Applications (Elsevier), Journal of Network and Systems Management, Telecommunication Systems.
- Razvan Stanica was a reviewer for the following journals: IEEE Transactions on Mobile Computing, IEEE Communications Magazine, IEEE Transactions on Big Data, IEEE Transactions on Vehicular Technology, Vehicular Communications, Wireless Networks, China Communications, Frontiers of Information Technology & Electronic Engineering.

10.1.4. Invited Talks

- Hervé Rivano was an invited speaker at the Intelligent Internet of Things Showroom (SIDO), Lyon, April 2016.
- Hervé Rivano gave an invited talk at the inauguration of the Sense City EquipEx, Paris, April 2016.
- Hervé Rivano gave an invited talk at the UCN@Sophia Labex seminar, Sophia Antipolis, April 2016.
- Hervé Rivano was an invited speaker at the Inria Alumni jam session on IoT, Paris, November 2016.
- Fabrice Valois gave a talk on the "Scientific Challenges of IoT: the viewpoint of the CITI Lab.", CA Foundation INSA Lyon, September 2016.

10.1.5. Leadership within the Scientific Community

- Hervé Rivano is member of the steering committee of the ResCom axis of the RSD CNRS GdR.
- Hervé Rivano is a member of the Scientific Council of TUBA Lyon.
- Fabrice Valois is a member of the Scientific Council of the LIMOS-UMR6158 laboratory, Clermont Ferrand.
- Fabrice Valois is member of the Scientifc Council of the Labex IMU (Intelligence des Mondes Urbains).
- Fabrice Valois is in the steering committee of the Féderation d'Information de Lyon (FR 2000 CNRS).

10.1.6. Scientific Expertise

- Walid Bechkit was a reviewer for ANRT for Cifre PhD thesis.
- Hervé Rivano was a reviewer for the Sino-French call for project of the Joint Research Institute for Science and Society.
- Razvan Stanica was a reviewer for the following calls: ANR appel générique (France), ANRT Cifre (France), CETIC (Cameroun).
- Fabrice Valois was a reviewer for ANRT for Cifre PhD thesis.

10.1.7. Research Administration

- Walid Bechkit is responsible for seminar organization and scientific animation within the CITI laboratory.
- Hervé Rivano is member of the Administration Council of the EquipEx Sense City as representative of Inria.
- Hervé Rivano is member in the CITI laboratory council.
- Razvan Stanica is the CITI laboratory correspondent with the Labex IMU.
- Razvan Stanica is member of the steering committee of the Volvo Chaire at INSA Lyon.
- Fabrice Valois is director of the CITI research laboratory of INSA Lyon.
- Fabrice Valois is in the steering committee of the SPIE INSA Lyon IoT Chaire.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence : Isabelle Augé-Blum, Operating Systems, 70h, L3, Telecom. Dpt. INSA Lyon.

Licence : Walid Bechkit, IP Networks, 40h, L3, Telecom. Dpt. INSA Lyon.

Licence : Hervé Rivano, IP Networks, 34h, L3, Telecom. Dpt. INSA Lyon.

Licence : Razvan Stanica, Network Programming, 90h, L3, Telecom. Dpt. INSA Lyon.

Licence : Razvan Stanica, Advanced Wireless Networks, 20h, L3, IST / Telecom. Dpt. INSA Lyon (lectures given in english).

Licence : Fabrice Valois, IP Networks, 100h, L3, Telecom. Dpt. INSA Lyon.

Licence : Fabrice Valois, IP Networks, 20h, L3, IST / Telecom. Dpt. INSA Lyon (lectures given in english).

Master : Isabelle Augé-Blum, Innovation project, 30h, M1, Telecom. Dpt. INSA Lyon.

Master : Isabelle Augé-Blum, Bibliographical study, 30h, M1, Telecom. Dpt. INSA Lyon.

Master : Isabelle Augé-Blum, Real-Time Networks, 25h, M2, Telecom. Dpt. INSA Lyon.

Master : Walid Bechkit, Network architectures, protocols and services, 12h, M1, Telecom. Dpt. INSA Lyon.

Master : Walid Bechkit, Performance evaluation of telecom networks, 100h, M1, Telecom. Dpt. INSA Lyon.

Master : Walid Bechkit, Wireless multihop networks, 10h, M2, University of Lyon.

Master : Walid Bechkit, Wireless networks: architecture and security, 18h, M2, INSA Lyon.

Master: Hervé Rivano, Wireless multihop networks, 10h, M2, University of Lyon.

Master: Hervé Rivano, Smart Cities, 4h, M2, Polytech Perpignan.

Master: Hervé Rivano, Smart Cities and IoT, 48h, M2, Telecom. Dpt. INSA Lyon.

Master : Razvan Stanica, Mobile Networks, 30h, M1, Telecom. Dpt. INSA Lyon.

Master : Razvan Stanica, Network Science, 10h, M2, Telecom. Dpt. INSA Lyon.

Master : Fabrice Valois, Mobile Networks, 30h, M1, Telecom. Dpt. INSA Lyon.

Master : Fabrice Valois, Wireless Sensor Networks, 6h, M2, University of Grenoble.

Isabelle Augé-Blum is in charge of the foreign affairs of the Telecommunications department at INSA Lyon, coordinating all incoming and outgoing student exchange programs.

Hervé Rivano is responsible for the coordination of all courses in the Smart Cities and IoT option at the INSA Lyon Telecommunications department.

Razvan Stanica is responsible for the administrative part related to all Master projects prepared by INSA Lyon Telecommunications department students.

Razvan Stanica is responsible of the research option at the Telecommunications department of INSA Lyon.

Fabrice Valois is responsible of the networking teaching team in the Telecommunications department at INSA Lyon, coordinating all the courses in the networking domain.

Fabrice Valois and Walid Bechkit are elected members of the Telecommunications Department Council at INSA Lyon.

10.2.2. Supervision

PhD : Jin Cui, Data aggregation in wireless sensor networks, INSA Lyon, 06/2016. Advisor: Fabrice Valois.

PhD : Guillaume Gaillard, Opérer les réseaux de l'Internet des Objets à l'aide de contrats de qualité de service (Service Level Agreements), INSA Lyon, 12/2016. Advisors:Dominique Barthel (Orange Labs), Fabrice Theoleyre (I-Cube CNRS), Fabrice Valois.

PhD in progress : Yosra Bahri Zguira, DTN for IoT, since 05/2015. Advisors: Aref Meddeb (Univ. Sousse, Tunisia), Hervé Rivano.

PhD in progress: Abderrahman Ben Khalifa, Cognitive mechanisms for IoT networks. Advisors: Hervé Rivano, Razvan Stanica.

PhD in progress: Ahmed Boubrima, Optimal deployment of wireless sensor networks for air pollution monitoring, since 10/2015. Advisors: Walid Bechkit, Hervé Rivano.

PhD in progress : Soukaina Cherkaoui, Energy-saving strategies for backhaul networks, since 11/2013. Advisor: Hervé Rivano.

PhD in progress : Rodrigue Domga Komguem, Autonomous WSN architectures for road traffic applications, since 11/2012. Advisors: Razvan Stanica, Maurice Tchuente (Univ. Yaoundé, Cameroun), Fabrice Valois.

PhD in progress : Alexis Duque, Use of visible light communication in a smart city context, since 10/2015. Advisors: Hervé Rivano, Razvan Stanica.

PhD in progress : Leo Le Taro, Recalibration of wireless sensors for pollution monitoring, since 11/2015. Advisor: Hervé Rivano.

PhD in progress: Abdul Aziz Mack, Data gathering in sensor and passive RFID with energy harvesting for urban infrastructure monitoring, since 10/2016. Advisors: Nathalie Mitton (FUN team), Hervé Rivano.

PhD in progress: Jad Oueis, Systèmes PMR très haut débit fédérateurs, since 10/2015. Advisors: Razvan Stanica, Fabrice Valois.

PhD in progress: Mihai Popescu, Mobilité au sein de flottes de robots sous contrainte de maintien de la connectivité, since 11/2015. Advisors: Olivier Simonin (Inria CHROMA), Anne Spalanzanni (Inria CHROMA), Fabrice Valois.

MS thesis: T.Alias, Univ. Bretagne Sud, Resource Allocation in Cloud RAN, 07/2016. Advisors: Hervé Rivano, Razvan Stanica.

MS thesis: M Biteau, Data Gathering in Linear WSN, 01/2016. Advisors: Isabelle Augé-Blum, Walid Bechkit.

MS thesis: L. Bontemps, INSA Lyon, Anonymization of Mobile Traffic Datasets, 10/2016. Advisors: Razvan Stanica.

MS thesis: N. Chovelon, INSA Lyon, Control Traffic Model for LTE Core Networks, 06/2016. Advisors: Razvan Stanica, Fabrice Valois.

MS thesis: A. Mermouri, INSA Lyon, User Mobility in Virtualized Cellular Networks, 10/2016. Advisors: Razvan Stanica.

10.2.3. Juries

- Hervé Rivano was reviewer in the following PhD defense committee:
  - L. Wang, Facilitating Mobile Crowdsensing from both Organizers' and Participants' Perspectives, Télécom SudParis and Université Pierre et Marie Curie – Paris 6, 05/2016.
- Razvan Stanica was member in the following PhD defense committee:
  - M. Abualhoul, Visible Light and Radio Communication for Cooperative Autonomous Driving, Mines Paris Tech, Université Paris Sciences et Lettres, 12/2016.
- Fabrice Valois was reviewer in the following PhD defense committee:
  - M. G. Chalhoub, Enhanced Communication in Data Collection Multihop WSN, LIMOS, Univ. Clermont Ferrand, 07/2016.
- Fabrice Valois was member in the following PhD defense committee:
  - M. B. Tian, Data Dissemination Protocols and Mobility Model for VANETs, LIMOS, Univ. Clermont Ferrand, 10/2016.

10.3. Popularization

- Hervé Rivano has been involved in several popularization actions, in particular with the Grand Lyon metropolis (on air quality monitoring, smart cities infrastructure), SPL Lyon Part Dieu (on sensors networks), the TUBA (on sensors, mobility, networking), and Cité du Design et de l'Industrie.
- Hervé Rivano was a panelist at a pubic debate on "revolutions in education, culture, thinking and public space".

11. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] J. CUI.*Data Aggregation in Wireless Sensor Networks*, INSA Lyon, June 2016, https://hal.inria.fr/tel-01428983.

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Articles in International Peer-Reviewed Journal

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